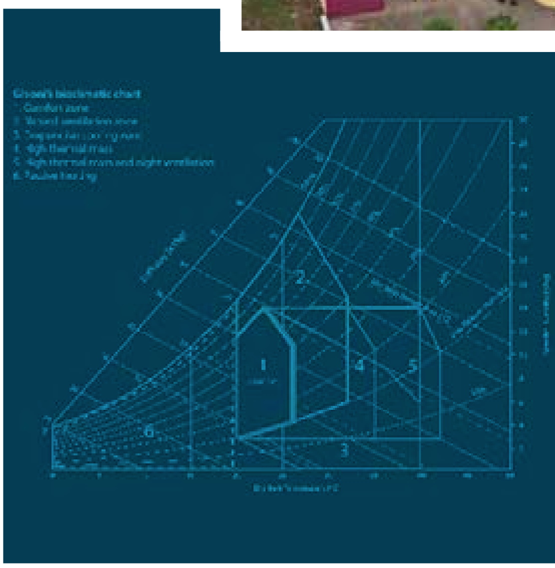
SUSTAINABLE BUILDING DESIGN FOR TROPICAL CLIMATES

Principles and Applications for **Eastern Africa**



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SUSTAINABLE BUILDING DESIGN FOR TROPICAL CLIMATES
Principles and Applications for **Eastern Africa**

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01 INTRODUCTION

.... The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by the other arts is put to test.....

... He ought, therefore, to be both naturally gifted and amenable to instruction. Neither natural ability without instruction nor instruction without natural ability can make the perfect artist. Let him be educated, skilful with the pencil, instructed in geometry, know much history, have followed the philosophers with attention, understand music, have some knowledge of medicine, know the opinions of the jurists, and be acquainted with astronomy and the theory of the heavens...

Marcus Vitruvius Pollio, De Architectura, Year 15 B.C.

1.1 BACKGROUND

Climate change and resource depletion are the main challenges that mankind has to face in the 21st century. Through its impact on ecology, rainfall, temperature and weather systems, global warming will directly affect all countries. Nobody will be immune to its consequences. However, some countries and people are more vulnerable than others. In the long term, the whole of humanity faces risks but the more immediate risks are skewed towards the world's poorest and most vulnerable people.

We know that the world is warming and that the average global temperature has increased by around 0.7 °C since the advent of the industrial era. We also know that this trend is accelerating: average global mean temperature is rising by 0.2 °C every decade. With the global rise in temperature, local rainfall patterns are changing, ecological zones are shifting, the seas are warming and the ice caps are melting.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change[1] (IPCC) states that significant global impacts on ecosystems and water resources are likely at global temperature rises of between 1 and 2 °C, and that net negative impacts on global food production are likely to occur at temperature increases from 2-2.5 °C upwards, compared to pre-industrial levels (Fig. 1.1-1). The IPCC report also says that up to 2050 substantial global emission reductions of at least 50% below 1990 levels are needed, with additional global emission reductions beyond 2050, moving towards a zero carbon economy by the end of the century. This is the only way to keep the temperature increase to 2 °C, which is considered to be the maximum we can afford without incurring catastrophic consequences.

The present situation is very worrying. In 2010, world greenhouse gas (GHG) emissions reached 7 tons CO_2 eq per capita[2], with a large gap between developed and developing countries (Fig. 1.1-2). To achieve the 2 °C target, world GHG emissions should be reduced to 2 tons CO_2eq per capita. EAC countries are presently at about this level; the challenge is to keep the same level of emissions without curbing economic development.

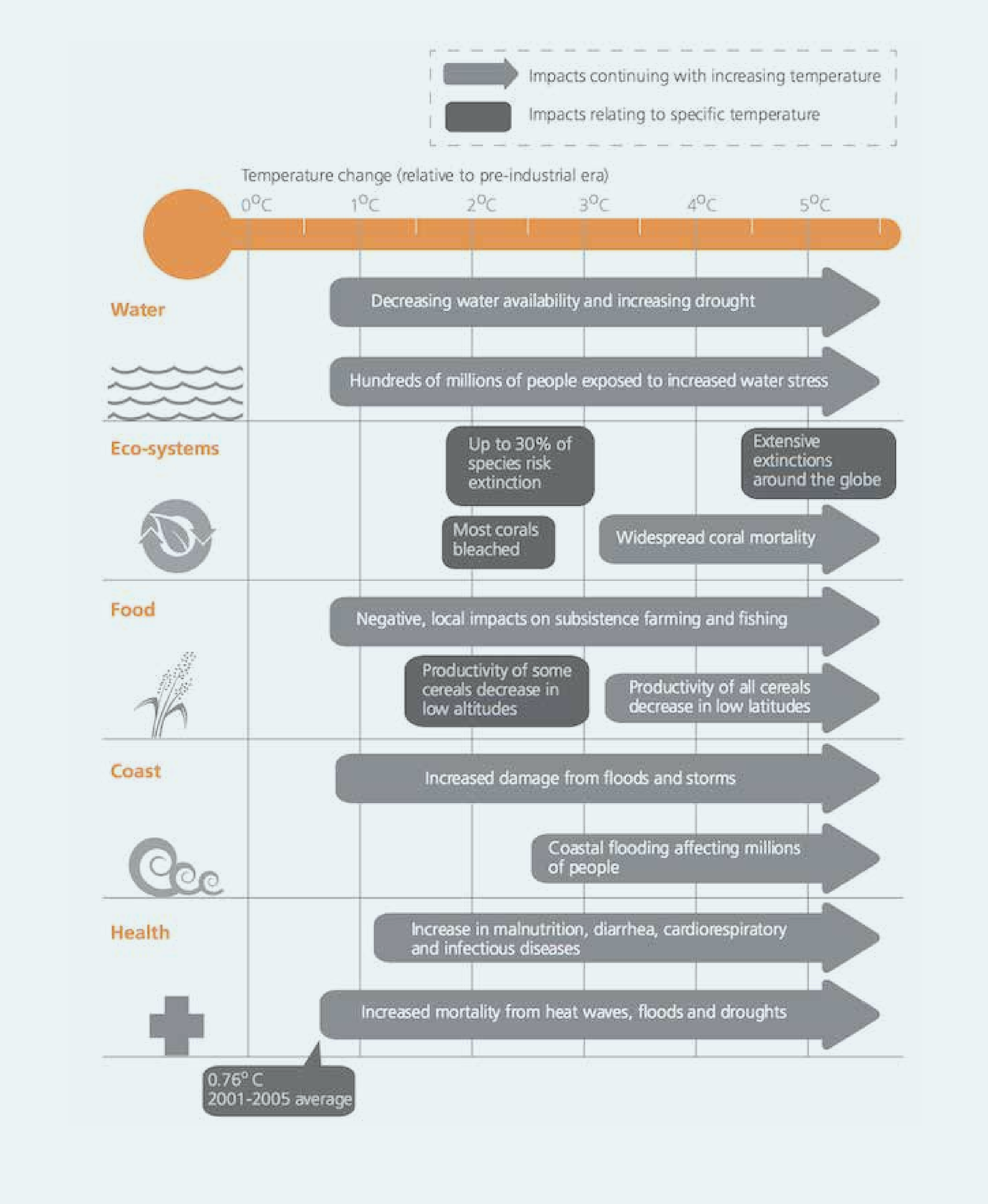
Resource depletion is another critical issue. Both mineral and biological and resources are being depleted and little is going to be left for our descendants. Most essential minerals are going to last less than 40 years (Fig. 1.1-3), because of the progressive reduction of the ore grades.

Biological resources are also being rapidly depleted: our ecological footprint is growing and the planet's biocapacity is shrinking. Since the 1970s, humanity's annual demands on the natural world have exceeded what the Earth can renew in a year. This "ecological overshoot" has continued to grow over the years, reaching a 50 per cent deficit in 2008.

1 http://www.ipcc.ch

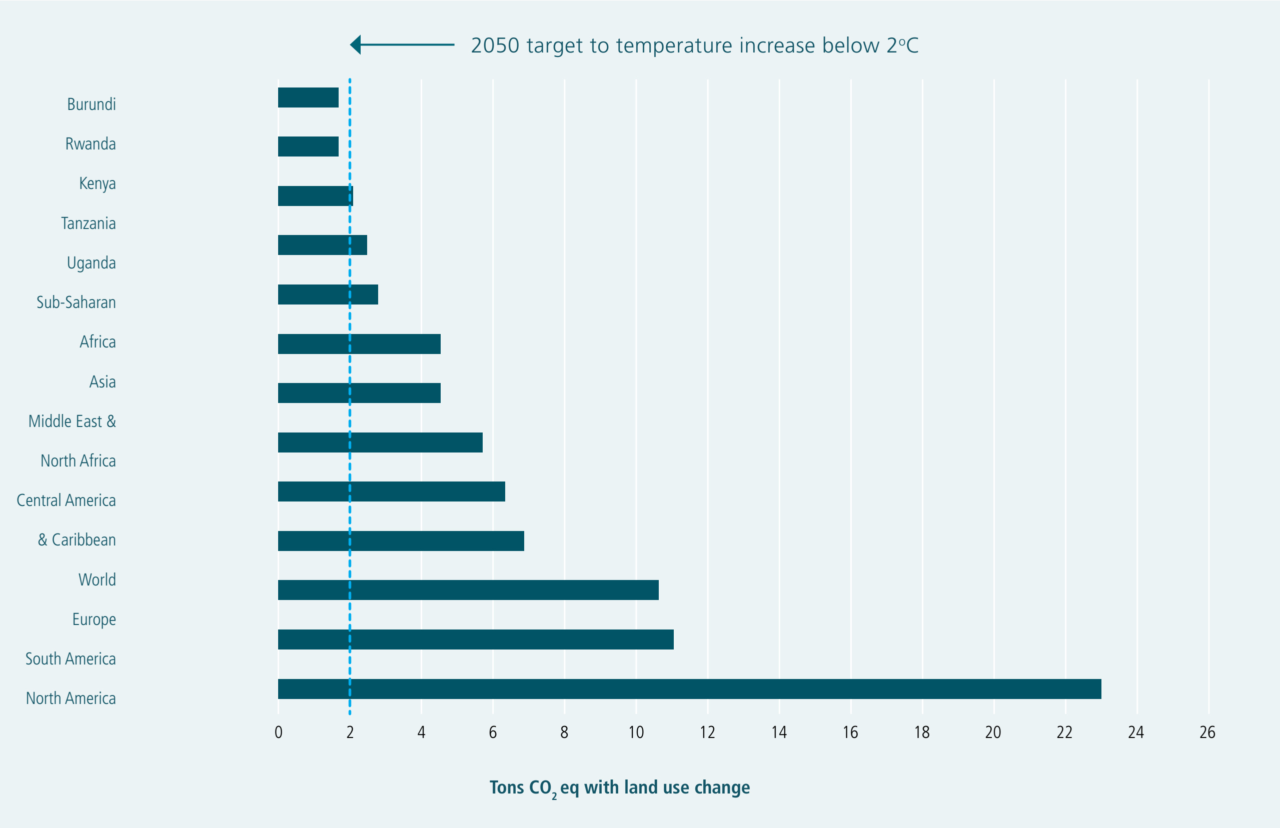
2 Total GHG gas emission in 2010 was 48628 Mton eq (source: Ecofys, Updated information on the world's greenhouse gas emissions, 2013 - http://www.ecofys.com/en/news/updated-information-on-the-worlds-greenhouse-gas-emissions/) and the world population 6916183 thousand (source: UN, Dept. Economic and Social Affairs - http://esa.un.org/unpd/wpp/unpp/panel_population.htm)

FIGURE 1.1-1 **IMPACT OF 2 °C GLOBAL TEMPERATURE INCREASE**



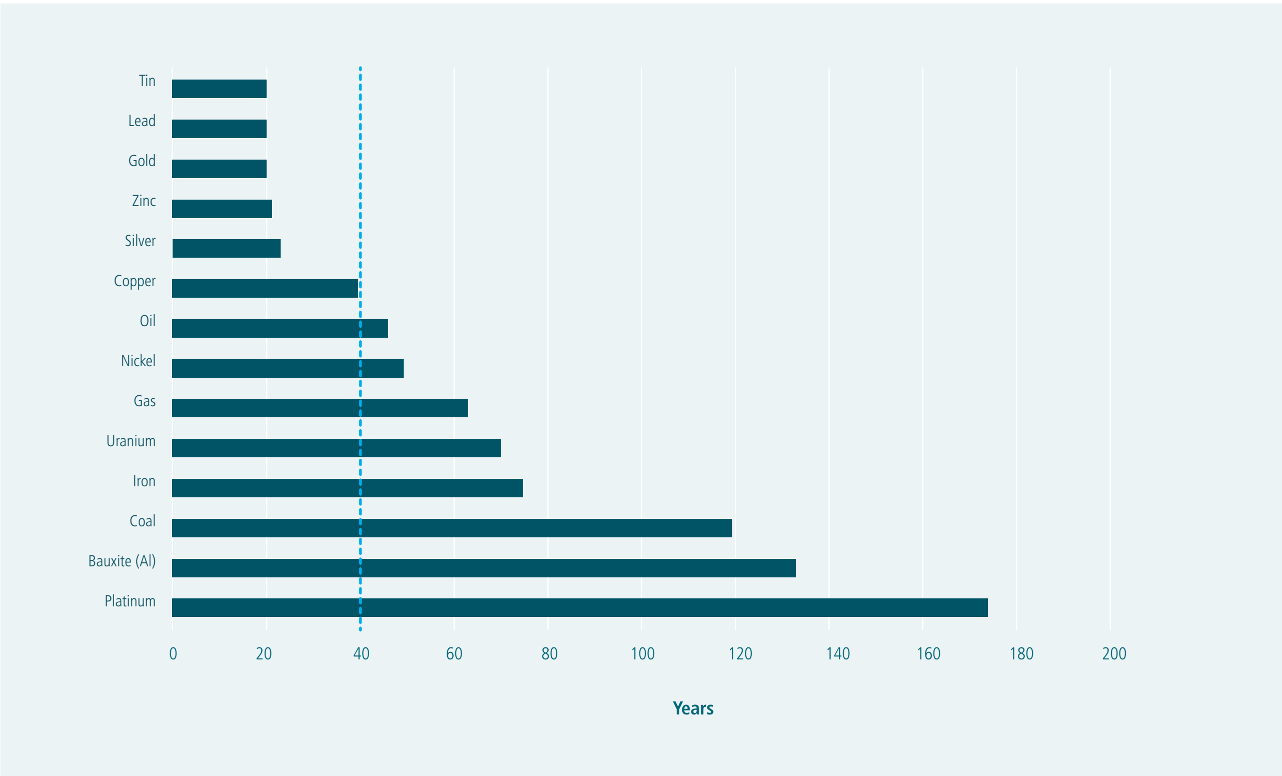
***Source:** UN-Habitat, Sustainable Urban Energy: A Sourcebook for Asia, 2012*

FIGURE 1.1-2 **GREENHOUSE GAS EMISSIONS IN THE YEAR 2000**



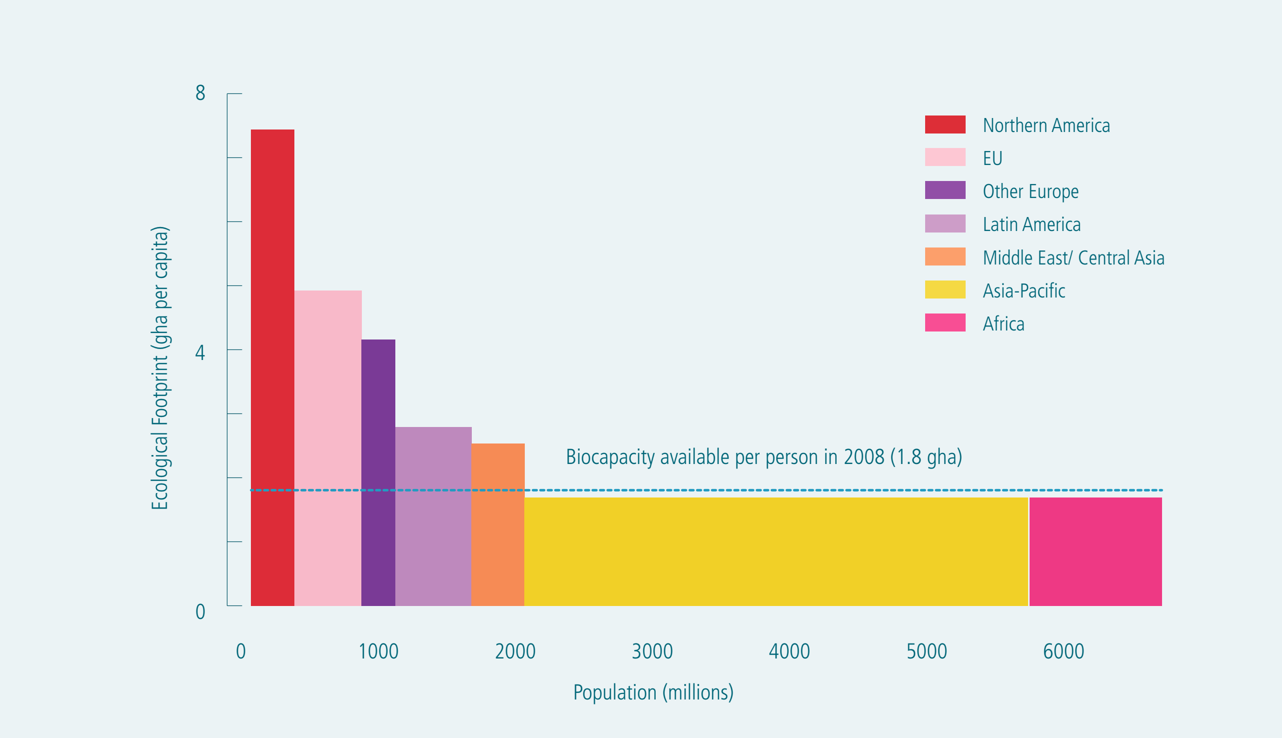
Source: *Wikipedia - http://en.wikipedia.org/wiki/List_of_countries_by_greenhouse_gas_emissions_per_capita*

FIGURE 1.1-3 **POTENTIAL SHORTAGE OF MATERIALS – RESERVES (2010 PRODUCTION)**



Adapted from: *McKinsey&Company, Resource Revolution: Meeting the world's energy, materials, food, and water needs, 2011.*

FIGURE 1.1-4 **ECOLOGICAL FOOTPRINT BY GEOGRAPHICAL GROUPING, 2008**



Source: *WWF, Living Planet Report 2012*

This means that it takes 1.5 years for the Earth to regenerate the renewable resources that people use, and to absorb the CO_2 waste they produce in one year[3]. Developed countries have a very high per capita ecological footprint, higher than developing countries. The overall impact on the global ecological footprint, however, is comparable because of the larger population of the latter (Fig. 1-4). It is also important to compare ecological footprint and biocapacity in each individual country. In 1961, for example, Kenya and Tanzania's Ecological footprint was lower than the countries' biocapacity. In 2009 the situation was reversed and Kenya had a deficit of about 0.5 Global Hectares per capita and Tanzania of about 0.2[4].

1.2 THE BUILDING SECTOR

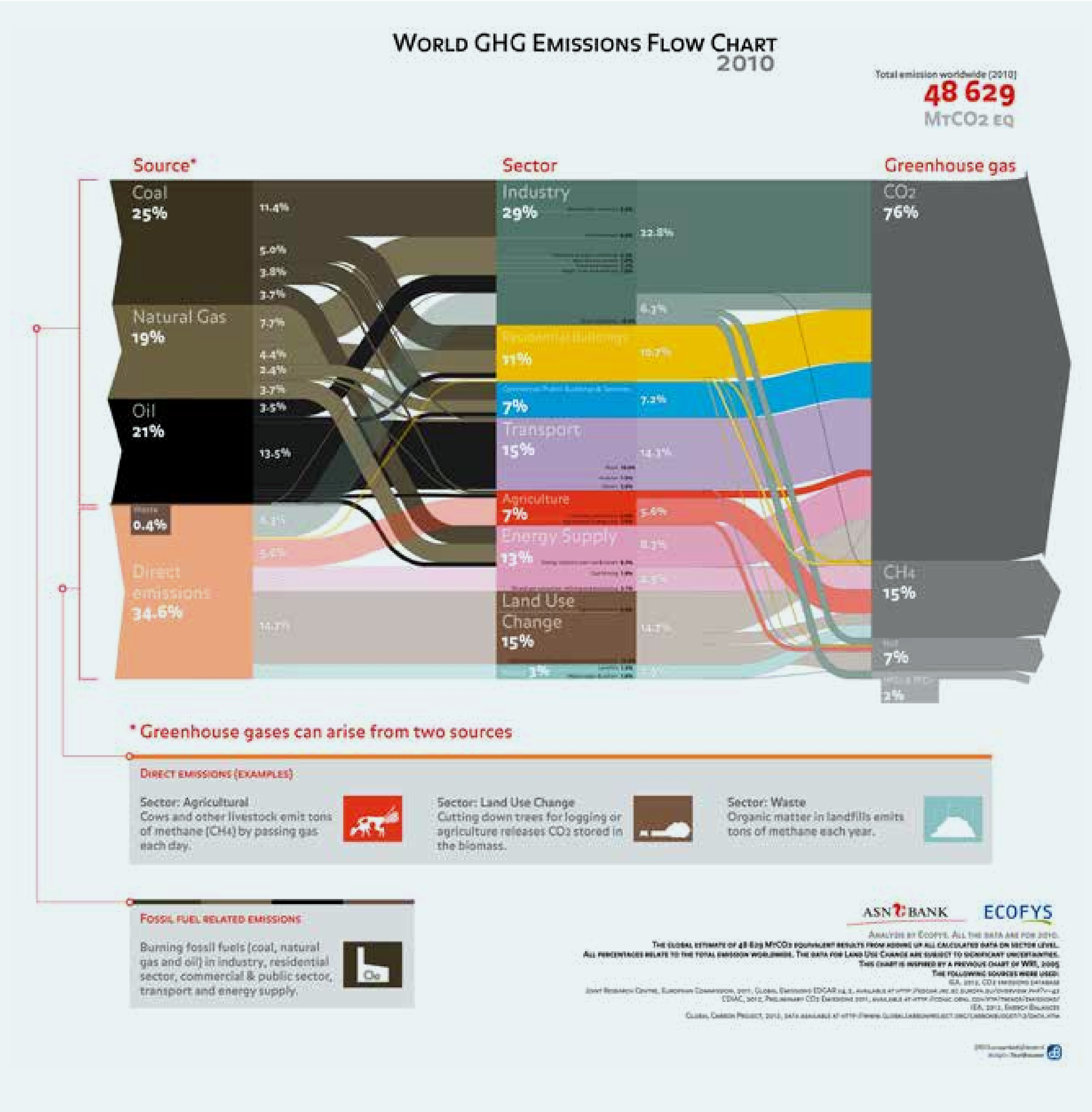
In 2010 the worldwide building sector was responsible for 24% of the total GHG emissions deriving from fossil fuel combustion, second only to the industrial sector (Fig. 1.2-1); but, if the embodied energy of construction materials is included, the share is far higher and the building sector becomes the prime CHG emitter. Thus, building design and construction have a significant effect on the chances of meeting the 2 °C target . This is even truer when we take into account the fact that most of the energy presently consumed in buildings in developing countries is biomass and that the expected improvement in living conditions will lead to a shift from biomass to fossil fuels, dramatically increasing CO_2 emissions (in developed countries, the building sector is responsible for 40% of fossil energy consumption). The increase in EAC countries, in the absence of sustainable building design and construction, would be even more dramatic, since the share of final energy consumption of the building sector is well above 60%.

Developing countries are going to play a decisive role in the future world energy scenario, as a consequence of their economic development. Industrial energy consumption will grow, and a dramatic increase in energy consumption for transport can be expected, with the growth in the number of vehicles on the roads - if the currently accepted worldwide approach to mobility does not change.

The increase in energy consumption in the building sector can be expected to be even more dramatic, not only because air conditioning will spread and the number of domestic electric and electronic appliances will grow, but also because of the increase in the number of buildings.

3 *WWF, Living Planet Report 2012*
4 *Global Footprint Network - http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_for_nations/*

FIGURE 1.2-1 **WORLD GHG EMISSION FLOW CHART, 2011**



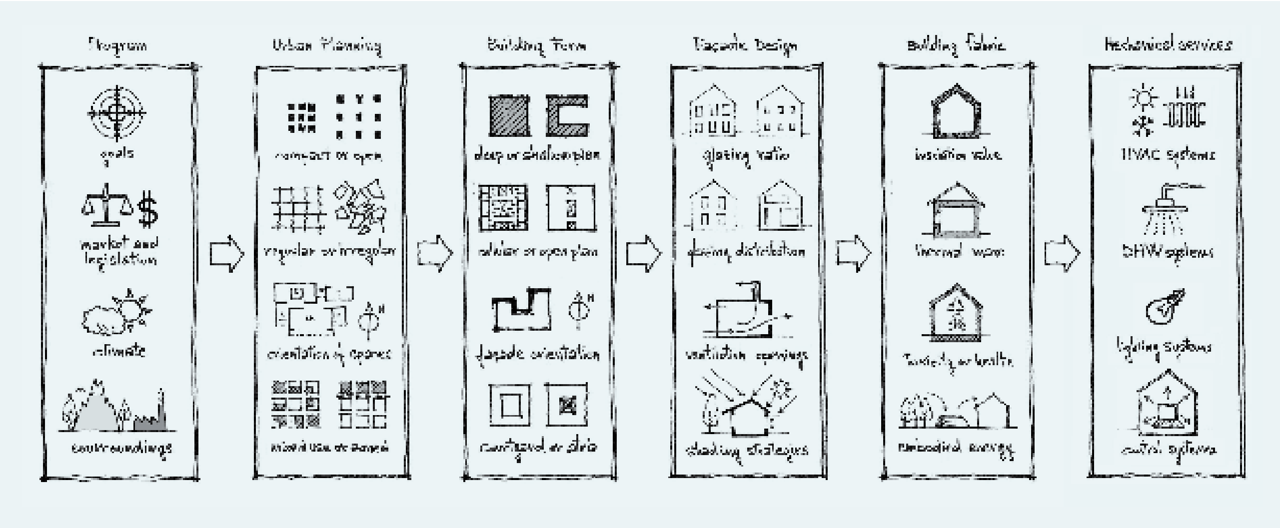
Source: *Ecofys, Updated information on the world's greenhouse gas emissions, 2013 - http://www.ecofys.com/en/news/updated-information-on-the-worlds-greenhouse-gas-emissions/*

While in Europe it is expected that, by the year 2050, some 25-30% of the building stock will have been built, in developing countries that figure can be estimated at close to 75%. If all these new buildings are as energy consuming as the present ones, it will be impossible to meet the target of curbing CO_2 emissions to an acceptable value.

The building sector must therefore do its part, and the long-term goal is to transform buildings from energy consumers into net energy producers. This, of course, will be possible for new buildings, which will have the task of compensating for the inevitable energy consumption of existing ones – but even this has to be greatly reduced.

The challenge is unprecedented and will require (in fact it already requires) a radical transformation of the methods of designing and building. The reduction of CO_2 emissions by reducing energy consumption is the top priority facing the construction industry today.

FIGURE 1.3-1 **THE PHASES OF THE DESIGN PROCESS IN WHICH CHOICES HAVE AN INFLUENCE ON A BUILDING'S ENERGY PERFORMANCE AND COMFORT**



1.3 INTEGRATED DESIGN

Building envelope design, which aims to achieve the maximum comfort with the minimum primary energy consumption (and thus to minimise GHG emissions), requires that the parameters of comfort and energy be integrated into each of the critical steps of the design process (Fig. 1.3-1). Factors such as climate, master plan, building shape, façade design, the thermo-physical characteristics of the materials, and finally the building plan, must play a role in decisions.

To achieve this goal, a high level of integration among the skills called into play in the design process is required.

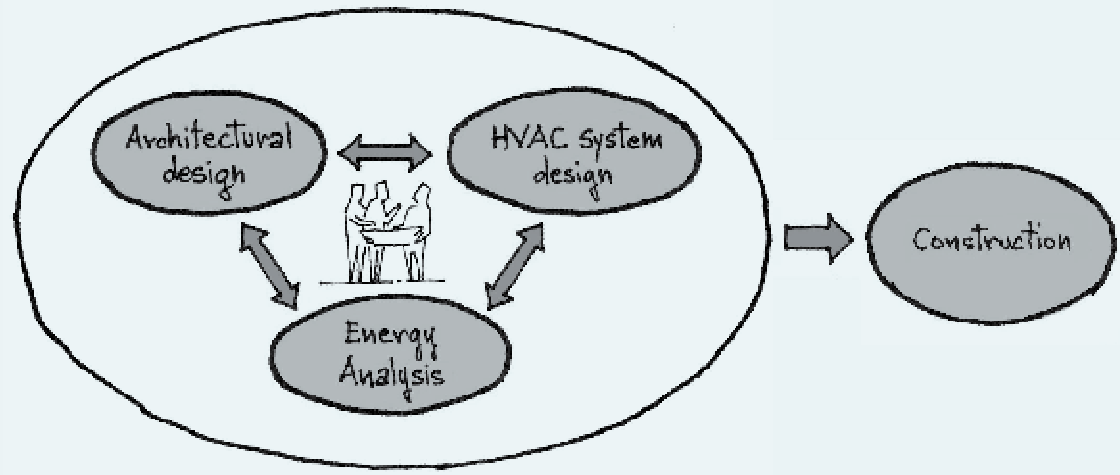
The design process, nowadays, is based on a linear path, in three steps: architectural design, followed by design of the mechanical systems (when the building is equipped with an air conditioning system), and then construction (Fig. 1.3-2). The architect – because of his training – usually knows little or nothing about building physics; consequently architectural choices very often have a negative impact on the building's energy performance, and on the occupants' comfort.

This approach is incompatible with the design of low energy, high comfort buildings. It is necessary to change the design methodology, and make use of an integrated design model that includes, inter alia, the introduction of new professional expertise: the energy expert (Fig. 1-8).

FIGURE 1.3-2 **USUAL DESIGN PROCESS**

The energy expert must have an in-depth knowledge of building physics; he must be able to interact with the architect and with the mechanical engineer; he must not only be capable of managing rules of thumb, but he must also be able to use sophisticated simulation tools for evaluating the energy performance of the building, thermal comfort, daylighting, natural ventilation and all the passive means of reducing energy demands. From these evaluations the energy expert derives recommendations for the architect and the mechanical engineer who, in turn, modify their design choices accordingly, proposing new solutions that have to be re-evaluated. This circular process is repeated until a satisfactory solution is reached, taking into account not only energy, but also aesthetics, functionality and economy (Fig. 1.3-4).

FIGURE 1.3-3 **INTEGRATED DESIGN**

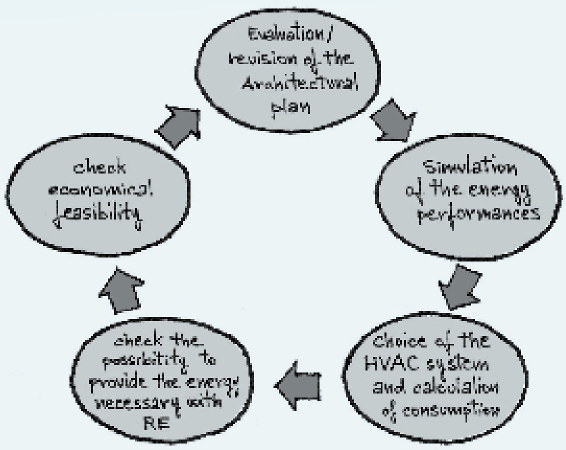


It is also essential that these skills are integrated from the earliest stages of the process. Indeed, it is in these phases that most critical decisions are taken, greatly influencing the energy performance of the building, the comfort of the occupants and construction costs (Fig. 1.3-5).

Of course, the new process is more time consuming and expensive, but its higher cost is outweighed not only by the lower energy bill and the greater comfort, but also by the lower construction costs, compared with the cost of a building with the same energy performance but designed through the usual design process; this is also because the unfortunately common practice of oversizing a building's components and HVAC systems can be avoided.

It is not sufficient, however, that the new design process integrates new expertise, and that it changes from linear to circular. It is also necessary to define a planning strategy which focuses on creating a low energy, comfortable building that is not simply a "normal" building in which renewable energy is used instead of oil or gas. It should be a building designed in a different way, using the planning strategy depicted in figure 1.3-6. which shows that maximum effort must go into minimising the amount of energy needed to provide high levels of thermal and visual comfort, by means of appropriate architectural design. Only after this has been done can the issue of maximising the energy efficiency of mechanical systems

FIGURE 1.3-4 **SUSTAINABLE DESIGN PROCESS**



and their appropriate control be tackled. Eventually, if the process has been carried out in the best possible way, the amount of primary energy needed will be very small and it will be easily supplied from renewable sources: the higher the energy efficiency of the whole building+HVAC system, the lower the size, and hence the cost, of the renewable energy production system.

FIGURE 1.3-5 **THE EARLIER THE INTEGRATION OF EXPERTISE IN THE DESIGN PROCESS, THE GREATER THE IMPACT ON PERFORMANCE, AND THE SMALLER THE COST**

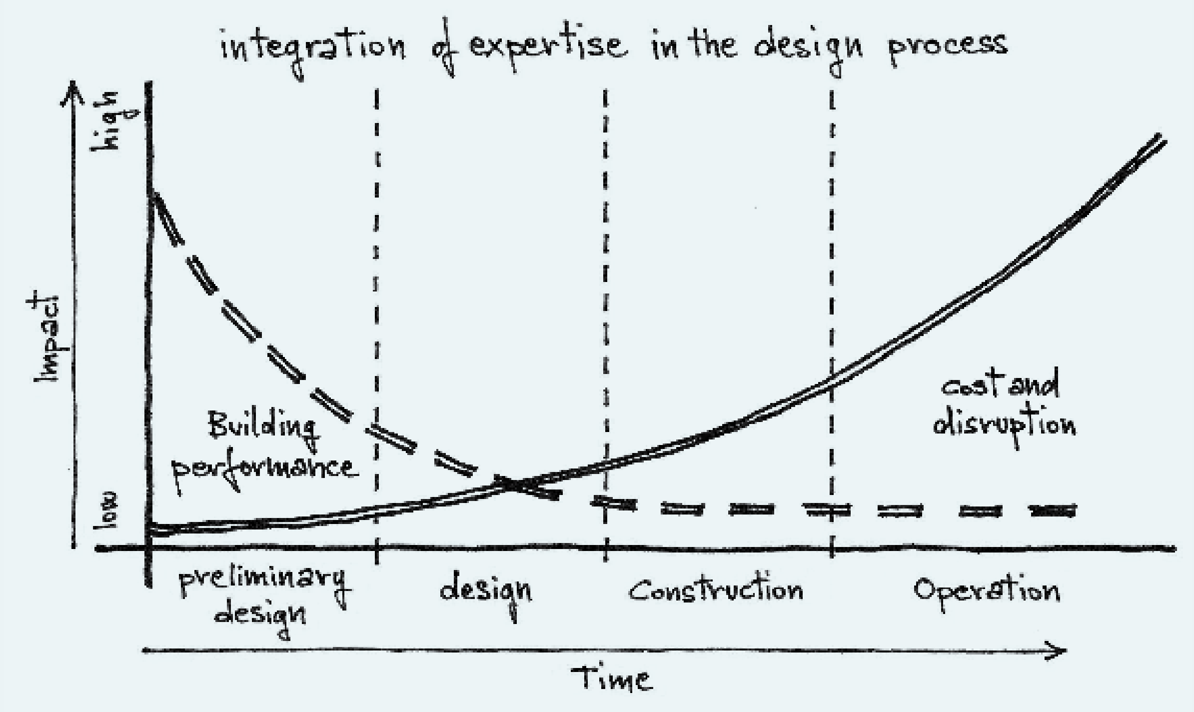
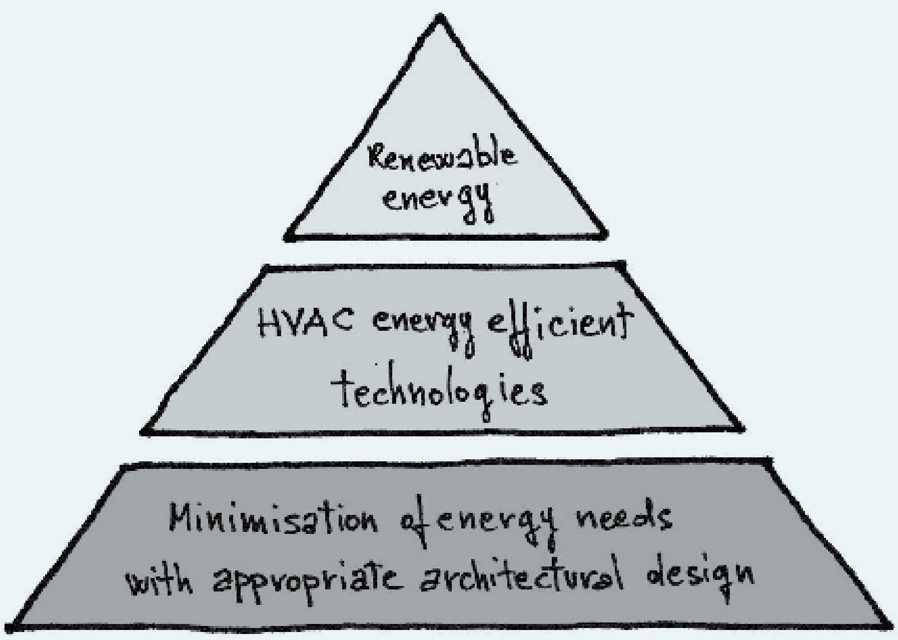


FIGURE 1.3-6 **TOWARDS LOW ENERGY, HIGH COMFORT BUILDINGS: DESIGN STRATEGY**



1.4 CONSTRUCTION MATERIALS

About 40% of the raw materials and energy produced worldwide are used in the building sector.

The production of cement, steel, glass, aluminium and baked bricks, which are the basic building materials for most modern constructions, have very high environmental impacts, consume the most energy and cause the majority of the GHG emissions in the construction sector[5] because their production requires the processing of mined raw materials at a very high temperature.

The cement industry is responsible for ~1/4 of the annual worldwide CO_2 emissions from fossil fuels[6].

The production of iron and steel, which is also used in reinforced concrete, is responsible for more than 4% of the total energy use worldwide and the related GHG emissions[7].

The production of glass also causes immense GHG emissions because its production is very heat energy intensive, but glass can also help to save and gain energy if it is utilised in an appropriate way, not according to the present architectural fashion. Intelligent use of the available natural materials such as inorganic materials (e.g. natural stones and clay) and especially the utilisation of building materials made out of organic raw materials, produced from biomass which is renewable, can lead to a significant reduction in the GHG emissions and the environmental impacts caused by the production of building materials.

Developing countries need not go through the same process of development as that followed by developed countries. Instead these countries can choose to base all future development on the principles of sustainability[8].

Sustainable construction practices in the developing world have to be achieved as soon as possible, because the building and construction sector in these countries is growing very fast. Additionally the shift towards sustainability in the construction sector may play an important role in shifting the economic structure towards sustainability and in improving the quality of life of the poor. Innovations in sustainable building materials, construction methods and architectural design can be based on traditional knowledge and practice, which are in general relatively well adapted to local climates (see chapter 4) and use locally available materials. Development also has to be adapted to specific ecological, economic and social conditions in order to meet present and future needs and requirements.

However, the majority of people want to use "modern" and "fashionable" building materials, such as metal sheets as roofing material and cement blocks and cement plaster as wall building materials, not because the indoor climate is better than in houses built with traditional materials and methods, but because it looks "modern". The utilisation of these techniques in cities requires rethinking; politicians, investors, city planners and architects in particular should abandon the vision of the architecture and town planning of the 20th century, which has proved to be unsustainable.

1.5 ARCHITECTURE IN TROPICAL CLIMATES

In developed countries, which are mostly located in cold climates, the main cause of energy consumption in buildings is heating, but the efforts to curb this consumption are being more and more frustrated by the growth of air conditioning. In EAC climates the challenge is only the latter[9]. The growth in energy consumption for air conditioning is due to the need to live in more comfortable spaces, and this is justified, but it is exacerbated by two other factors: inappropriate architecture and the wrong approach to thermal comfort. The former can be offset by following the principles of sustainable building design, but the latter requires a behavioural change. Temperatures in North American air conditioned buildings, and unfortunately also in buildings in most developing countries, are far below the physiological requirements for thermal comfort. Temperatures set below 24 °C are common in all commercial buildings, often requiring occupants to wear a pullover or a jacket and – in hotels – to use blankets. This does not happen in Europe, where temperatures in air-conditioned spaces do not usually fall below 25 °C.

In tropical climates, therefore, the challenge for containing the growth of energy consumption in buildings is not limited to a change in the mentality of architects and builders, but also in the mentality of final users.

The combination of both a well-designed building, where solar gains are controlled and natural ventilation is fully exploited, along with a change in comfort principles, can dramatically reduce energy consumption for air conditioning and provide very good conditions of comfort.

Sustainable architecture in tropical climates is a still an unexplored field, and it is an extraordinary challenge for architects, who should be willing to integrate basic information about building physics and aesthetics, and to

5 *CIB, UNEP – IETC; "Agenda 21 for Sustainable Construction in Developing Countries"; South Africa 2002*

6 *UNEP DTIE IETC, Basic Principles and Guidelines in Design and Construction to Reduce Greenhouse Gases in Buildings*

7 *World Resources 2000-2001, http://www.wri.org*

8 *C. du Plessis, Agenda 21 for Sustainable Construction in Developing Countries, CSIR Building and Construction Technology, 2002 - http://www.cidb.org.za/documents/kc/external_publications/ext_pubs_a21_sustainable_construction.pdf*

9 *Some increase of energy consumption for heating can be expected in high upland climate, but is absolutely negligible compared to that of air conditioning in all other climates.*

abandon the approach, (now old and out-dated) which imitates the architecture of developed countries.

1.6 A NEW ENERGY SYSTEM FOR CITIES

When, about two centuries ago, the first gas networks were built in our cities, the basis for the present urban energy system was set up. At that time coal was the only fossil energy source used. A little more than a century ago urban electric grids appeared, and coal was slowly replaced by oil and natural gas. Wood and charcoal soon disappeared; horses were substituted by cars and public transportation systems started to develop. At the beginning of the last century the main cities of the western world were provided with a sewage system, a water network and a solid waste collection system. There was no more hard work carrying water from the fountains, there were no more epidemics, instead there were comfortable interiors with heating, cooling and electric lighting, an easier life at home with domestic appliances, and fast mobility. The quality of life was revolutionised thanks to cheap fossil fuels and to the technologies fed by them.

Cities slowly changed, and learnt to metabolise fossil fuels, building up an urban energy system and an overall metabolic system that left no room for recycling: the saturation of the environment with wastes was not an issue. At the end of the process a new organism, the modern city, was born, fit for an environment that was assumed to be an infinite source and an infinite sink. The present urban energy system is designed on this assumption, and for this reason, it is incompatible with the extensive use of renewable energy sources; in the same way you cannot feed a lion with vegetables, it needs meat. Our task is to transform, with some sort of genetic engineering, our carnivore – the fossil energy based city – into a herbivore, the renewable energy based city. Unfortunately we do not have two centuries in front of us; we must do it in less than forty years. Forty years to redesign the energy systems of our existing settlements and less than twenty to learn how to design all the new ones in a different way. In the 1970s – after the first oil shock – a few pioneers began to introduce the energy issue into architectural design. Guidelines for low energy building design were implemented, and now they are becoming compulsory practice in the European Union and in some other countries .

Now is the time to introduce the energy issue into urban design, since the most significant energy savings can be obtained on this scale by redesigning the overall energy system.

This implies changing the priorities in the formal design of urban layout and in the organization of urban functions, but this is not all. The Distributed Energy Resources (DER) approach must be introduced. This consists of many small scale interconnected energy production and consumption units instead of a few large production plants.

It is the only way to design new settlements (or re-design existing ones) that are capable of relying mostly on renewable energy sources. It also implies an evolutionary jump towards a far more “intelligent” urban energy system, because a distributed control system is also needed – made possible by the present developments in the information and communication technologies. A change in the energy paradigm is the only chance we have of coping with the present world trend, which is leading to either economic or ecological catastrophe, or both.

It is not an easy task, because it is a technological change that implies a cultural change. The culture of architects and city planners, of citizens, of entrepreneurs, of city managers and politicians has to change.

02 CLIMATES AND BUILDING DESIGN

2.1 CLIMATIC PARAMETERS

Weather is the state of the atmospheric environment over a brief period of time in a specific place. Integrated weather conditions over several years are referred to as climate.

Different terms are used depending on the size of the geographical area considered. We refer to macroclimate for a large territory, meso-climate for a medium-size area, local climate and microclimate for a small area at the level of the individual or of a single confined space.

Local climate is generally related to an area ranging from a few square meters to a few hectares. For example, it can apply to the side of a hill, a valley or a portion of the built area, and is characterized by more or less marked changes in temperature, relative humidity, wind, sunshine, etc., due to the particular nature of the topography, urban morphology, orientation, nature of materials, proximity to water, presence or absence of vegetation, etc.

The main climatic parameters influencing the energy performance of a building are:

- solar radiation;
- air temperature;
- relative humidity;
- wind.

Solar radiation is the main driver of climate, since it influences temperature and gives rise to regional winds. The temperature at a given latitude depends on the angle of incidence of solar rays to the ground: it is highest at the equator and lowest at the poles. The higher the angle of incidence (and thus the lower the latitude) the more energy reaches the ground and the higher the air temperature.

Regional winds derive from the difference in air temperature (and thus pressure) between northern and equatorial latitudes.

2.1.1 SOLAR GEOMETRY

The earth moves along an elliptical orbital trajectory around the sun in a little more than 365 days, and also rotates around its own axis, which is inclined by about 67° to the plane of the orbit. It takes about 24 hours to perform a complete 360° revolution (Fig. 2.1-1). The earth's position during its own rotation may be defined by the hour angle ω, which is the angular distance between the meridian of the observer and the meridian whose plane contains the sun. This angle varies 15 degrees per hour, is zero at noon and has positive values in the morning and negative values in the afternoon (for example: at 10 a.m. ω = +30°; at 13 p.m. ω = -15°)

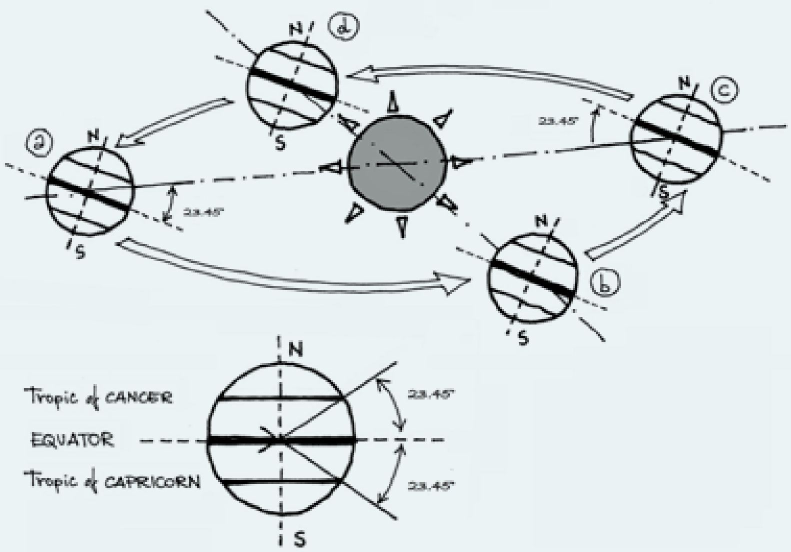
Seasonal climate change is the result of the different ways in which the sun's rays hit the various regions of the earth during the year. This is due to the inclination of the plane of the equator, thus to the inclination of earth's axis. The tilt of earth's axis with respect to the plane of the orbit is constant but the angle formed between the line joining the centre of the earth with the centre of the sun and the equatorial plane changes day by day, or, it is better to say, instant by instant. This angle is called the solar declination δ, is equal to zero at the spring and autumn equinoxes, and is +23.45° at the summer solstice and -23.45° at the winter solstice.

The angle of solar declination varies continuously, very slowly, and for our purposes it can be assumed that its value is approximately constant in a single day; it can be calculated using the formula:

$$\delta = 23.45\ sin\left[\frac{360}{365}(N + 284)\right]$$

Where N is the progressive number of the day of the year (N = 1 for 1st Jan., N = 365 for December 31st; for example: March 21st corresponds to N = 31 +28 +21 = 80).

FIGURE 2.1-1 **SOLAR DECLINATION ANGLE. (A) SUMMER SOLSTICE; (B) AUTUMN EQUINOX; (C) WINTER SOLSTICE; (D) SPRING EQUINOX**



As a consequence of the earth's movements around the sun, in the course of the year an observer on earth perceives different solar paths, which are characterized by variable heights and lengths, depending on time of year and latitude. The latitude is represented by the angle between the equatorial plane and the radius from the earth's centre to its surface at the specific location and ranges from 0° at the Equator to 90° (North or South) at the poles. Generally, in the calculations, the northern latitudes are considered positive and the southern ones negative.

In order to make the study of the solar geometry more intuitive, it is convenient to refer to the apparent movement of the sun, assuming that it moves on the inner surface of a sort of dome (the sky dome), having as its base the horizon line of the site (Fig. 2.1–2). In this way (and it is consistent with our perception), the sun rises in the east, climbs in the sky with a trajectory depending on the hemisphere, the latitude angle Φ and on the day of the year, and sets in the west.

FIGURE. 2.1-2 **APPARENT SUN PATH (EQUATOR)**

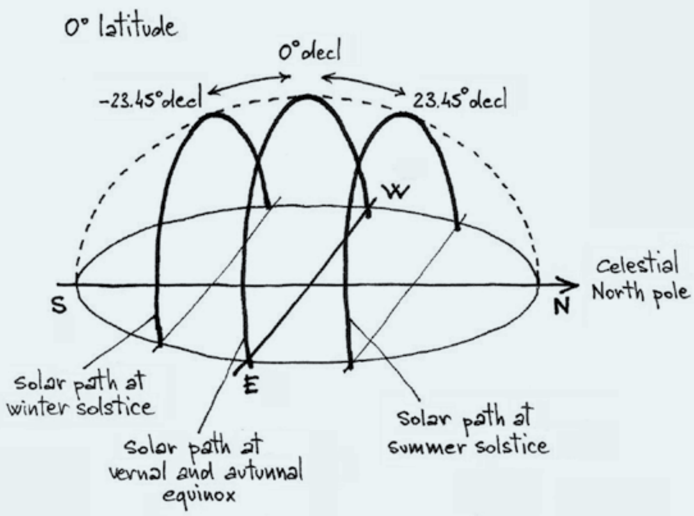
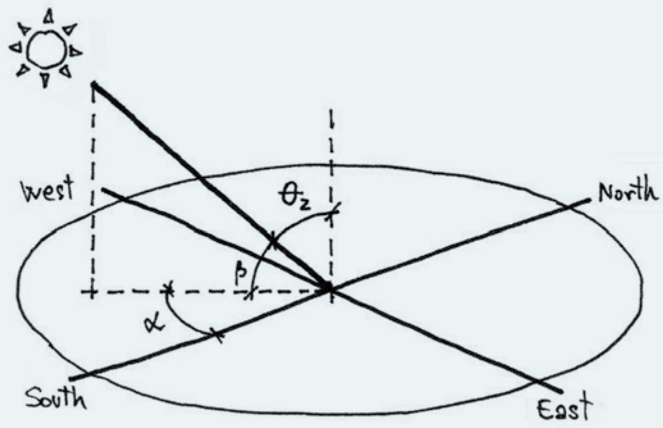


FIGURE 2.1-3 **ANGULAR COORDINATES OF THE SUN**



According to this assumption, the solar paths can be defined, and the consecutive positions of the sun in different days and months of the year can be found through two angular coordinates (Fig. 2.1-3): solar altitude, represented by the angle β between the direction of the geometric centre of the sun's apparent disk and the horizontal horizon plane, and the solar azimuth angle α, which is the angle, measured on the horizontal plane, from the south-pointing[10] coordinate axis to the projection of the line of sight to the sun on the ground.

Generally it is assumed that α is zero when the sun is exactly in the south, has positive values eastward and negative westward.

It should be noted that, in some of the literature, instead of the angle β, the angle θ_z is used, which is its complementary angle; this is the zenith angle.

Knowledge of solar geometry is very important for architectural design and energy efficiency strategies, since solar energy greatly influences the energy performance of buildings. When the sun is low on the horizon, it is more difficult to control its effect and the rays can penetrate deeply through the windows. The contribution of light could certainly be useful, but the associated thermal loads can result in heavy energy consumption or in conditions of discomfort.

It should be noted that in tropical and equatorial regions, the sun has an altitude higher than 30° for about 75% of the year. However, the high solar altitude makes the south or north facades, on which more inclined rays fall in the central part of the day, less critical than the east and west ones during morning and evening, when the sun is low and can penetrate more deeply into the buildings.

10 North as reference for measuring the azimuth angle may also be found

2.1.1.1 **SOLAR AND LOCAL TIME**

Solar time is usually used in solar work. This is measured from the solar noon, i.e. the time when the sun appears to cross the local meridian. This will be the same as the local (clock) time only at the reference longitude of the local time zone[11]. The time adjustment is normally one hour for each 15° longitude from Greenwich, but the boundaries of the local time zone can be different, for social, economical or political reasons. In most applications in architecture it makes no difference which time system is used: the duration of exposure is the same; it is worth converting to clock time only when the timing is critical.

Clocks are set to the average length of day, which gives the mean time, but on any reference longitude the local mean time deviates from solar time of the day[12] by up to -16 minutes in November and +14 minutes in February (Fig. 2.1-4) and its graphic representation is the analemma (Fig. 2.1-4).

2.1.1.2 **SUN CHARTS**

The apparent position of the sun can be calculated at any place and time, using different algorithms taking into account geographical, astronomical and time variables.

Alternatively, accepting some simplification, specific charts can be used, referring to the latitude of the site, in which the values of monthly average hourly solar elevation and azimuth are shown.

11 This means that, if the site is located east of the reference meridian, when the clock marks noon, the sun has already passed its highest point in the sky, and vice versa if the site is located west.

12 The variation of day length is due to the variation of the earth's speed in its revolution around the sun (faster at perihelion but slowing down at aphelion) and minor irregularities in its rotation.

FIGURE 2.1-4 **EQUATION OF TIME DIAGRAM**

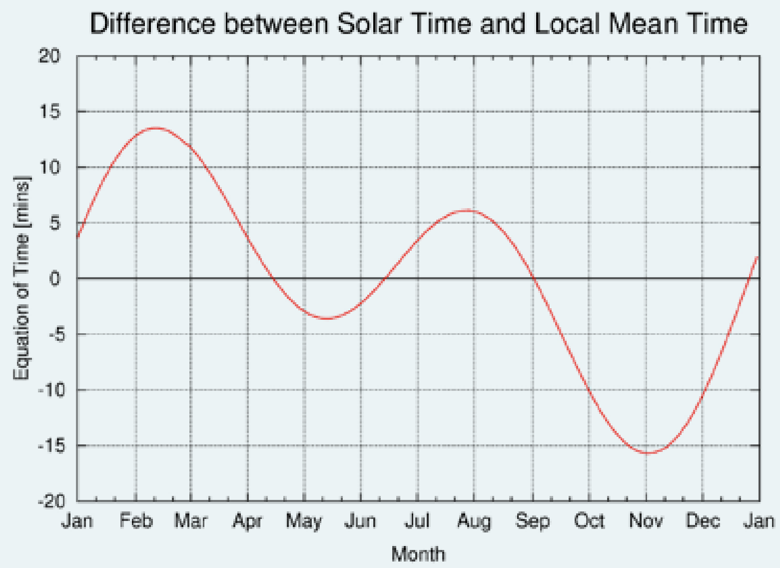
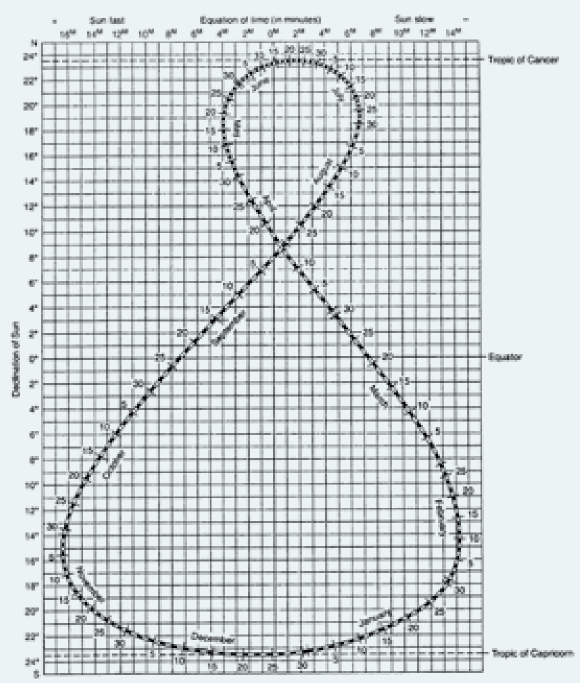


FIGURE 2.1-5 **ANALEMMA**



Sun path diagrams are a convenient way to represent the annual changes in the sun path through the sky on a single 2D diagram.

There are several ways of showing the 3-D sky hemisphere on a 2-D circular diagram. They can be thought of as paths traced on the overhead sky dome, projected on a horizontal plane (polar diagrams, or on a vertical plane[13] (cylindrical diagrams). The most widely used is the stereographic (or radial) representation, which uses the theoretical *nadir* point as the centre of projection (Fig. 2.1-6).

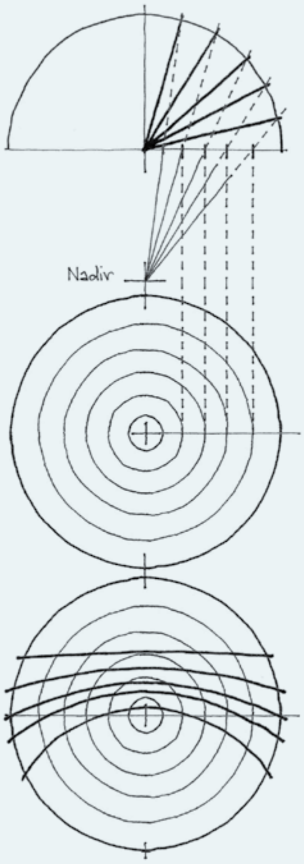
Polar diagrams

The polar sun charts are obtained by projecting the solar paths onto a horizontal plane, on which the four cardinal axes are represented. These charts have a common base, represented by a series of concentric circles and radial straight lines that branch out from the centre (Fig. 2.1-7).

The values of solar altitude β are represented by the circumferences (the outermost corresponds to $\beta = 0°$, horizon, while the centre corresponds to $\beta = 90°$, zenith).

13 *In this text we will refer only to the polar diagrams, more suitable in the equatorial belt.*

FIGURE 2.1-6 **STEREOGRAPHIC POLAR DIAGRAM CONSTRUCTION**



The values of solar azimuth α are indicated by the radial lines, and can be read out as the angular distance from the south-pointing coordinate axis. Polar diagrams show seven curves, different for each latitude, plotting the average path of the sun in two particular months (solstices, December and June) and 5 pairs of symmetrical months (in which the plots are practically coincident), i.e. :

- January and November;
- February and October;
- March and September (equinoxes);
- April and August;
- May and July.

The slightly curved lines intersecting the seven monthly paths join the points corresponding to the same hour of the different months. (Fig. 2.1-8).

Designing with sun charts

Sun path diagrams are used to evaluate how the sun affects the design context. For instance, once the sun's position (that corresponds to a point on the chart) at a given monthly average day and hour has been found, it is possible to draw an imaginary line, ideally representing the sun's rays, from this point to the building (Fig. 2.1-9). In this way one can predict which part of the building will receive direct solar radiation at that time and at which angle.

FIGURE 2.1-7 **PROJECTION OF SOLAR PATH ON THE POLAR CHART**

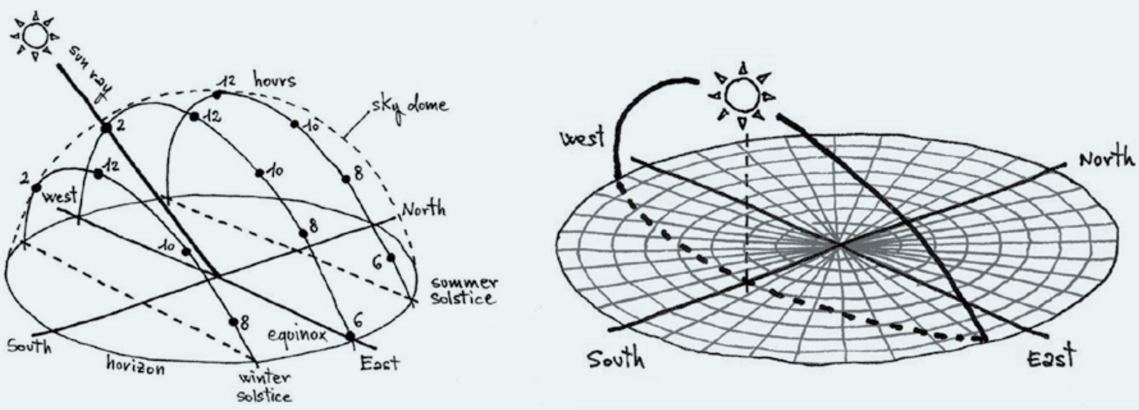


FIGURE 2.1-8 **POLAR SUNPATH DIAGRAM OR SUNCHART AT THE EQUATOR**

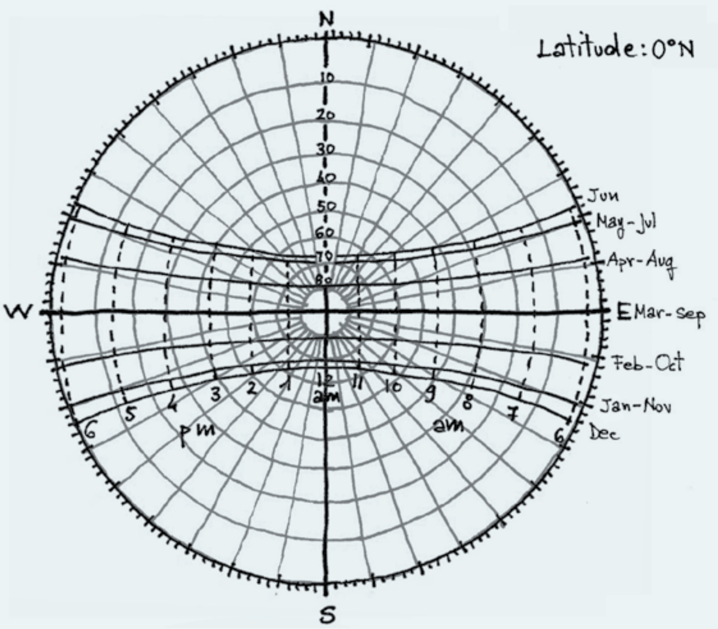
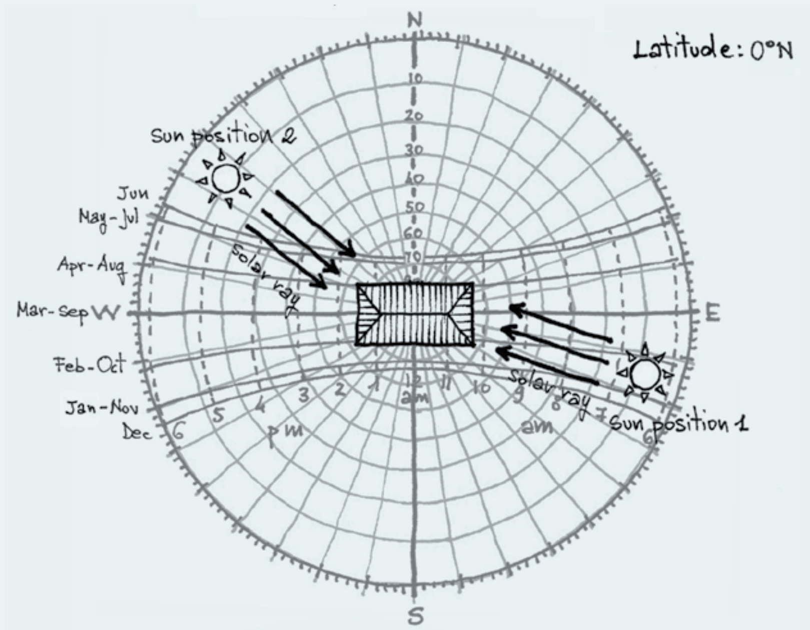


FIGURE 2.1-9 **USE OF SUNCHART EXAMPLE**



2.1.1.3 **SURFACE SPATIAL COORDINATES**

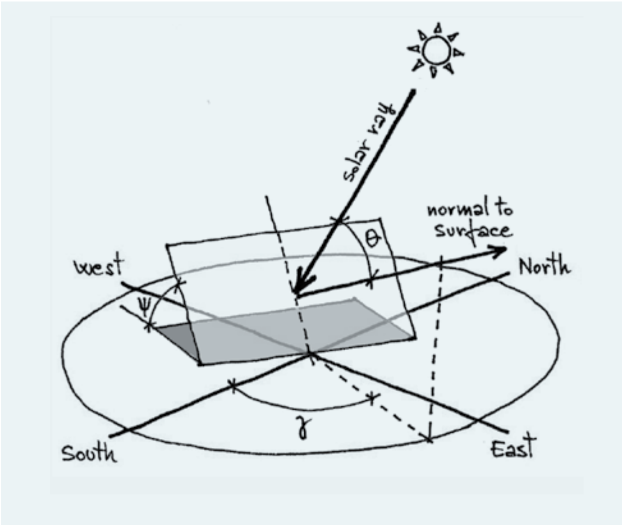
Once the position of the sun has been defined, the description of the spatial position of irradiated surfaces is needed, in order to analyse mutual interactions. For this purpose, the following parameters are used (Fig. 2.1-10):

- γ, surface azimuth, is the angle between the horizontal projection of the normal to the surface with the south-pointing axis. It is 0° when the orientation coincides exactly with the south, and takes positive values eastward and negative westward, so that you have γ = 90° for east, γ = -90° for west and γ = 180 ° for north orientation.

- ψ, tilt angle of the surface, indicates the angle formed by the surface with the horizontal plane. It is ψ = 0° for horizontal and ψ = 90° for vertical arrangement.

- θ, angle of incidence; it is formed by the sun's rays with the normal to the irradiated surface. It is 0° when sun's rays are perpendicular to the surface and 90° when they are parallel to it.

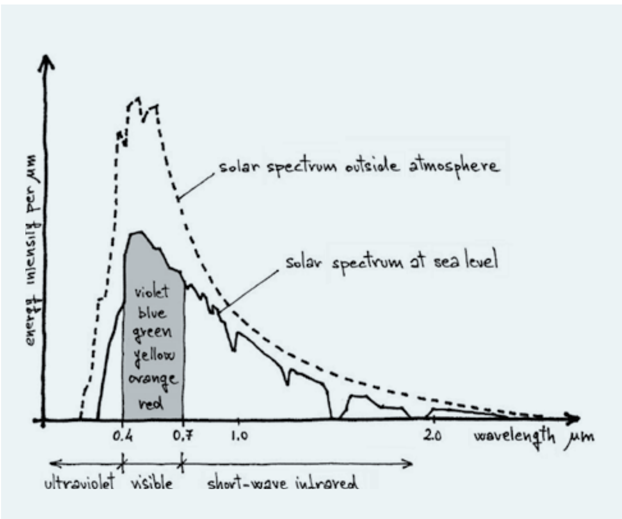
FIGURE 2.1-10 **SURFACE AZIMUTH γ, TILT ANGLE ψ AND INCIDENCE ANGLE θ**



2.1.2 SOLAR RADIATION

The sun emits electromagnetic waves characterized by wavelengths of between 0.1 nm and 10 km, which include, among others, the ultraviolet, visible and infrared bandwidths;. However, the range in which most of the energy falls is much more restricted: 95% of all the energy that reaches the earth falls between 300 and 2400 nm. A more detailed analysis of the spectrum (Fig. 2.1-11) shows that nearly 50% of the solar energy reaching the earth falls in the visible range (380-780 nm).

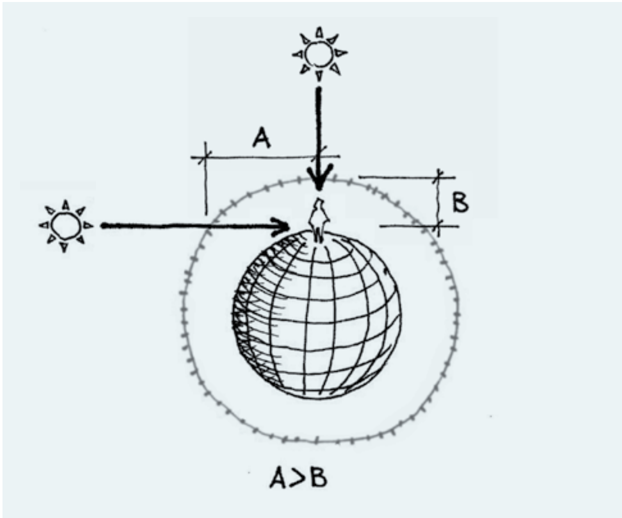
FIGURE 2.1-11 **SOLAR SPECTRUM**



The average power density of solar radiation on a perpendicular surface outside the earth's atmosphere is about 1370 W/m^2. On the earth's surface, however, the maximum value rarely exceeds 1100 W/m^2, because of the filter effect due to the atmospheric components (gas, vapour, dust), which absorb and scatter part of the energy.

The attenuation of the radiation penetrating the atmosphere depends on the thickness it crosses. When the sun is low on the horizon, the ray's path through the atmosphere is longer and the radiation undergoes a higher attenuation, and vice versa when the sun is high in the sky (Fig. 2.1-12).

FIGURE 2.1-12 **SUN PATH LENGTH ACROSS THE ATMOSPHERE**



The attenuation of the radiation is due to the absorption and the scattering caused by the components of the atmosphere (oxygen, ozone, nitrogen and nitrogen oxides, carbon dioxide, water vapour, aerosol, etc.). Both phenomena modify the solar spectrum; absorption because it is selective (i.e. it takes place only for certain wavelengths); scattering because the ratio of the energy scattered in all directions (and thus also back towards space) to that transmitted varies as a function of wavelength and of the characteristics of the medium crossed. The quota of radiation that reaches the earth's surface after the scattering process is called diffuse radiation, while the radiation that comes directly from the sun and penetrates the atmosphere is called direct radiation.

Diffuse radiation is a significant part of the radiation flux incident on a horizontal surface. On a clear day, when the sun is low on the horizon, the share of diffuse radiation can be up to 50%. On a cloudy day scattered radiation represents the total solar energy available at ground level.

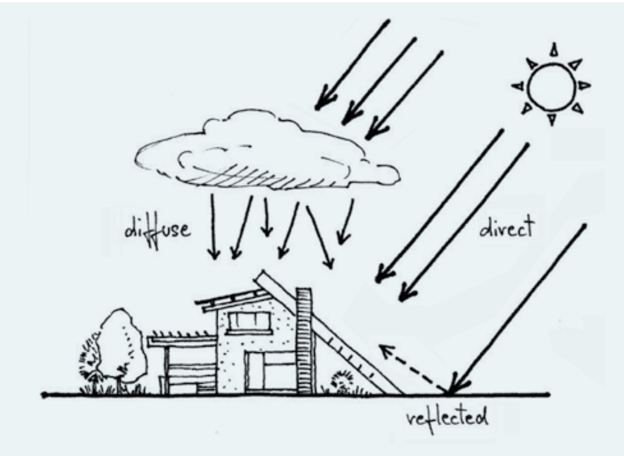
2.1.2.1 SOLAR RADIATION ON A SURFACE

When calculating the solar radiation incident on a surface, one can refer to two parameters, irradiance and irradiation. Irradiance is the instantaneous solar power incident on the surface; it varies instant by instant and is measured in W/m^2. Irradiation is the cumulative energy captured from the surface in a given period (day, month, year) and is measured in kWh/m^2.

Different methods can be applied to calculate the two parameters, using mathematical algorithms or deriving values from databases. For example the values referring to a clear day may be derived from calculations that take into account the latitude, the day and the thickness of the atmosphere passed through hour by hour. It should be noted, however, that not every day is clear and therefore, for evaluations of long periods, it is convenient to refer to average data, which take into account all the weather conditions that may occur during the period under consideration. These data may refer to the mean monthly days or to the typical reference day, whichever one is included in the typical reference year.

Any oriented and inclined surface on the earth receives global solar radiation, which is the sum of three components: direct, diffuse and reflected from the ground or the surrounding surfaces (Fig. 2.1-13). It has to be noted that in the case of a horizontal surface, which does not "see" the ground, the reflected component is zero.

FIGURE 2.1-13 **DIRECT, DIFFUSE AND REFLECTED RADIATION**



Global irradiation can range from a few dozen watts per square metre (at sunrise, sunset, or when the sky is overcast) to over a thousand (at noon or when the sky is clear), while the value and the ratio of the three components are highly variable and depend on specific location, time, weather conditions and context.

In general, global irradiation increases from dawn until noon and then decreases until sunset, but its values are greatly affected by cloud cover and possible shading obstructions.

Direct irradiation, which comes straight from the sun, is influenced by the spatial disposition of the surface: the more perpendicularly the rays strike it, the higher the amount of energy incident on it.

Diffuse irradiation also depends on the spatial disposition of the surface, and more precisely on how this "sees" the sky dome. Since we can assume that the diffuse component comes from all directions of the atmosphere, the greater the portion of sky seen from the surface, the greater the collected diffuse irradiation.

Reflected irradiation depends on the mutual spatial disposition of the absorbing and the reflective surface, on the incident radiation onto the reflecting surface and on the albedo of the reflecting surface. The albedo is the fraction of the total radiation that is reflected from the irradiated surface and characterizes the reflective properties of a surface, of an object or of an entire system. Thus we speak of the albedo of desert, steppe, forest, glacier, clouds, atmosphere, sea, of a continent or of the Planet as a whole.

The local albedo is a fairly stable function of solar height and varies considerably in relation to the colour, texture and moisture of the surface. The values are lowest in the case of ploughed and humid soil, and higher with light-coloured sand (Table 2.1-1). By decreasing the compactness of the soil or increasing its moisture content, the albedo substantially decreases.

TABLE 2.1-1 **ALBEDO OF SURFACES**

SURFACE TYPE	ALBEDO COEFFICIENT
Sand	0.75
Body of water	0.07
Soil, clay	0.14
Dirt roads	0.04
Forests, plants	0.26
Worn asphalt	0.1
Worn concrete	0.22
Fallen leaves	0.3
Dry grass	0.2
Green grass	0.26
Bricks	0.27
Dark plaster	0.2
Clear plaster	0.6
Field with woods on the edge	0.7
Large field with soil and dry grass	0.65
Field with scattered trees	0.62
Parks	0.5
Urban areas	0.25

2.1.2.2 LOCAL SOLAR RADIATION

Solar radiation incident on a surface varies continuously depending on geographic location, slope, orientation, season, time of day and atmospheric conditions (see paragraph 2.1.2).

At a local level, the amount of solar radiation incident on a surface is mainly affected by three parameters: the length of the path of the sun's rays across the atmosphere, the composition of the atmosphere and shading obstructions.

Length of the path of the sun's rays across the atmosphere

On clear days solar radiation incident on a surface increases with elevation. This is due to the fact that the higher the site, the shorter the path of the solar rays through the atmosphere before they reach the ground (Fig. 2.1-12). Diffuse radiation varies differently with altitude on clear and cloudy days. Daily global radiation increases on average by 1% for every 100 meters above sea level on sunny days and 4% on overcast days.

Composition of the atmosphere

The effect of the composition of the atmosphere is related mainly to the amount of water vapour and suspended particulate. The influence of humidity is particularly evident by comparing the blue colour of the sky on a hot, dry day with the whitish colour typical of a hot, humid day.

Due to air pollution, particulate is present mainly in urban areas; for this reason solar radiation is typically attenuated. In general there is an attenuation of direct radiation and an increase in diffuse radiation.

Shading obstructions and topography

The shadows cast by surrounding obstructions can change the actual availability of solar radiation on a given site, as can mountains or hills. The topography can also influence the local intensity of solar radiation due to cloud formations around the peaks or behind mountain chains.

Coastal areas

Coastal areas are subject to various factors that can affect solar radiation. The development of sea breezes sometimes leads to the formation of clouds which move inland with increasing speed and density during the day, and so the local solar radiation pattern is also affected.

Another factor to be considered is that the atmosphere of the coastal zones is characterized by greater turbidity than that of the inner zones, due to the presence of aerosols and saltiness; this factor can contribute significantly to a change the in the ratio between the values of direct and global radiation.

On the other hand it can also happen that, thanks to the breezes, some of the convective phenomena that create the clouds are suppressed, and the mean values of radiation on the coast are higher than those found inland.

2.1.2.3 IRRADIANCE AND IRRADIATION DURING THE YEAR

Solar radiation incident on a surface at a given time of the year depends on the spatial arrangement of the surface and the solar path, as shown in figures 2.1-14, 15, 16, where solar radiation in Nairobi (latitude Φ = 1.6° South) is plotted for 3 characteristic days: the two solstices and the vernal equinox; monthly mean daily solar radiation values are used.

It can be seen that horizontal surfaces, or those slightly inclined (depending on season and orientation), always collect the greatest amount of daily solar radiation.

FIGURE 2.1-14 **NAIROBI, DECEMBER SOLSTICE IRRADIANCE (ALBEDO = 0.2)**

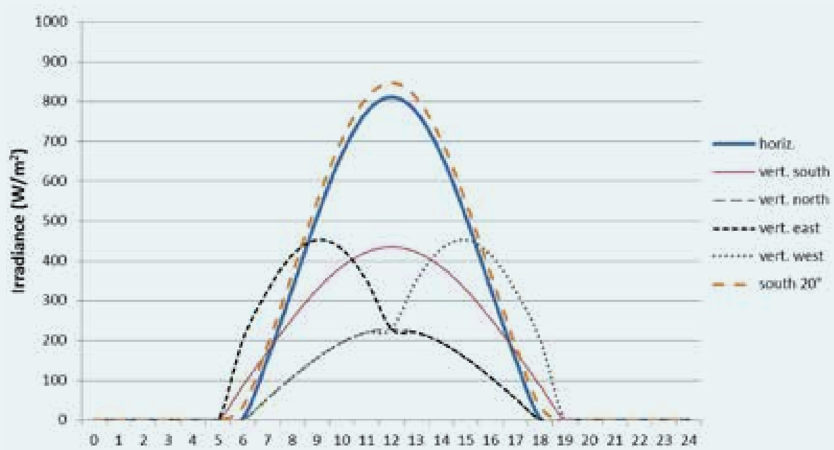


FIGURE 2.1-15 **NAIROBI, VERNAL EQUINOX IRRADIANCE (ALBEDO = 0.2)**

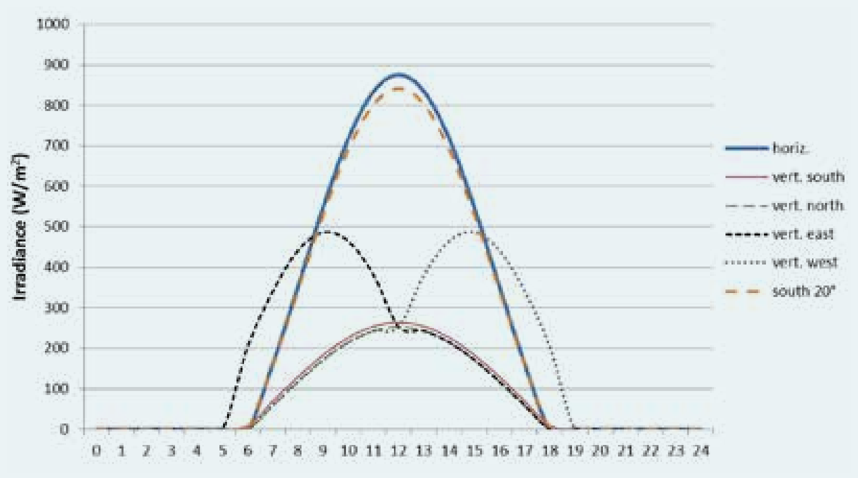


FIGURE 2.1-16 **NAIROBI, JUNE SOLSTICE IRRADIANCE (ALBEDO = 0.2**)

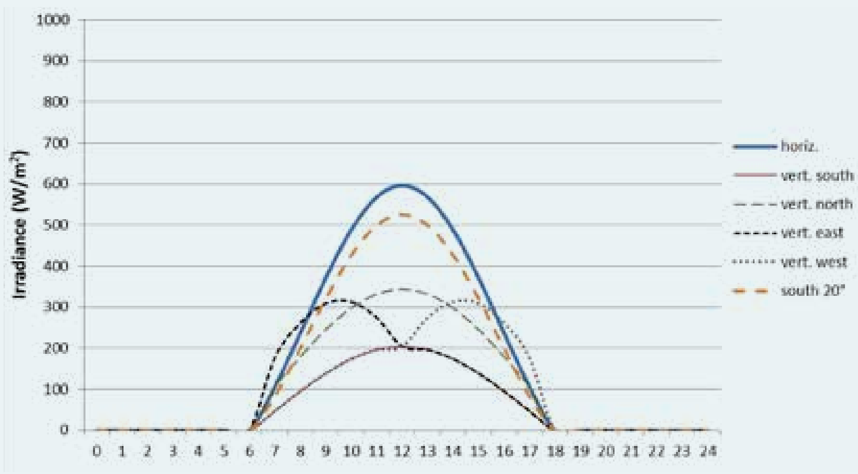


FIGURE 2.1-17 **MONTHLY IRRADIATION IN THREE SITES**

SOLAR IRRADIANCE CALCULATION

Solar energy incident on a given surface at a given time and in a given site, known as the hourly direct and diffuse irradiance values on the horizontal plane, can be evaluated with:

$$I_t = I_b R_b + I_d F_s + \rho I F_c \qquad (2.1\text{-}1)$$

where:
I_t is the total instantaneous irradiance incident on the surface considered [W/m²];
I_b is the direct irradiance incident on the horizontal plane [W/m²];
R_b represents the ratio between the direct solar irradiance on the horizontal and that on the surface considered, as shown below;
I_d is the diffuse irradiance on the horizontal plane [W/m²];

$F_s = \frac{1+\cos\psi}{2}$ is the view factor of the sky dome from the surface considered, as shown below;

ρ is the albedo;
I is the total irradiance ($I = I_b + I_d$) on the horizontal plane [W/m²];
F_c = 1 - Fs represents the view factor of the surrounding context, from which the reflected radiation reaches the surface considered, as shown below.

The R_b ratio depends on surface position, site, day and time. It is therefore a function of solar azimuth α, solar altitude β, surface's inclination ψ and orientation γ, local latitude Φ, day's declination δ, hour angle ω, and is given by the following expression:

$$R_b = \frac{\cos\beta\cos(\alpha-\gamma)\sin\psi + \sin\beta\cos\psi}{\cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta} \qquad (2.1\text{-}2)$$

If there are obstructions around the surface considered, then the values of F_s and F_c must be appropriately corrected. For the above calculations, the monthly average hourly values of I_b and I_d and are available in databases.

Vertical surfaces display great variability during the day and the year. East-facing surfaces collect more radiation in the morning. After midday they are hit only by diffuse radiation, because they don't "see" the sun directly any more. West-facing surfaces, on the other hand, are more radiated in the afternoon. Vertical north and south-facing surfaces are constantly exposed to or hidden from direct solar radiation, depending on the season (the sun travelling in the northern or in the southern quadrant).

The final graph (Fig. 2.1-17) shows the overall trend of monthly irradiation on a horizontal surface for three locations: Nairobi (Φ: 1.6° South, upland climate), Dar es Salaam (Φ: 6.8° South, hot-humid climate) and Lodwar (Φ: 3.12° North, hot-arid climate).

As can be seen, values are contained in a range between 120 and 180 kWh/m² per month, where the oscillations depend on the season and the specific climatic context.

Note that Lodwar, with a less cloudy climate, is characterized by higher solar radiation values during the summer period.

Solar radiation data are provided for selected EAC locations in the form of "radiation squares", as shown in Tables 2.1-2, 3 and 4.

Each radiation square shows the mean monthly hourly solar irradiance on a horizontal surface, subdivided into its direct (I_b) and diffuse (I_d) components. In order to better display the magnitude of solar radiation, the boxes in the chart are given different backgrounds, depending on the value of the total irradiance ($I = I_b + I_d$).

TABLE 2.1-2 **RADIATION SQUARE, NAIROBI**

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.																								
6 a.m.	2	2	1	2	0	0													1	1	1	2	2	3
7 a.m.	90	77	90	78	75	85	57	78	43	76	34	73	39	59	32	73	54	81	73	75	56	86	75	79
8 a.m.	212	146	214	149	187	166	146	152	116	149	94	143	102	116	90	143	138	156	177	144	142	104	181	150
9 a.m.	348	205	353	211	315	234	250	216	203	211	168	203	177	165	161	203	238	221	296	203	243	231	300	211
10 a.m.	472	251	480	258	433	286	347	265	285	259	239	250	247	202	229	249	331	271	404	248	337	283	410	257
11 a.m.	559	280	568	287	515	319	416	296	343	280	289	279	296	226	277	278	397	302	481	277	403	315	487	287
12 a.m.	590	289	600	297	545	331	440	306	364	290	307	289	314	234	295	288	420	313	508	287	427	326	515	297
1 p.m.	559	280	568	287	515	319	416	296	343	280	289	279	296	226	277	278	397	302	481	277	403	315	487	287
2 p.m.	472	251	480	258	433	286	347	265	285	250	239	250	247	202	229	249	331	271	404	248	337	283	410	257
3 p.m.	348	205	353	211	315	234	250	216	203	211	168	203	177	165	161	203	238	221	296	203	243	231	300	211
4 p.m.	212	146	214	149	187	166	146	152	116	149	94	143	102	116	90	143	138	156	177	144	142	104	181	150
5 p.m.	90	77	90	78	75	85	57	78	43	76	34	73	39	59	32	73	54	81	73	75	56	86	75	79
6 p.m.	2	2	1	2	0	0													1	1	1	2	2	3
7 p.m.																								
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

I < 300 W/m² | I < 600 W/m² | I ≥ 600 W/m²

Radiation square: Hourly direct and diffuse irradiance [W/m²] on a horizontal surface, Nairobi, Kenya (temperate climate)

TABLE 2.1-3 **RADIATION SQUARE, LODWAR**

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d	I_h	I_d
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.																								
6 a.m.	2	2	1	2	0	0													1	1	1	2	2	3
7 a.m.	90	77	90	78	76	86	57	78	43	76	34	73	39	59	32	73	54	81	73	75	56	86	75	79
8 a.m.	212	146	214	149	187	166	146	152	116	149	94	143	102	116	90	143	138	156	177	144	142	164	181	150
9 a.m.	348	205	353	211	315	234	250	216	203	211	158	203	177	165	151	203	238	221	296	203	243	231	300	211
10 a.m.	472	251	480	258	433	286	347	265	285	259	239	250	247	202	229	249	331	271	404	248	337	283	410	257
11 a.m.	559	280	568	287	515	319	416	296	343	289	289	279	296	226	277	278	397	302	481	277	403	315	487	287
12 a.m.	590	289	600	297	545	331	440	306	364	299	307	289	314	234	235	288	420	313	508	287	427	326	515	297
1 p.m.	559	280	568	287	515	319	416	296	343	289	289	279	296	226	277	278	397	302	481	277	403	315	487	287
2 p.m.	472	251	480	258	433	286	347	265	285	259	239	250	247	202	229	249	331	271	404	248	337	283	410	257
3 p.m.	348	205	353	211	315	234	250	216	203	211	158	203	177	165	151	203	238	221	296	203	243	231	300	211
4 p.m.	212	146	214	149	187	166	146	152	116	149	94	143	102	116	90	143	138	156	177	144	142	164	181	150
5 p.m.	90	77	90	78	76	86	57	78	43	76	34	73	39	59	32	73	54	81	73	75	56	86	75	79
6 p.m.	2	2	1	2	0	0													1	1	1	2	2	3
7 p.m.																								
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

I < 300 W/m² | I < 600 W/m² | I ≥ 600 W/m²

Radiation square: Hourly direct and diffuse irradiance [W/m²] on a horizontal surface, Nairobi, Kenya (temperate climate)

TABLE 2.1-4 **RADIATION SQUARE, DAR ES SALAAM**

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d	I_b	I_d
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.																								
6 a.m.							1	3	3	6	4	7	2	7	2	5	0	1						
7 a.m.	49	80	56	79	62	81	34	96	60	85	64	87	52	92	56	96	76	81	74	78	53	71	52	72
8 a.m.	135	160	146	155	157	158	98	182	147	161	154	161	131	171	144	181	187	156	187	154	140	142	139	146
9 a.m.	236	230	252	222	268	224	177	257	247	226	257	225	225	236	247	254	313	221	315	219	242	204	242	209
10 a.m.	332	283	351	272	370	274	253	314	341	275	354	274	312	290	343	310	428	271	433	269	338	251	338	258
11 a.m.	400	316	421	304	443	306	309	350	407	306	421	305	374	323	417	345	510	302	516	300	405	280	406	288
12 a.m.	425	328	447	315	469	317	327	362	431	317	446	316	397	334	437	357	539	312	546	311	429	290	431	298
1 p.m.	400	316	421	304	443	306	309	350	407	306	421	305	374	323	417	345	510	302	516	300	405	280	406	288
2 p.m.	332	283	351	272	370	274	253	314	341	275	354	274	312	290	343	310	428	271	433	269	338	251	338	258
3 p.m.	236	230	252	222	268	224	177	257	247	226	257	225	225	236	247	254	313	221	315	219	242	204	242	209
4 p.m.	135	160	146	155	157	158	98	182	147	161	154	161	131	171	144	181	187	156	187	154	140	142	139	146
5 p.m.	49	80	56	79	62	81	34	96	60	86	64	87	52	92	56	96	76	81	74	78	53	71	52	72
6 p.m.							1	3	3	6	4	7	2	7	2	5	0	1						
7 p.m.																								
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

I < 300 W/m² I < 600 W/m² I ≥ 600 W/m²

Radiation square: Hourly direct and diffuse irradiance (W/m²) on a horizontal surface. Lodwar, Kenya (hot-dry climate)

2.1.3 AIR TEMPERATURE

Air temperature is greatly influenced by context, depending primarily on geographical factors (latitude and hydrography), topography (altitude and topography), surface textures (composition and colour of the soil) and location (urban or rural), as well as solar radiation and wind, which, through hot or cold airstreams, can cause more or less significant variations, which can be permanent or temporary.

Temperature is subject to cyclical variations during the day and throughout the year, following periodic oscillations, with maxima and minima delayed in relation to peak sunshine. In the course of the day, air temperature reaches its minimum value just before dawn, then increases until it reaches its maximum value in the early afternoon, and then begins to decrease slowly (Fig. 2.1-18). The daily temperature range is very important because it allows us to predict the effect of thermal inertia on comfort and energy consumption.

Temperature data are available in different forms: maximum and minimum annual, monthly and daily averages, or as a frequency distribution of hourly values, etc. For the purposes of evaluation of the climatic context, the values most commonly used are the monthly average daily temperature, and the difference between the mean maximum and minimum (Fig. 2.1-19).

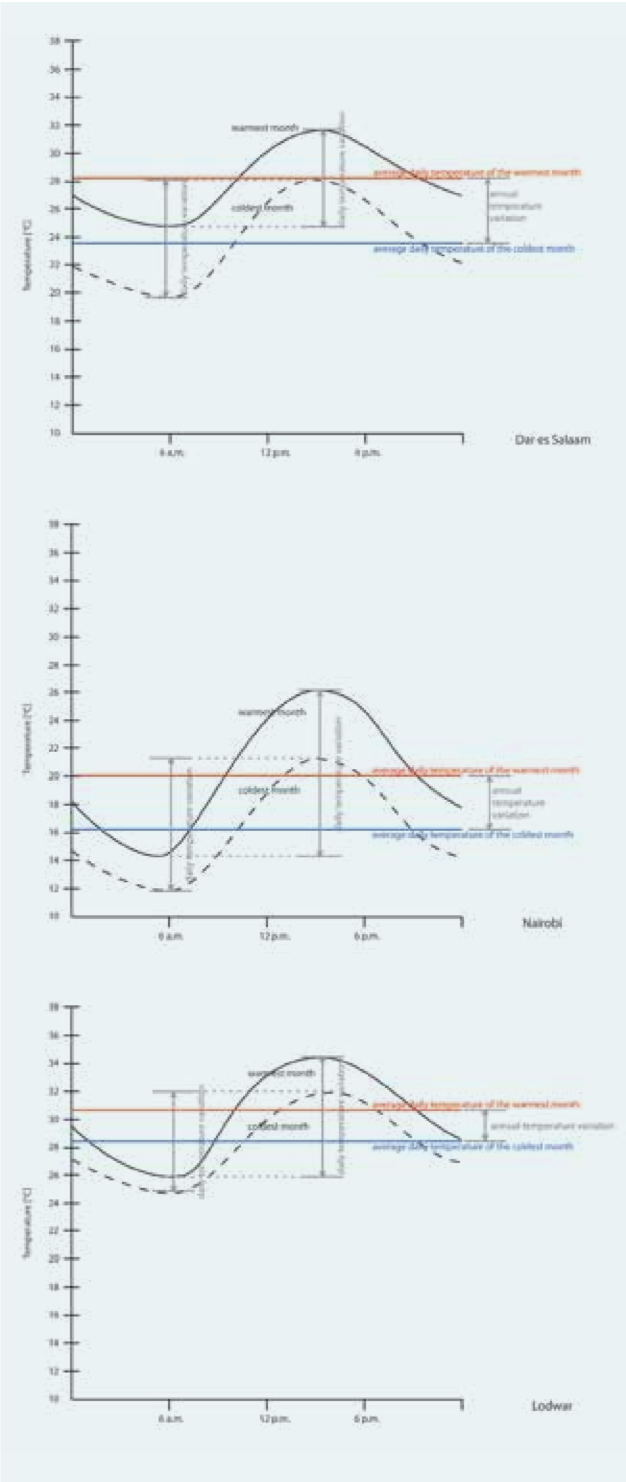
Close to ground level when wind speed is low, local temperatures are mainly influenced by topographic, orographic, surface, and location factors.

2.1.3.1 **TOPOGRAPHICAL FACTORS**

Height above sea level is one of the most significant topographical factors. Temperature variation due to altitude takes place in relation to the temperature itself, air pressure and absolute humidity. Usually, for rough evaluations, it can be considered that air temperature decreases with altitude by about 0.5 °C/100 m.

Topography also has an impact on air temperature. On clear, calm nights the ground cools down due to the infrared radiation towards the sky dome, and a layer of cold air in contact with the surface is generated. On a slope, the layer of cold air flows down and collects in hollows in the ground or in depressions. In this way so-called cold air lakes are formed (Fig. 2.1-20).

FIGURE 2.1-18 **TEMPERATURE TYPICAL PATTERN (MONTHLY AVERAGE VALUES)**



Source: *Climate Consultant*

According to this phenomenon, a valley carved in a plateau should contain a deep cold air lake. This, however, does not happen because of the large size of the valley, which allows a certain amount of air circulation between the coldest area along the slope and the warmest above. The cold air lake, for this reason, is formed only at the bottom of valley (Fig. 2.1-21).

The maximum height of cold air lakes depends on the width of the valleys:

- narrow valleys: 3 m;
- average valleys: 8 m;
- wide valleys: 30 – 75 m.

2.1.3.2 **SURFACE FACTORS**

Generally, air temperature decreases or increases with soil temperature. The heat balance on the surface of the ground- and hence its temperature - is affected by its colour and texture (solar reflection coefficient, or albedo, see Table 2.1-1, paragraph 2.1.1.1), infrared emissivity and specific heat of the material the soil is made of, as shown in figure 2.1-22.

2.1.3.3 **LOCATION**

Since air temperature depends significantly on that of the ground or surrounding context, areas of urbanized land have – because of the their morphological configuration and the characteristics of the materials they are made of - a greater capacity to absorb solar radiation; to this has to be added the heat generated due to the heating and cooling of buildings and vehicular traffic. For these reasons, temperatures in urban areas are higher by a few degrees than in their rural surroundings (Fig. 2.1-23). This phenomenon, called the urban heat island, increases with the size of the city and towards its centre (which generally has higher building density).

In other words, the urban heat island occurs because the materials and morphology characterising the urban context act as a heat trap (Fig. 2.1-24). The heat island effect in warm to hot climates exacerbates the amount of energy used for cooling, but this can be reduced by using materials with high reflection coefficients, as well as by applying sunscreens (e.g. vegetation) in the most critical areas.

Urban size influences the heat island effect, as shown in figure 2.1-25, where the correlation between the maximum urban-rural temperature difference and urban size, expressed as urban population, is plotted for North American and European cities.

FIGURE 2.1-19 **MONTHLY PATTERN AND TEMPERATURE VARIATION**

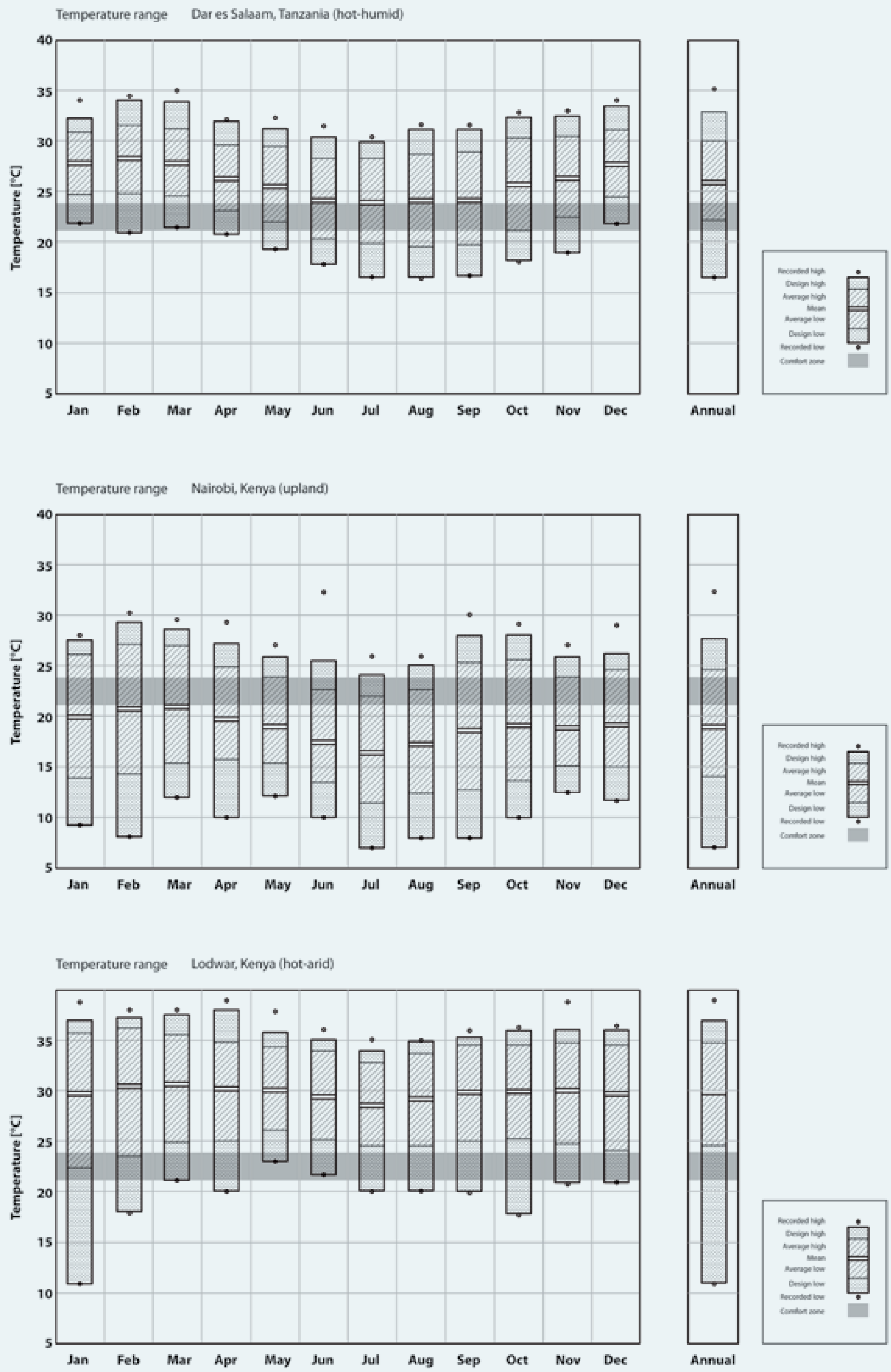
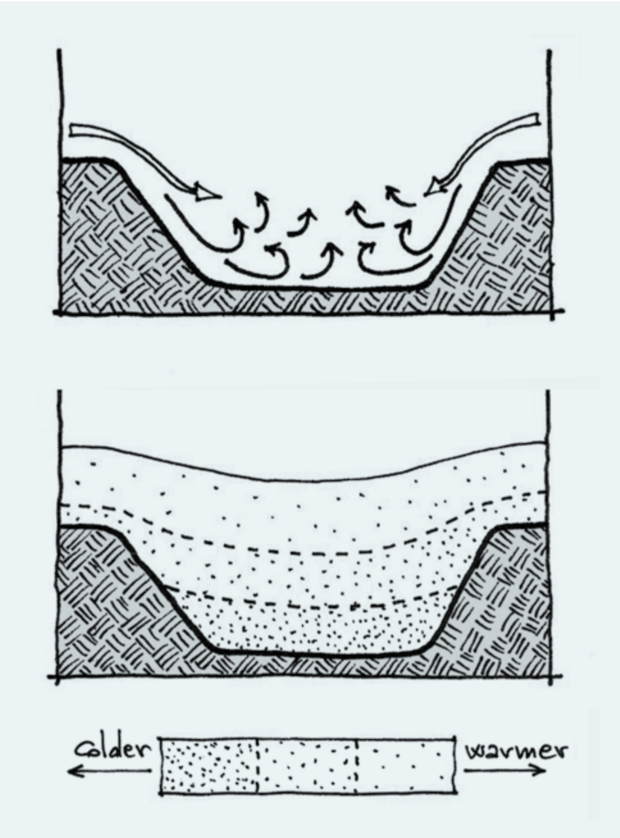


FIGURE 2.1-20 **COLD AIR LAKE**

FIGURE 2.1-21 **COLD AIR LAKE STRATIFICATION**



2.1.4 RELATIVE HUMIDITY

Relative humidity expresses the ratio of the quantity of water vapour actually contained in the air, to the maximum amount that can be contained before condensation occurs. It is normally expressed as a percentage.

Relative humidity is subject to cyclical fluctuations; it generally increases during the night and during the cold season, when air temperature is at its lowest, and decreases as air temperature rises (Fig. 2.1-26).

At local level, relative humidity can be affected by various factors, such as vegetation, distance from water bodies and solar exposure.

The presence of vegetation, in particular, due to evapotranspiration, generally increases the relative humidity, so that values recorded in urban areas are typically lower than 5 - 10% compared to those recorded in rural areas.

Humidity generally increases in proximity to seas, lakes and rivers, due to evaporation.

On a shaded slope or in a valley bottom relative humidity is generally higher than elsewhere, because of the lower temperature.

Relative humidity and temperature follow an opposite trend during a clear day: when the temperature reaches its maximum, humidity reaches its minimum, and vice versa. This is due to the fact that the amount of water vapour in the air (grams of water per kilogram of dry air) is almost constant.

FIGURE 2.1-22 **SOIL NATURE AND TEMPERATURE**

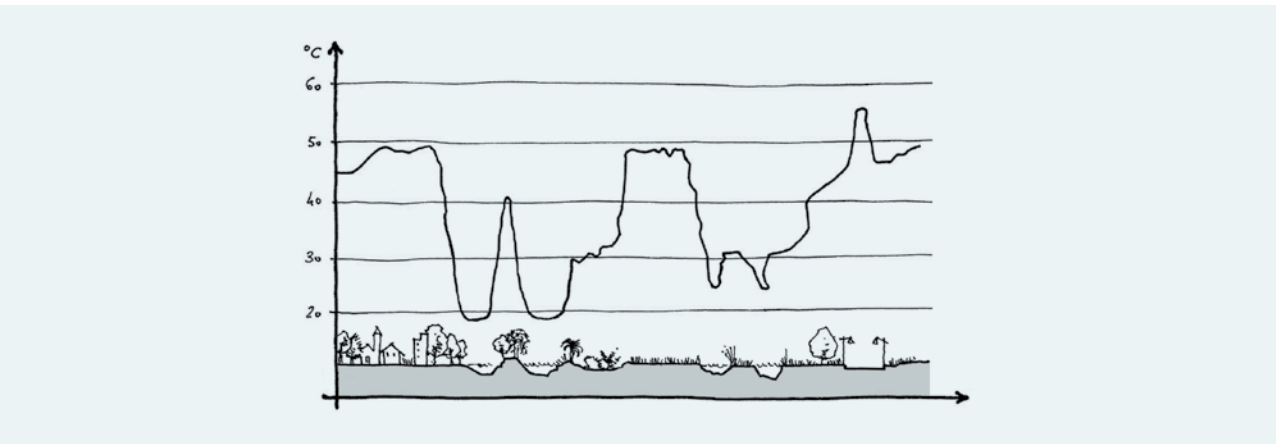


FIGURE 2.1-23 **EFFECT ON AIR TEMPERATURE OF THE URBAN HEAT ISLAND**

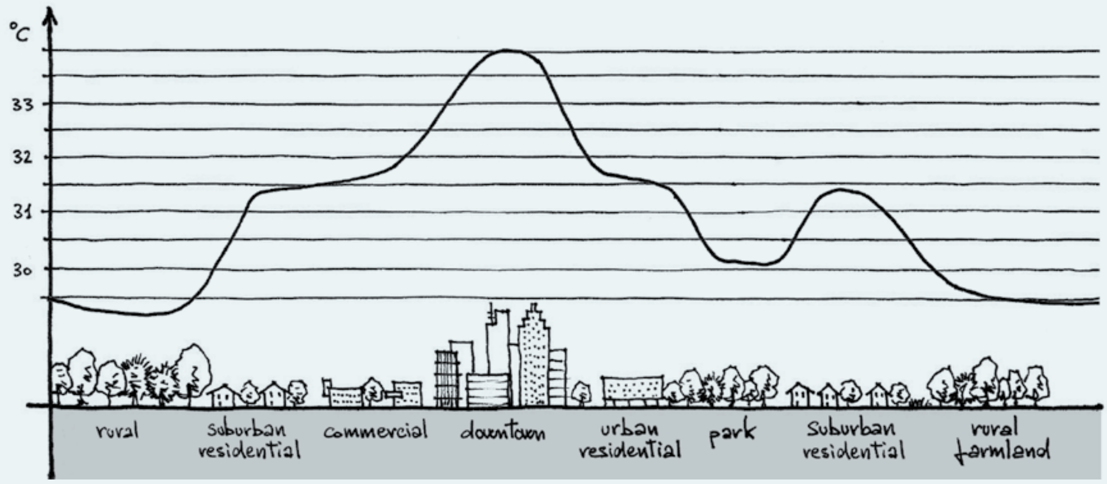


FIGURE 2.1-24 **VARIOUS URBAN ENVIRONMENT ALBEDOS (LEFT) AND HEAT TRAP OR URBAN CANYON EFFECT (RIGHT)**

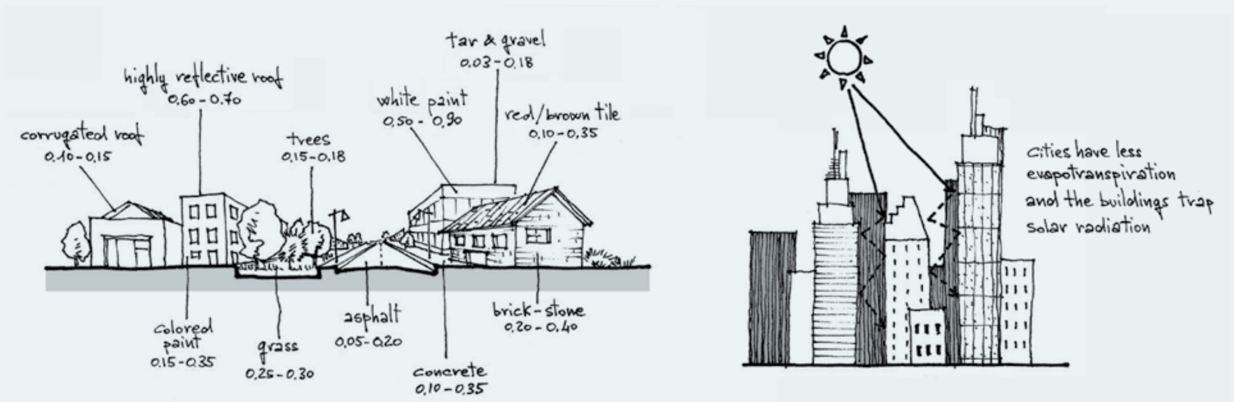
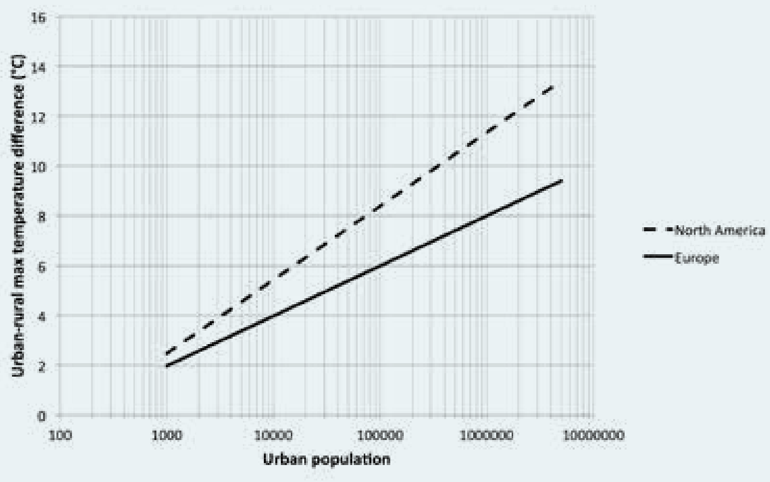
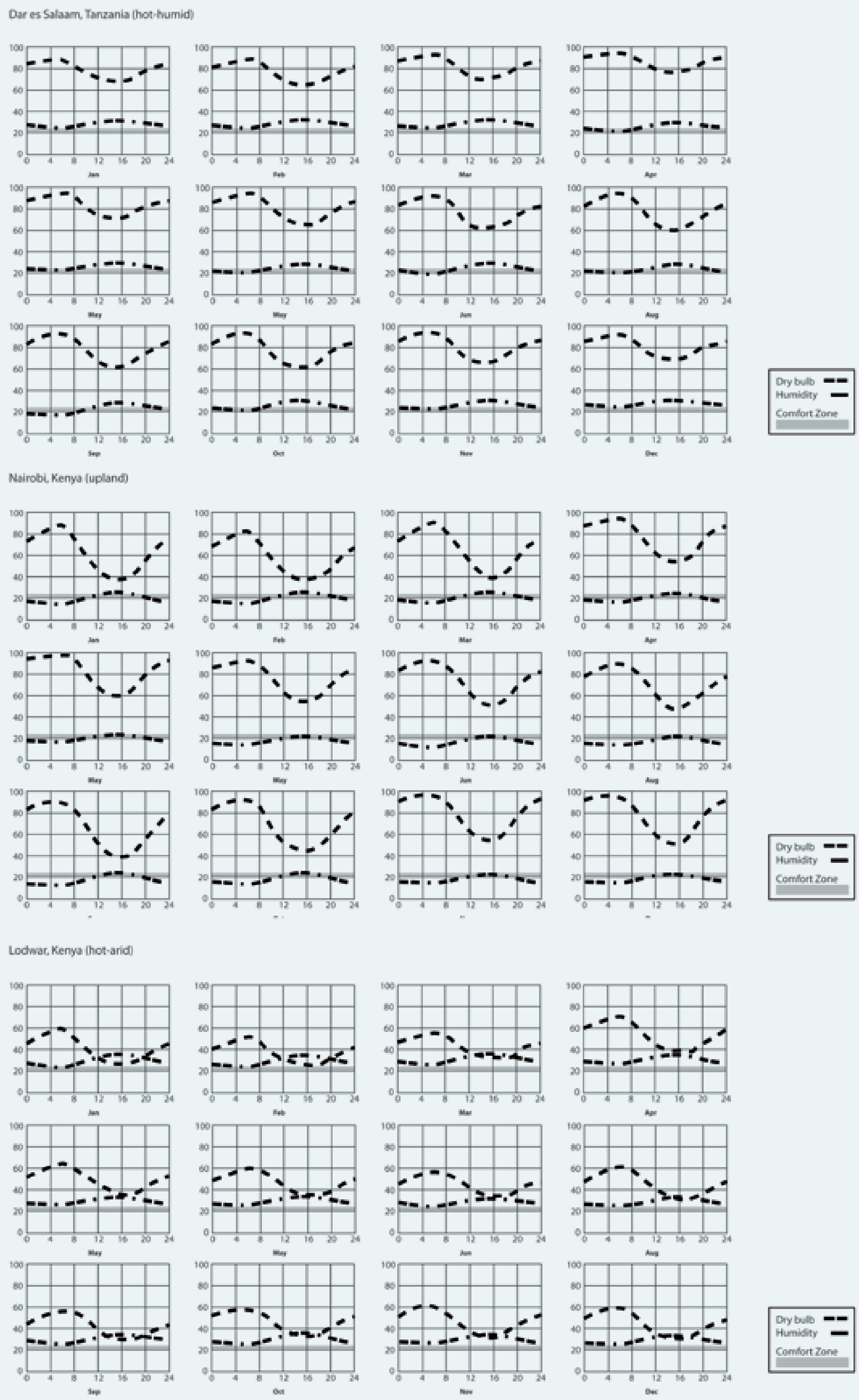


FIGURE 2.1-25 **EFFECT OF URBAN SIZE ON HEAT ISLAND**



Adapted from: *T.R. Oke, City size and the urban heat island. Atmospheric Environment 7: 769- 779, 1973*

FIGURE 2.1-26 **RELATIVE HUMIDITY VS. DRY BULB TEMPERATURE**



Source: *Climate Consultant*

2.1.5 WIND

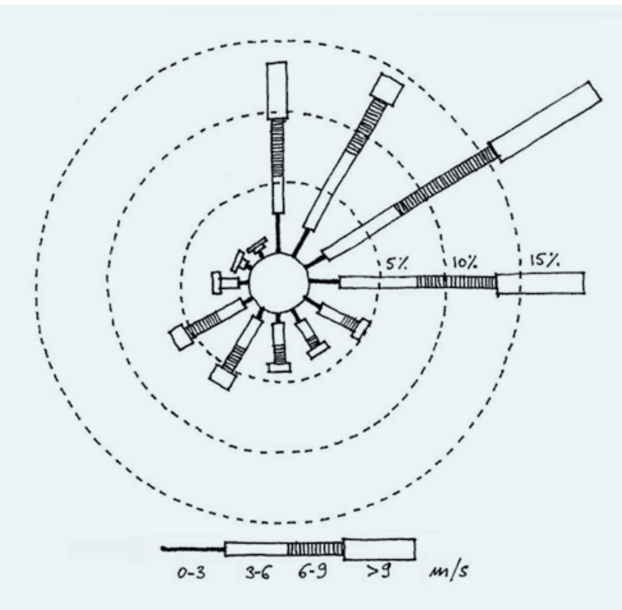
Wind is the movement of air masses caused by differences in atmospheric pressure related to land, water and air temperature gradients, which may occur at a macro-territorial level (between one geographical region and another) or on a local scale (waterfront, lakeside area, valleys, etc.).

In the first case we refer to regional winds, in the second to local winds.

The parameters which characterize wind are: speed, direction from which it flows and frequency.

A schematic representation of the three parameters is given by the wind rose (Fig. 2.1-27). Presented in a circular format, the wind rose shows the frequency of winds blowing from particular directions. The length of each "spoke" around the circle is related to the frequency with which the wind blows from a particular direction in a given period of time (month, season, year). Each concentric circle represents a different frequency, ranging from zero at the centre to increasing frequencies at the outer circles. A wind rose plot may contain additional information, in that each spoke can be broken down into colour-coded bands that show wind speed ranges. The most useful values are the averages over a long period of time.

FIGURE 2.1-27 **WIND ROSE**



2.1.5.1 REGIONAL WINDS

The effect of topography on regional winds is remarkable and can be quantitatively assessed. On flat ground, without obstructions, wind speed varies as a function of two parameters: surface roughness of the ground and height. In figure 2.1-28 some examples of wind speed profiles are shown; it may be noted that - at the same height - velocity is greater in open countryside than in an area of high building density. Wind is measured by weather stations, situated in a given topographical context. Changing this context also changes the speed, which also changes, in the same site, in relation to the height.

Usually, wind data available for a location are those measured at the nearest airport, at a height of 10 m from the ground.

To calculate wind speed at different heights, the following formula can be used:

$$\frac{V_Z}{V_{10}} = KZ^{\alpha} \qquad (2.1\text{-}3)$$

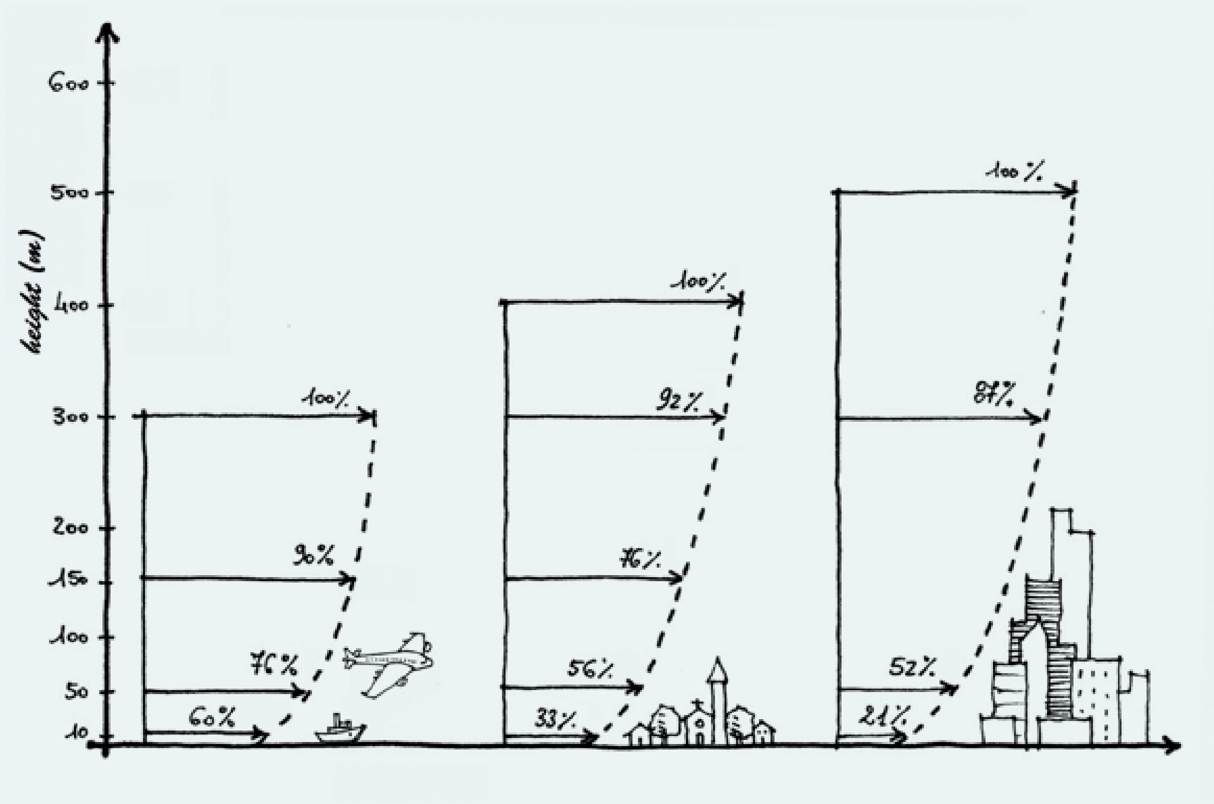
where:
V_Z = wind speed at the height Z [m/s];
V_{10} = wind speed at 10 m [m/s];

K and α are two coefficients that vary depending on the type of ground, as shown in Table 2.1-5.

TABLE 2.1-5 **CORRECTION FACTORS AS A FUNCTION OF THE HEIGHT AND ROUGHNESS OF THE GROUND**

Terrain type	α	K
I - Open countryside, flatland	0.17	0.68
II - Low-density urban periphery	0.20	0.52
III – Urban area	0.25	0.35
IV – Downtown	0.33	0.21

FIGURE 2.1-28 **WIND SPEED PROFILES**



The graph shown in Fig. 2.1-29 enables us to calculate graphically the average wind speed at a height Z from the ground, with respect to a given type of soil, once the value measured at 10 meters is known. If, for example, we want to know the average wind speed at the level of the tenth floor (about 30 m) of a building located in a low-density urban area, we read in the graph the corresponding value V_Z/V_{10} (= 0.82 in our case); knowing that at the airport the average speed is 4 m/s, the speed at 30 meters is: 0.82×4 = 3.28 m/s.

In areas characterized by complex orography, winds can be reinforced, deviated or weakened, as shown in Fig. 2.1-30.

2.1.5.2 **LOCAL WINDS**

A combination of contrasting thermal environments results in the development of horizontal pressure gradients that, in the absence of regional winds, cause air movements, and thus local winds.

In some cases, such as breezes over seas and lakes and in mountain valleys in summer, these movements can be predicted.

The soil-water temperature difference and its inversion during 24 hours (in daytime soil is hotter than water, but it is colder at night) produce a corresponding pressure difference of the air above the water and the ground. This difference, in turn, causes an air flow across the coastline. The breeze reverses direction from day to night, and vice versa (Fig. 2.1-31).

In a valley, air movement is more complex, as shown schematically in figure 2.1-32. In general the prediction of local air movements on the basis of a few parameters is very difficult, because of the large number of variables involved. Wind speed and direction also undergo variations on a smaller scale: buildings or rows of trees change, sometimes significantly, the characteristics of the local wind, as shown in figure 2.1-33.

FIGURE 2.1-29 **WIND SPEED VARIATION ACCORDING TO TYPE OF GROUND**

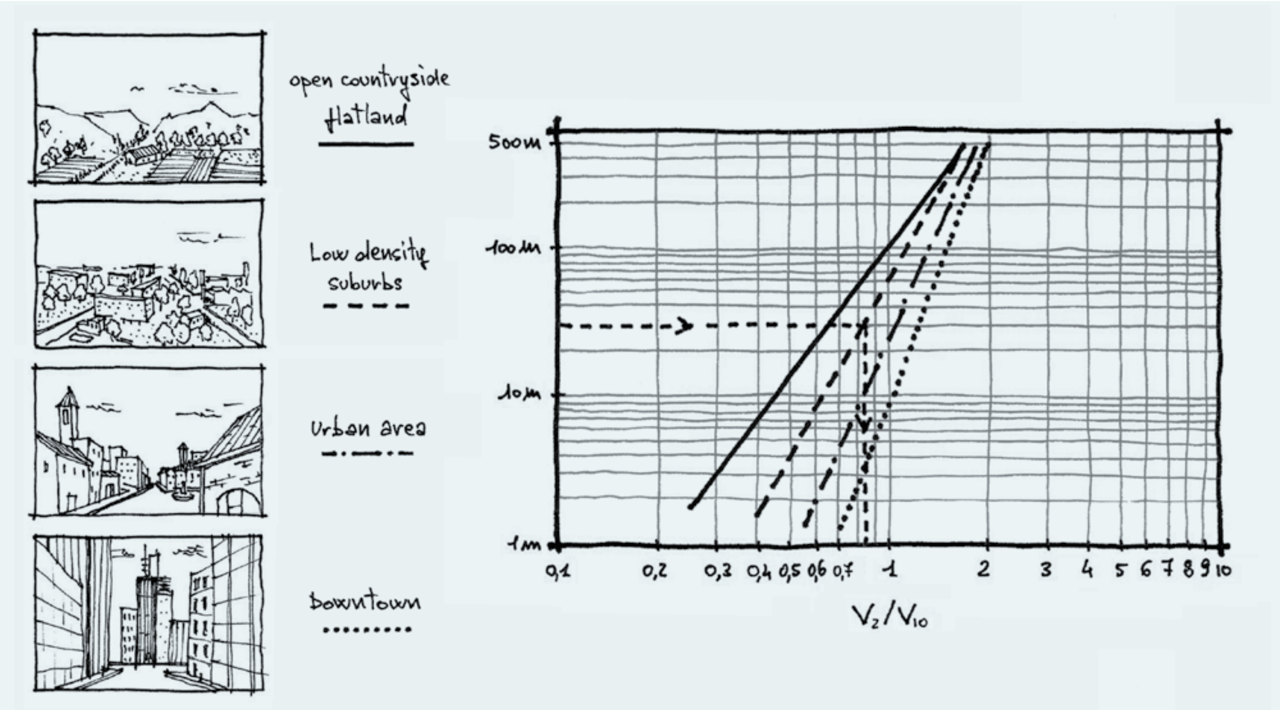


FIGURE 2.1-30 **TOPOGRAPHY EFFECTS ON WIND; DEVIATION (LEFT), REINFORCEMENT (RIGHT)**

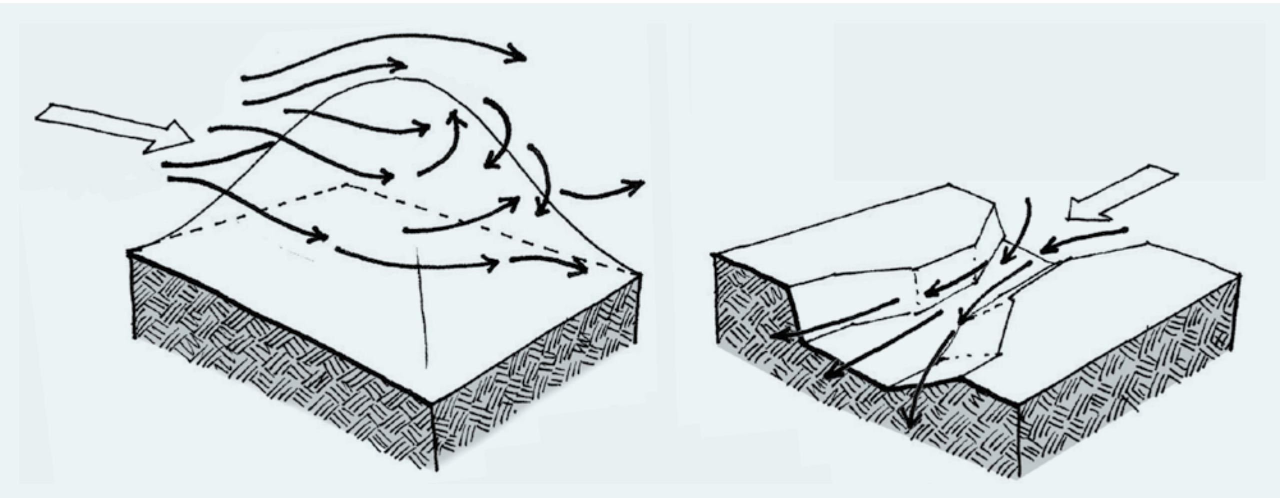


FIGURE 2.1-31 **GROUND-WATER TEMPERATURE DIFFERENCE; SEA (LEFT) AND LAND (RIGHT) BREEZE**

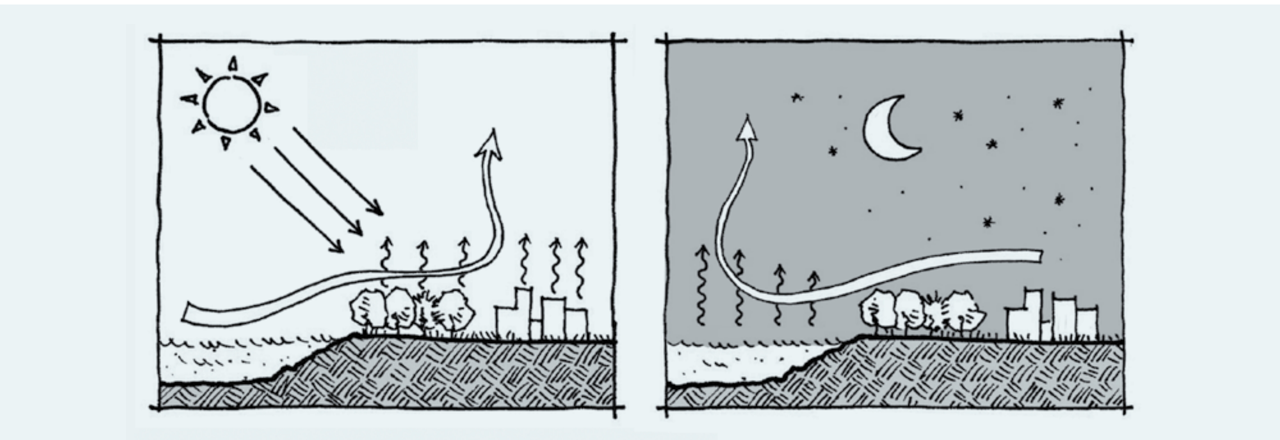


FIGURE 2.1-32 **AIR MOVEMENT IN A VALLEY**

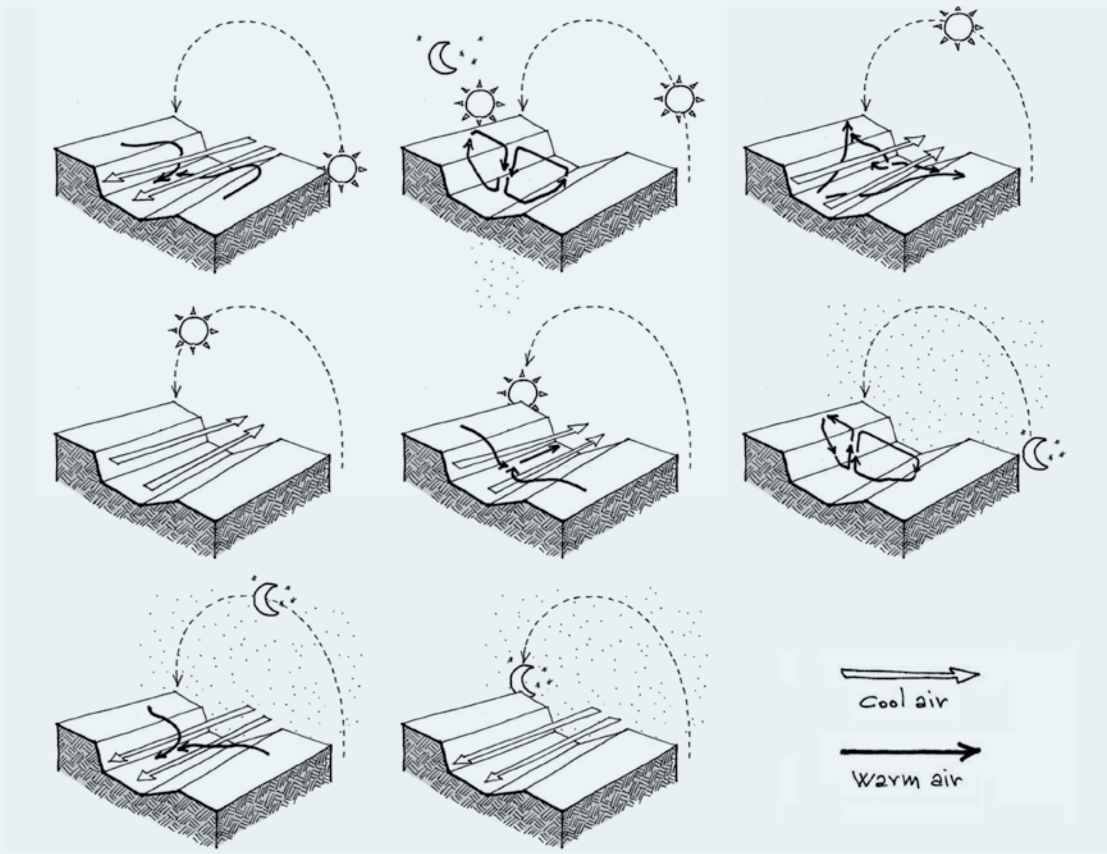
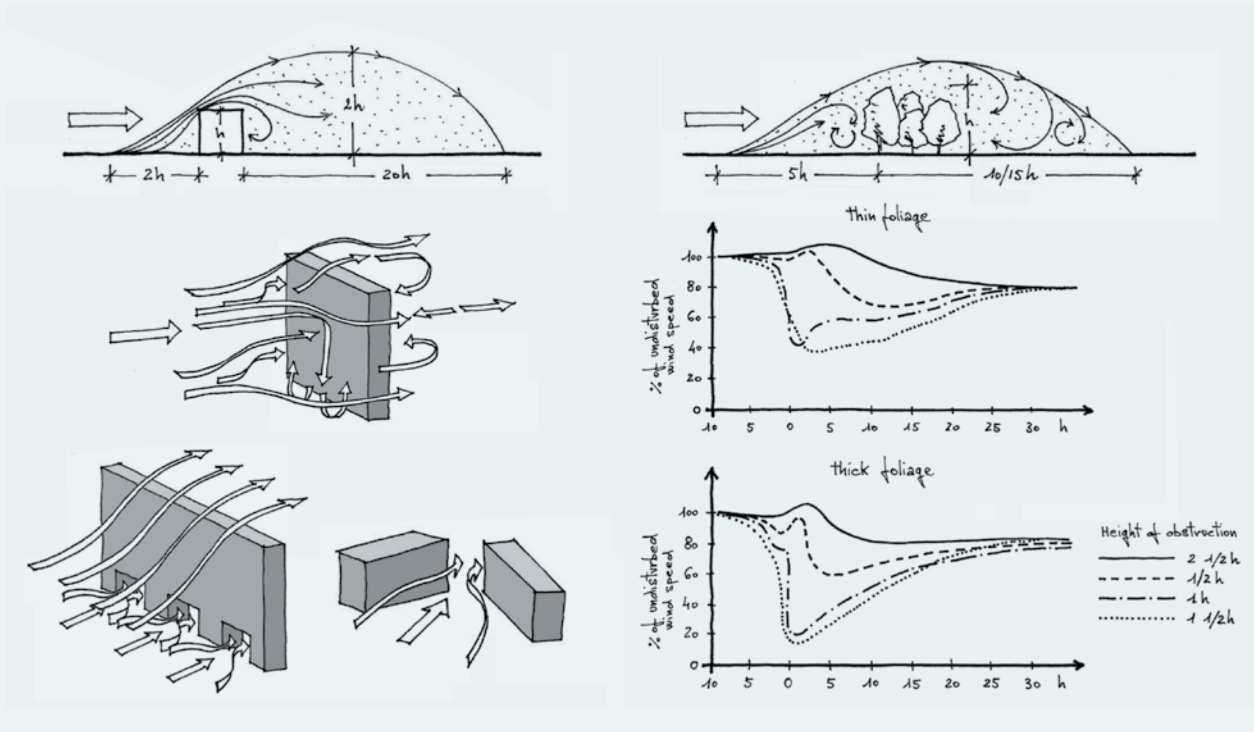


FIGURE 2.1-33 **BUILDINGS AND ROWS OF TREES EFFECTS ON THE WIND'S CHARACTERISTICS**



2.1.6 AGGREGATION OF CLIMATE DATA

The most common methods for calculating the energy performance of buildings are based on the use of Degree Day, on the mean monthly average daily values (for steady-state calculations) and of the TRY, Test Reference Year (for dynamic simulations).

Degree Days

Closely interconnected to that of the air temperature is the degree-days parameter, which expresses the sum of the differences between the average daily outdoor temperature and a given constant temperature inside buildings, in a selected period of time (generally the heating and the cooling season).

The indoor temperature taken as reference for the calculation of the degree-days (DD) is usually 20 or 18 °C for heating DD. The number of winter degree-days is a rough measure of the heating needs of a building.

Similarly, the cooling degree-days are calculated, as a sum of the difference between the average daily outdoor and indoor temperatures; the indoor temperature used as reference is usually 24 or 18 °C, but 10 °C is also used in order to obtain higher, more significant, values.

Monthly averages of daily mean values

These are the values of temperature, humidity and solar radiation on a horizontal plane, and they are used to evaluate the energy performance of buildings by making use of semi-stationary calculation methods.

TRY, Test Reference Year

To remedy the simplifications of the monthly average day and in order to obtain more accurate calculations of the energy balances of buildings, especially in cooling mode, it is necessary to use hourly values of the meteorological parameters.

For this purpose, TRY(Test Reference Year), is used, which is defined as a set of measured hourly values of air temperature and humidity, global and diffuse solar radiation, wind velocity and direction. The data are in true sequence within each month. The data are selected from a multiple year data set of observations for a given location processed in such a way that the resulting TRY is typical for the location.

2.2 CLIMATES IN THE EAST AFRICAN COMMUNITY

The first, comprehensive, climate classification system was developed by Wladimir Köppen in 1884.It is based on the concept that native vegetation is the best expression of climate. Thus, climate zone boundaries were selected with vegetation distribution in mind.

Existing classifications of the climatic zones of EAC countries are based on the same concept.

Buildings, to be low energy and sustainable, must be climate responsive, i.e. their features must be climate dependent. This dependence, however, is different from the kind of dependence shown by vegetation. Both, buildings and vegetation, are best suited to the environment according to climatic parameters such as temperature, humidity, solar radiation, and wind (for vegetation precipitation has to be added), but they react differently to the same climatic input.

For this reason, the climate classification developed for this Handbook is based on a building's response to climate and not on the response of vegetation.

To accomplish this task, a methodological approach based on the processing and analysis of climatic data in relation to their impact on building design strategies was used. Mahoney Tables[14] and Givoni bioclimatic charts (see paragraph 3.2) were used and, in addition, data were analysed in detail according to their average hourly trend, and thereby design strategies were derived.

The combination of these three methods led to the development of a map of climate zones based on the effect of the climatic context on building design strategies. On this basis, six homogeneous climatic zones were defined, each characterised by a set of strategies that should be adopted to minimize energy consumption and maximize thermal comfort.

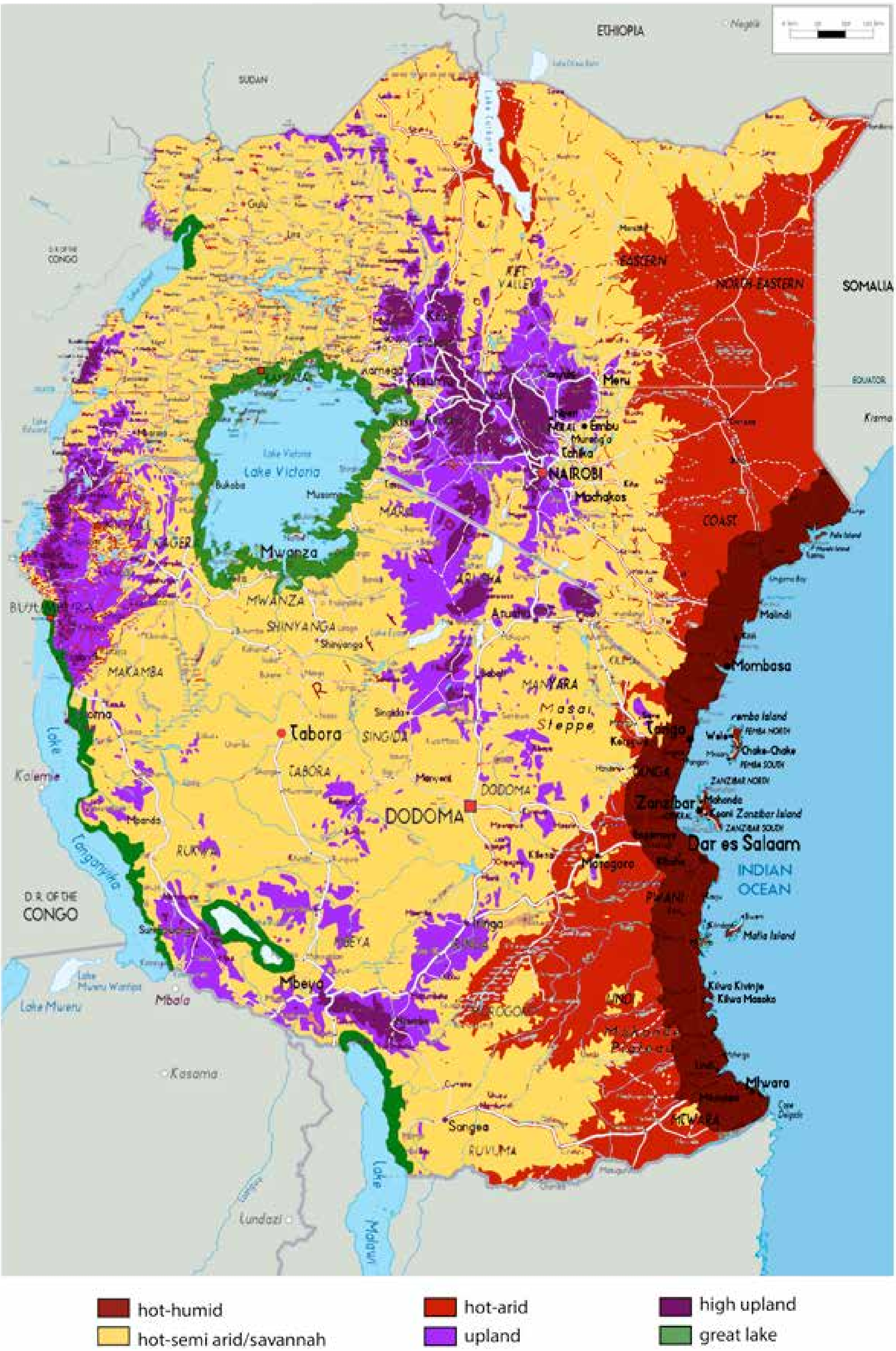
Within each zone, some of the strategies may be more or less critical, in relation to the specific local climate. So, for some climate zones, if in general a medium-high thermal inertia of the wall is recommended, the thickness of the wall should be calibrated on the basis of climatic data specific to the location. Also, the same strategy can provide higher or lower thermal comfort, in relation to the more or less severe external environmental conditions of the specific place. It should be noted that the deviation from comfort conditions in the absence of air conditioning is an indicator of the potential energy consumption when air conditioning is used.

The EAC can be divided into the following six bioclimatic zones for energy efficient building design (Fig. 2.2-1):

Zone I: Hot-humid
Zone II: Hot-arid
Zone III: Hot semi-arid/savannah
Zone IV: Great lakes
Zone V: Upland
Zone VI: High upland

14 The Mahoney tables are a set of reference tables used in architecture, used as a guide to climate-appropriate design. They are named after architect Carl Mahoney. They were first published in 1971 by the United Nations Department of Economic and Social Affairs.

FIGURE 2.2-1 **CLIMATE ZONES FOR EAC**



ZONE I: **HOT-HUMID**

This zone includes the coastal areas, islands and a strip of land from 20 to 100 km wide along the coast. Most of the zone is less than 300 m above sea level. It is never excessively hot, but has high humidity, which causes discomfort. The zone is characterized by permanent high humidity, generally high temperatures, small daily temperature swing, moderate breezes and high values of solar radiation, except on cloudy days. Along the coast and up to 2-8 km inland, depending on the terrain the prevailing north-east and south-east monsoon winds are modified by sea-land breezes during the day and, to a much lesser extent, by land-sea breezes at night.

In the hottest month, the mean maximum air temperature is about 32 °C, the mean minimum air temperature is 25-26 °C, and the mean temperature swing is about 3-7 °C. The mean relative humidity along the coastal area is about 80%, and for the strip of land from 20-100 km along the coast, the mean relative humidity is 65%-72%. A more comfortable season is experienced between June and September due to a small temperature drop together with a lower humidity level and relatively higher wind velocity.

Global solar radiation over a horizontal surface is 5.0-5.4 kWh/m^2 day and progressively lowers to 4.5 kWh/m^2 moving away from the coastline. The cooling degree days (base 10 °C) are in the range of 5500-6200. The monsoons blow from the northeast from November to March and from the southeast from April to September.

The average annual precipitation is 900-1250 mm.

Some of the representative locations for this zone are: Mombasa, Malindi (Kenya), Dar es Salaam and Tanga (Tanzania).

Comfort

The combination of high temperatures and high humidity causes discomfort. Ventilation that facilitates convective and evaporative cooling of the body is essential for comfort by both day and night.

Nights, which are often still and sultry, bring little or no relief to the heat of the day. Even correctly designed lightweight houses will release heat, very often causing an indoor temperature higher than that of outdoors Therefore, minimizing discomfort at night is of utmost importance.

The period from June to September is less critical.

A high incidence of glare can be expected from bright overcast skies.

ZONE II: **HOT-ARID**

The hot-arid zone includes the areas that are far from the sea, with altitudes ranging from 0 m to 500 m.

Maximum temperatures are high, higher than those of the hot-humid climate and the daily temperature variation is also high. Humidity, especially in the hottest hours, is low. Breezes are generally light with no strong predominant direction.

The wet and dry seasons correspond to the wet and dry seasons on the coast at the same latitude, and both these seasons are much drier.

For the hottest month, the mean maximum air temperature is about 36 °C, the mean minimum air temperature is 23 °C, the mean temperature swing is about 12 °C, mean relative humidity is about 40%, and global solar radiation over a horizontal surface is about 7.0 kWh/m^2 day. The cooling degree days are about 6700-7200. The average annual Rainfall is 0-500 mm.

Some of the representative locations for this zone are: Garissa and Lodwar (Kenya).

Comfort

Days are invariably very hot. The high daytime temperatures are accompanied by moderate to low humidity such that even a gentle breeze will usually be sufficient to prevent skin surfaces from becoming moist. Low humidity in the hottest hours attenuates the level of discomfort and a wider daily temperature swing means that nights are relatively comfortable. Winds are generally weak, and persistent, at times strong winds are experienced locally. Sudden severe and violent windstorms accompanied by thick rising sand occur from time to time in some parts of the zone (*e.g.* Lake Turkana). Fresh breezes from mid to late evening are common in some places (*e.g.* Garissa).

Heat during the day imposes severe restrictions on people’s outdoor activities. Houses should aim at keeping indoor temperatures low during hot days, and should be provided with shaded outdoor areas where occupants can carry out various activities. Very often people like to rest and sleep inside during these hot hours.

ZONE III: **HOT SEMI-ARID / SAVANNAH**

This zone covers the widest area of the EAC, and includes some parts of Kenya and a large part of Tanzania and Uganda, with altitudes ranging from 500 m to 1500 m. The difference between this zone and the hot-arid zone is that it has relatively higher humidity values, lower peak temperatures and smaller daily temperature swings.

The mean air temperature range is 20-22 °C. In summer the temperatures are about 29-31 °C and can rise to 33 °C in semi-arid areas. Mean relative humidity is about 65%, but it can go as low as 40% in parts of the savannah plains. Global solar radiation over a horizontal surface is about 6.3 kWh/m^2 day. The cooling degree days are 4600-5400.

The mean annual rainfall varies according to topography and ranges from 500 mm-750 mm in semi-arid areas to 1000-1500 mm in savannah regions.

Some of the representative locations for this zone are: Machakos, Isiolo, Mavoko, Thika (Kenya), Tabora, Dodoma (Tanzania), Gulu, Kabale, Iganga, Kasese, Lira (Uganda).

Comfort

The comfort conditions are similar to those in the hot-arid climate zone.

The discomfort caused by the high daytime temperatures that prevail during most of the year can be critical, though steady breezes often alleviate the heat of the afternoon. It can be chilly during the cloudy months of July and August and during and immediately after rains.

Mosquitoes are troublesome in some of the small townships, particularly where stagnant water abounds.

Comfort conditions at night vary considerably over the year. It is often likely to be uncomfortably warm inside massive walls and poorly ventilated houses. From June to August and during the rainy season it can, however, be distinctly cool at night.

ZONE IV: **GREAT LAKES**

This zone includes a strip 0-25 km wide along the shores of Lakes Victoria, Nyasa, Rukwa and Tanganyika. The zone ranges in average from lake level to about 150 m above lake level.

The temperature is slightly lower than that in the savannah zones, but daily variations are comparable.

Due to the lakes, humidity is higher than in the savannah zone, even though it is in the same altitude range.

In the hottest month, the mean maximum air temperature is about 28-29 °C, the mean minimum air temperature is 16-17 °C, the mean temperature swing is about 12 °C, the mean relative humidity is about 60-70%, and global solar radiation over a horizontal surface is about 5.5 kWh/m^2 day. The average annual precipitation is more than 1200 mm.

The cooling degree days are about 4100-4800.

Some of the representative locations for this zone are: Kisumu, Homabay, Kakamega (Kenya), Bukoba, Mwanza (Tanzania), Kampala, Hoima, Jinja (Uganda), Kibuye, Gisenye (Rwanda), Bujumbura (Burundi).

Comfort

This is a remarkably stable climate. There are very slight seasonal and daily differences in temperature and humidity. Day temperatures are rather similar to those in the hot-humid Coastal Zone, but nights may be uncomfortably cold for some periods of the year. The hot and comparatively humid climate of this zone is considerably modified by the zone's altitude, from 475 m (Lake Nyasa) to 1133 m (Lake Victoria). Due to the high altitude of Lake Victoria, early mornings may be uncomfortably cold during the cold season and the rains. Therefore, complete sun exclusion is not desirable in this area, whereas in other parts of the zone sun exclusion is required. Shaded outdoor spaces facing the lake in order to catch the cooling afternoon breeze are highly appreciated.

During chilly and rainy mornings, the heat from a fire is most desirable.

ZONE V: **UPLAND**

This zone refers to areas at altitudes between about 1500 and 2000 m, mainly mountains and plateaus. They are generally cool areas where some heating is welcome on the coolest days of the year. High relative humidity is rare during the day, but is the norm at night. Breezes are moderate with no predominant direction.

For the hottest month, the mean maximum air temperature is about 26-27 °C, the mean minimum air temperature is 14-16 °C, the mean temperature swing is about 10-12 °C, mean relative humidity is about 60-65%, and global solar radiation on horizontal surface about 6-7 kWh/m^2 day.

For the coldest month, the mean maximum air temperature is about 20-24 °C, the mean minimum air temperature is 14-15 °C, the mean temperature swing is about 6-10 °C, mean relative humidity is about 60-75%, and global solar radiation over a horizontal surface is about 5-6 kWh/m^2 day. The heating degree-days are about 25-370 (base 18 °C) and the cooling degree days are about 3000-3700.

The average annual precipitation is more than1200 mm.

Some of the representative locations for this zone are: Nairobi, Kitale, Nakuru (Kenya), Arusha, Mbeya, Iringa (Tanzania), Mbale (Uganda), Kigali (Rwanda).

Comfort

The upland zone has a pleasant climate. Because of the high altitude, the conditions in this zone are similar to spring or autumn in a temperate climate. Temperatures are moderate and during daytime rarely exceed the upper limits of the comfort zones. During nighttime, the temperature is likely to drop below the lower limit of the comfort zone.

The low night temperatures are a major source of discomfort.

ZONE VI: **HIGH UPLAND**

This zone refers to altitudes above 2000 m. These are generally cold areas where heating is necessary for most of the year. The humidity is fairly high. For the coldest month, the mean maximum air temperature is about 20 °C, the mean minimum air temperature is 12 °C, the mean temperature swing is about 8 °C, mean relative humidity is about 80%, and global solar radiation over a horizontal surface is about 5.3 kWh/m^2 day. The heating degree-days are more than 480. The cooling degree-days are less than 3700. The average annual precipitation is more than 1200 mm.

One of the representative locations for this zone is Eldoret (Kenya).

Comfort

Due to the altitude, daytime temperatures are never high, but nights are very cold. During most nights, temperatures are well below the comfort zone, and a rapid temperature drop takes place at sunset.

The zone contains a large number of exposed localities with brisk winds and good air movement, which in cold weather may be uncomfortable. However, high wind velocities are uncommon.

The frequent cold and rainy weather makes people stay indoors close to the fire.

03 CLIMATE RESPONSIVE BUILDING DESIGN

3.1 PASSIVE DESIGN

The term "passive design" refers to a building whose architectural features are such that they take advantage of local climatic resources to provide an indoor environment which is as comfortable as possible, thus reducing energy consumption due to the need for mechanical heating or cooling.

So-called solar architecture has been classified as passive or active, depending on the technologies/techniques used for solar collection. Solar passive is a term applied to a building where solar radiation enters the interior space through windows, while solar active refers to a building where solar thermal collectors are added to the architectural envelope. It should be noted that in solar passive buildings solar energy can be used only for space heating, while in solar active buildings solar energy can be used for space heating, space cooling and hot water production.

Another term often used to define passive architecture is "Bioclimatic architecture", which was introduced for the first time by Olgyay (1963) and later developed by Givoni (1969). More recently the term "green architecture" is also used, which includes the principles of passive or bioclimatic architecture.

Conventional buildings do not use the resources of their natural environment effectively, but consume energy and materials and produce waste (Fig. 3.1-1). Houses like these create costs and environmental problems by necessitating extensive supply and disposal facilities.

A bioclimatic building is completely integrated into the cycles of nature and is able to use them without causing damage (Fig. 3.1-2). The interaction of the main cycles involving the basic elements of soil, water, energy and air should be carefully considered and integrated into the design of buildings and residential developments.

In passive architecture the means that the architect can use for creating a thermally and visually comfortable indoor environment are: solar radiation, wind, orientation and shape of the building, thermal mass of walls and roof, thermal transmittance and colour, opening size and type of glazing.

FIGURE 3.1-1 **CONVENTIONAL BUILDING DESIGN**

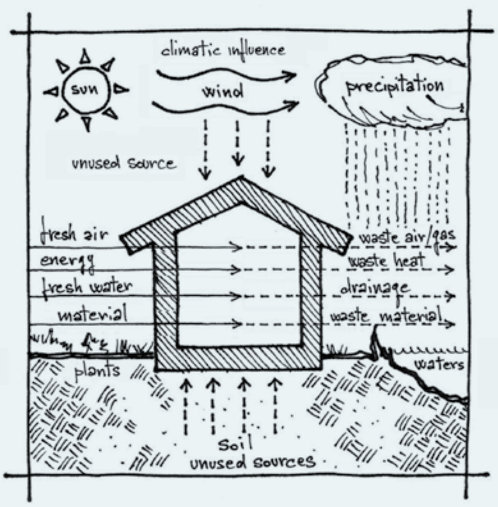
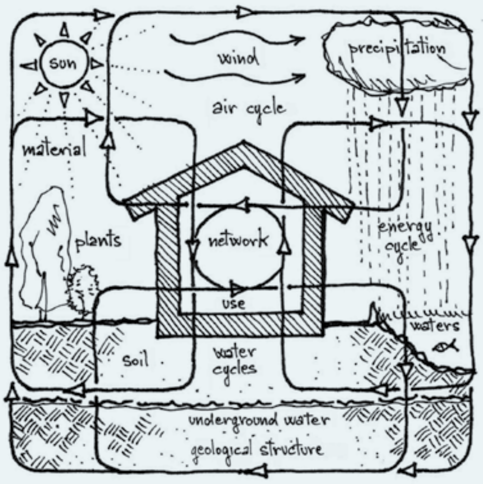


FIGURE 3.1-2 **BIOCLIMATIC BUILDING DESIGN**



3.2 BIOCLIMATIC CHARTS

Passive strategies for building design derive from climatic conditions, since it is the gap between these and comfort conditions, and the reasons for this gap, that create the need to take appropriate measures to reduce the gap as much as possible, without using any artificial heating or cooling systems.

In the 1950s, to help the designer choose the most appropriate design strategies for local climatic conditions, Victor Olgyay developed what he called a "bioclimatic chart".

Olgyay's bioclimatic chart (Fig. 3.2-1) is a simple tool for analysing the climate of a particular place. It indicates the zones of human comfort based on ambient temperature and humidity, mean radiant temperature, wind speed, solar radiation and evaporative cooling. On the chart, dry bulb temperature is used as the ordinate, and relative humidity as the abscissa. Based on the dry bulb temperature and humidity of a place, one can locate a point on the chart. If it lies within the comfort zone, then the conditions are comfortable. For any point falling outside this zone, corrective measures are required to restore the feeling of comfort. For example, at dry bulb temperature 25 °C, relative humidity, 50%, none are needed as the point is already in the comfort zone. If it is above the zone, cooling is required; if it is below the zone, heating is needed. For example, at dry bulb temperature 15 °C, relative humidity 50%, the need is: 500 W/m^2 solar radiation. If the point is higher than the upper perimeter of the comfort zone, air movement needs to be increased. For example, at dry bulb temperature 30 °C, relative humidity 70%, the need is: 0.4 m/s wind to reach the comfort level. For conditions when the temperature is high and relative humidity is low, air movement is not enough. If the point lies below the lower perimeter of the comfort zone, heating is necessary to counteract the low dry-bulb temperature. If the point lies to the left of the comfort zone, either radiant heating or cooling is necessary. Thus, a bioclimatic chart can give information about the requirements for comfort at a particular time. Design decisions can be taken accordingly.

In 1969 Givoni developed a bioclimatic chart for buildings, correcting some of the limitations of Olgyay's diagram. While Olgyay applied his diagram closely to outdoor conditions, Givoni's chart is based on the indoor temperature of the building, and suggests design strategies to adapt architecture to climate. The chart uses as a basis a psychrometric chart (see Appendix 1 – Principles of Building Physics) on which temperature and humidity data (monthly, daily or hourly) are plotted for a given site[15].

Givoni's chart identifies a suitable cooling or heating technique on the basis of the outdoor climatic conditions.

3.2.1 GIVONI CHARTS

There are different types of Givoni charts, adapted to specific climates, and with a large number of strategies (Fig. 3.2-2). Software has also been developed that, in conjunction with a climatic data base, plots on the chart the values of temperature and humidity, suggests the best strategies and shows the corresponding improvement in the comfort conditions for each strategy[16].

Six zones for passive design strategies are identified on Givoni's chart (Fig. 3.2-2):

1. Comfort zone;
2. Natural ventilation zone;
3. Evaporative cooling zone;
4. High Thermal mass;
5. High Thermal mass and night ventilation;
6. Passive heating.

Three other zones corresponding to different strategies e.g. air-conditioning, humidification and artificial heating are not passive design strategies, so are not discussed here.

Climatic data (outdoor temperature and relative humidity) can be plotted directly onto the chart, and we can check which of the six zones of the chart those conditions fall into.

The zones are defined, in the chart, as follows.

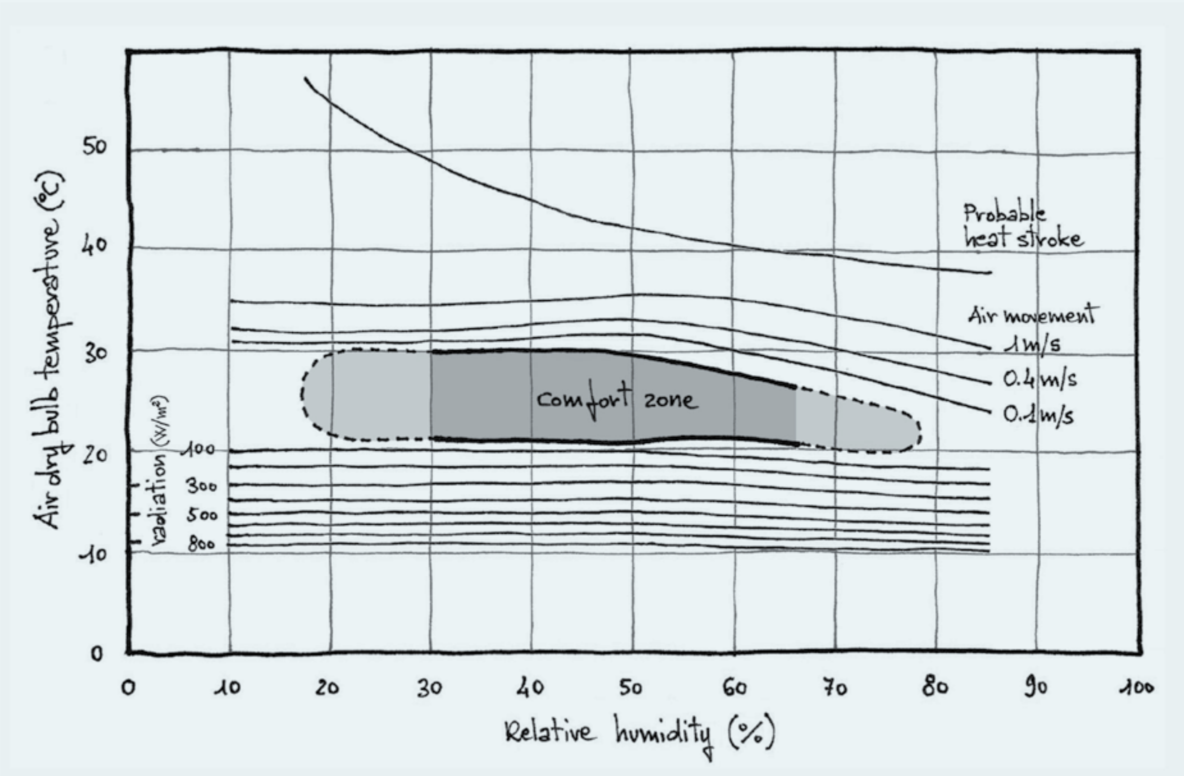
Comfort zone

In the conditions defined for this zone, it is assumed that a person is in thermal comfort conditions in the indoor space (Fig. 3.2-3). According to Givoni, it can be noted that people can be in thermal comfort conditions in different boundaries of relative humidity (between 20% and 80%) and air temperature (between 20 °C and 26 °C). When the indoor air temperature is near 20 °C, the effect of wind must be prevented, because it can cause discomfort. When the air temperature is near 26 °C, solar radiation control is necessary to avoid overheating; thermal comfort is assumed to be close to 26 °C if people are wearing light clothes and there is a small amount of ventilation.

15 The most reliable way to use the Givoni bioclimatic chart is by plotting hourly data on it, since average daily and monthly even out actual temperatures and humidity too much and the most uncomfortable conditions are not recorded, even if they are frequent. For example, in a climate with a large daily temperature and humidity variation, the daily or monthly averages do not represent correctly the actual climatic conditions in terms of the consequent comfort level and –thus – of design strategies to apply.

16 Climate Consultant, http://www.energy-design-tools.aud.ucla.edu

FIGURE 3.2-1 **OLGYAY'S BIOCLIMATIC DIAGRAM, CONVERTED TO METRIC**



Source: *O.H. Koenisberger et al., Manual of tropical housing and building, Longman, 1973*

FIGURE 3.2-2 **GIVONI BIOCLIMATIC CHART**

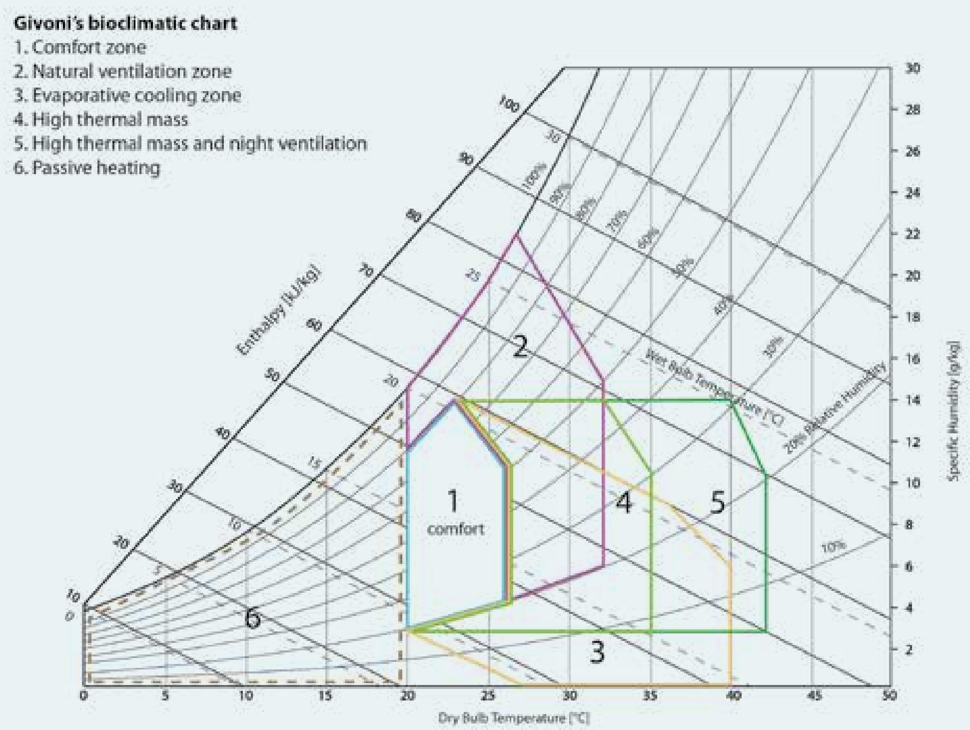
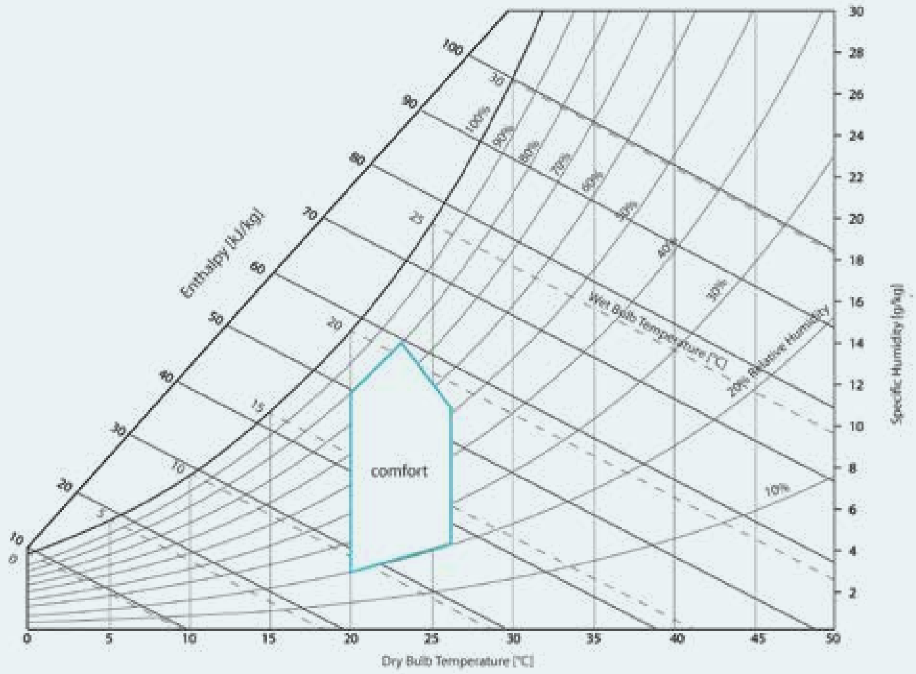


FIGURE 3.2-3 **COMFORT ZONE**



Natural Ventilation zone

If the temperature in the indoor space exceeds 26 °C or relative humidity is quite high, natural ventilation can improve the thermal comfort (Fig. 3.2-4). In hot and humid climates, cross ventilation is the simplest strategy to adopt if the indoor temperature is almost the same as the outdoor temperature. Givoni assumes that the maximum allowed indoor air speed is about 2 m/s, thus ventilation maintains comfort up to an outdoor temperature limit of 32 °C (see Appendix 2, Thermal and visual comfort).

When the temperature is well above 26 °C and relative humidity is lower than 50%, night cooling is more appropriate than day ventilation. This may happen in hot arid regions, where the daytime temperature is between 30 °C and 36 °C and the nighttime temperature is below 20 °C. In these conditions daytime ventilation is not suitable because it would warm up the building. The best strategy is to limit ventilation during the day to reduce the flow of hot air coming in and to use nighttime ventilation, exploiting the cooler air to cool the indoor space.

Evaporative cooling

Water evaporation can reduce air temperature and at the same time increase the relative humidity of a living space. The direct cooling of the indoor spaces through evaporative cooling needs a good ventilation rate to avoid the accumulation of water vapour.

In the evaporative cooling process, both the temperature and the humidity of air change along the lines of constant wet bulb temperature and enthalpy. There is no change in heat content and the energy is merely converted from sensible energy to latent energy (Fig. 3.2-5).

High thermal mass

The use of high thermal mass in a building can reduce the variation of the indoor temperature compared to the outdoor space, reducing peaks. This solution can be successfully used in places where the temperature and relative humidity are within the limits of the thermal mass zone in figure 3.2-6.

The levelling out of indoor temperature is due to:

- stored heat in the building structure during the day is released to the indoor space during the night when outdoor temperatures decrease;
- in a complementary way, the thermal structure is cooled during the night and remains cool during the greater part of the day, reducing daytime indoor temperatures.

In addition to the use of the thermal mass of the envelope, the thermal mass from the ground can also be exploited.

FIGURE 3.2-4 **NATURAL VENTILATION ZONE**

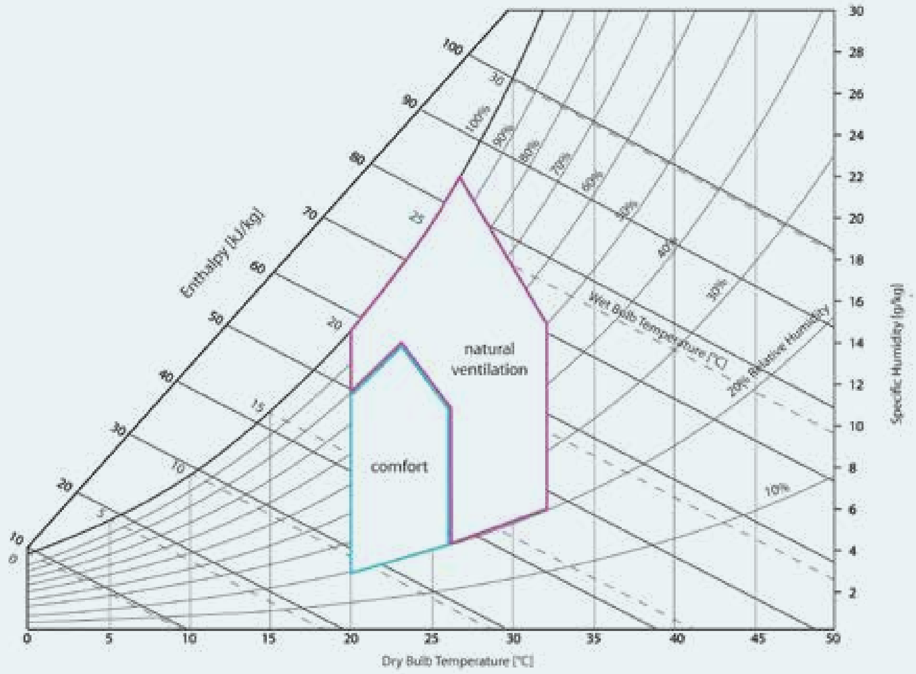


FIGURE 3.2-5 **EVAPORATIVE COOLING ZONE**

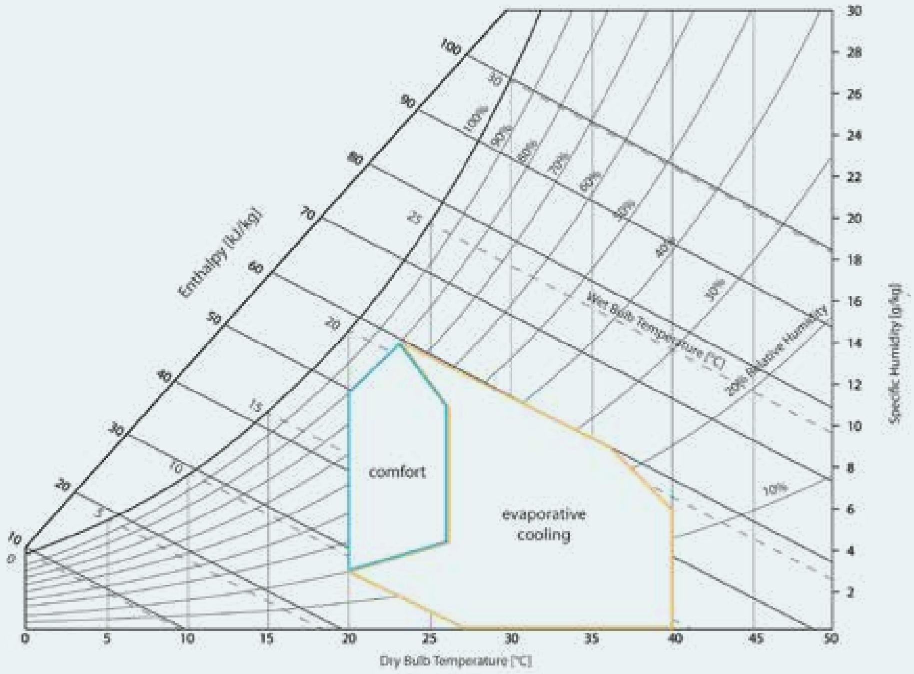
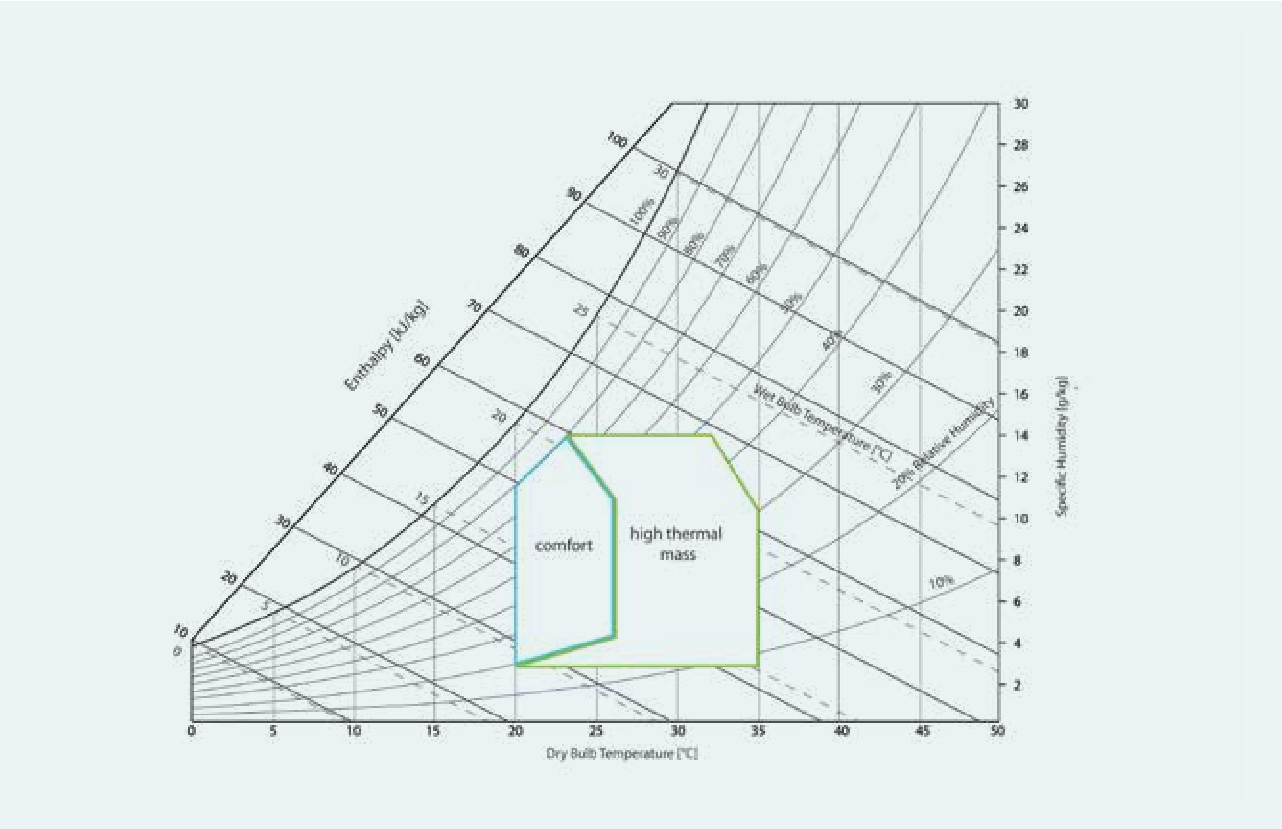


FIGURE 3.2-6 **HIGH THERMAL MASS ZONE FOR COOLING**



High thermal mass and night ventilation

Thermal mass can be used in conjunction with night ventilation of to provide passive cooling (Fig. 3.2-7). During the night outside air is circulated through the building, cooling the building fabric. The cooling that is stored in the building fabric is then available to offset heat gains the following day and keep temperatures closer to comfort limits.

Night ventilation is most effective in a hot-arid climate where the diurnal temperature swing is high and the nighttime temperature falls below 20 °C. The use of thermal mass in conjunction with night ventilation can be used to minimise or eliminate the need for mechanical cooling. This solution can be applied in locations where the conditions of temperature and relative humidity are within the limits of the high thermal mass and night ventilation zone.

Passive solar heating

The use of the passive solar heating is more suitable for the locations where seasonal air temperatures are lower than 20 °C (Fig. 3.2-8). Thermal insulation of the building, because of the heat losses, and appropriately sized glazed windows facing towards the sun in the coolest period are recommended.

3.2.2 COMBINED STRATEGIES

Some intersections can be found between the natural ventilation zone (2), the evaporative cooling zone (3), the high thermal mass (4) and the high thermal mass and night ventilation (5) as highlighted in figure 3.2-9.

Region A represents the intersection between the natural ventilation zone and the high thermal mass zone (along with night ventilation). For this situation both the strategies can be adopted at the same time. In the same way, in region B, the advantages of high thermal mass (along with night ventilation) and evaporative cooling can be exploited. In region C, the three strategies can be adopted separately or together.

Hot-humid climate (Dar es Salaam, Tanzania)

According to the Givoni bioclimatic chart (Fig. 3.2-10), in a hot-humid climate like Dar es Salaam, natural ventilation and solar shading are the most effective passive design strategies for improving thermal comfort.

FIGURE 3.2-7 **HIGH THERMAL MASS AND NIGHT VENTILATION ZONE FOR COOLING**

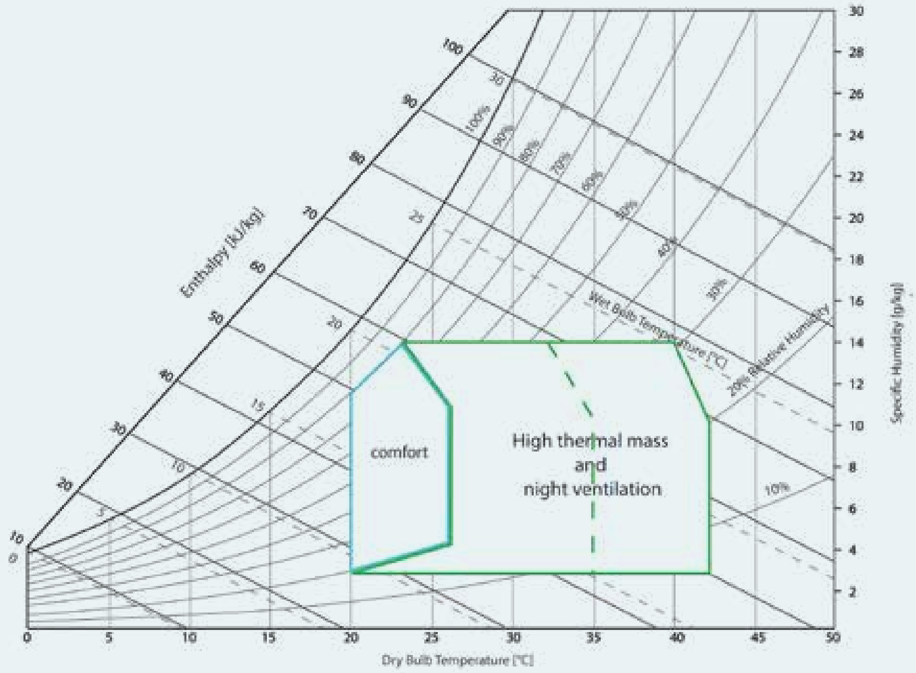


FIGURE 3.2-8 **PASSIVE HEATING ZONE**

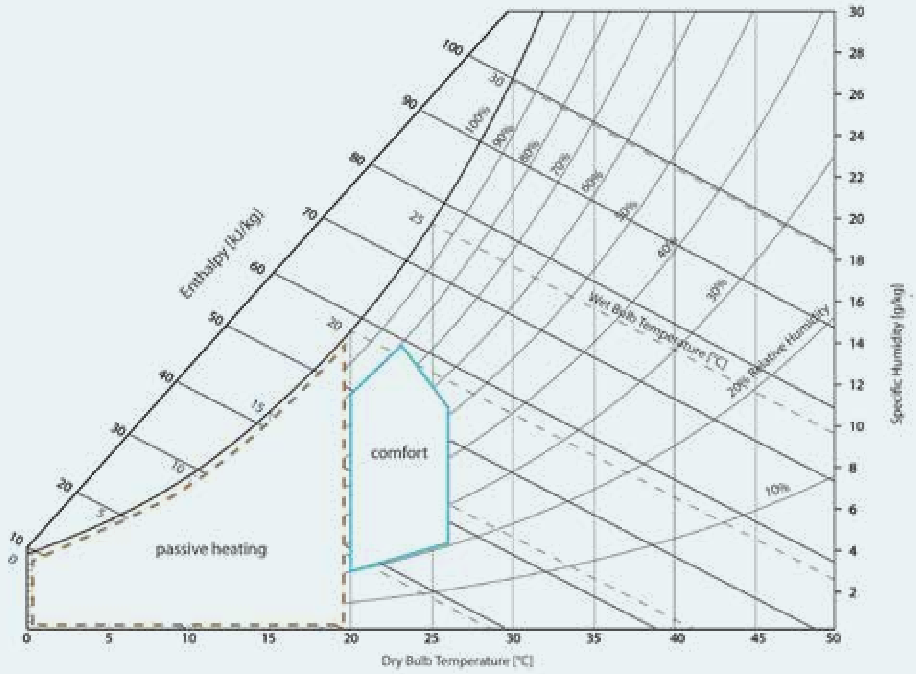


FIGURE 3.2-9 **INTERSECTION BETWEEN NATURAL VENTILATION, HIGH THERMAL MASS (AND NIGHT VENTILATION) AND EVAPORATIVE COOLING**

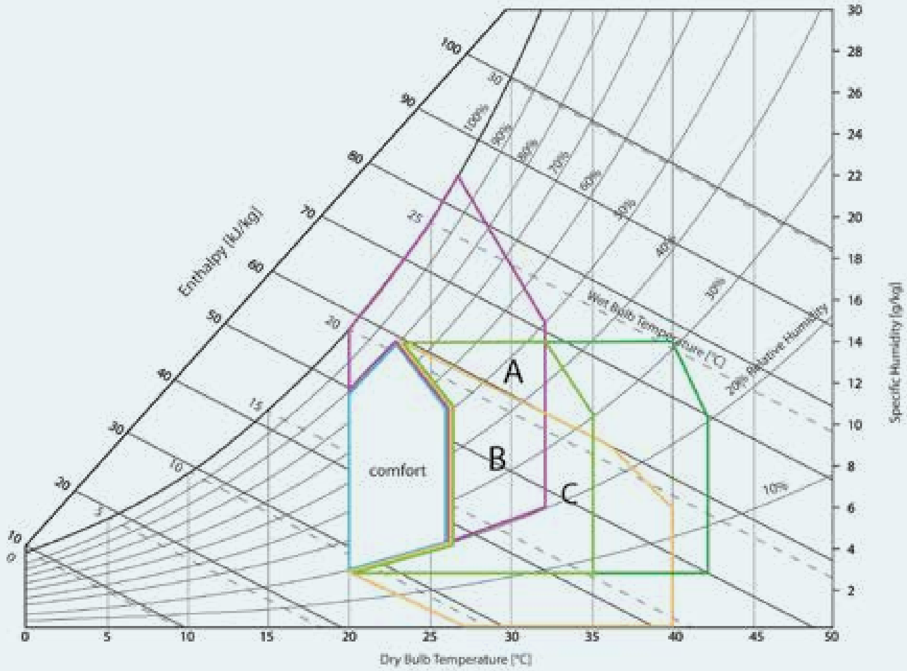
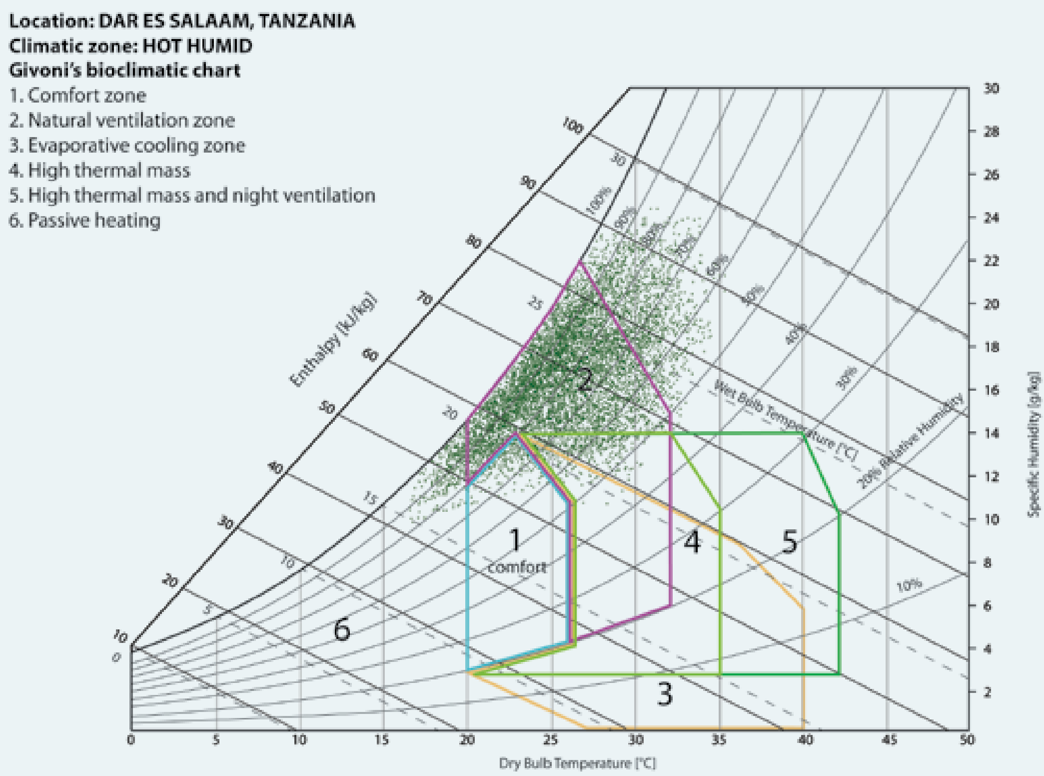


FIGURE 3.2-10 **GIVONI BIOCLIMATIC CHART FOR DAR ES SALAAM**



Hot-arid climate (Lodwar, Kenya)

In a hot-arid climate like Lodwar (Fig. 3.2-11), natural ventilation (night ventilation), high thermal mass, solar shading and evaporative cooling are the most effective passive design strategies for improving thermal comfort.

Hot semi-arid/Savannah climate (Tabora, Tanzania)

In a hot semi-arid/savannah climate like Tabora (Fig. 3.2-12), natural ventilation (night ventilation), high thermal mass and solar shading are the most effective passive design strategies for improving thermal comfort.

Great lakes climate (Kampala, Uganda)

In a Great Lakes climate like Kampala (Fig. 3.2-13), natural ventilation, passive heating and solar shading are the most effective strategies for improving thermal comfort.

Upland climate (Nairobi, Kenya)

In an upland climate like Nairobi (Fig. 3.2-14), passive heating and medium thermal mass are the most effective strategies for improving thermal comfort.

Upland climate (Eldoret, Kenya)

In a high upland climate like Eldoret (Fig. 3.2-15), passive heating is the most effective design strategy for improving thermal comfort.

FIGURE 3.2-11 **GIVONI BIOCLIMATIC CHART FOR LODWAR**

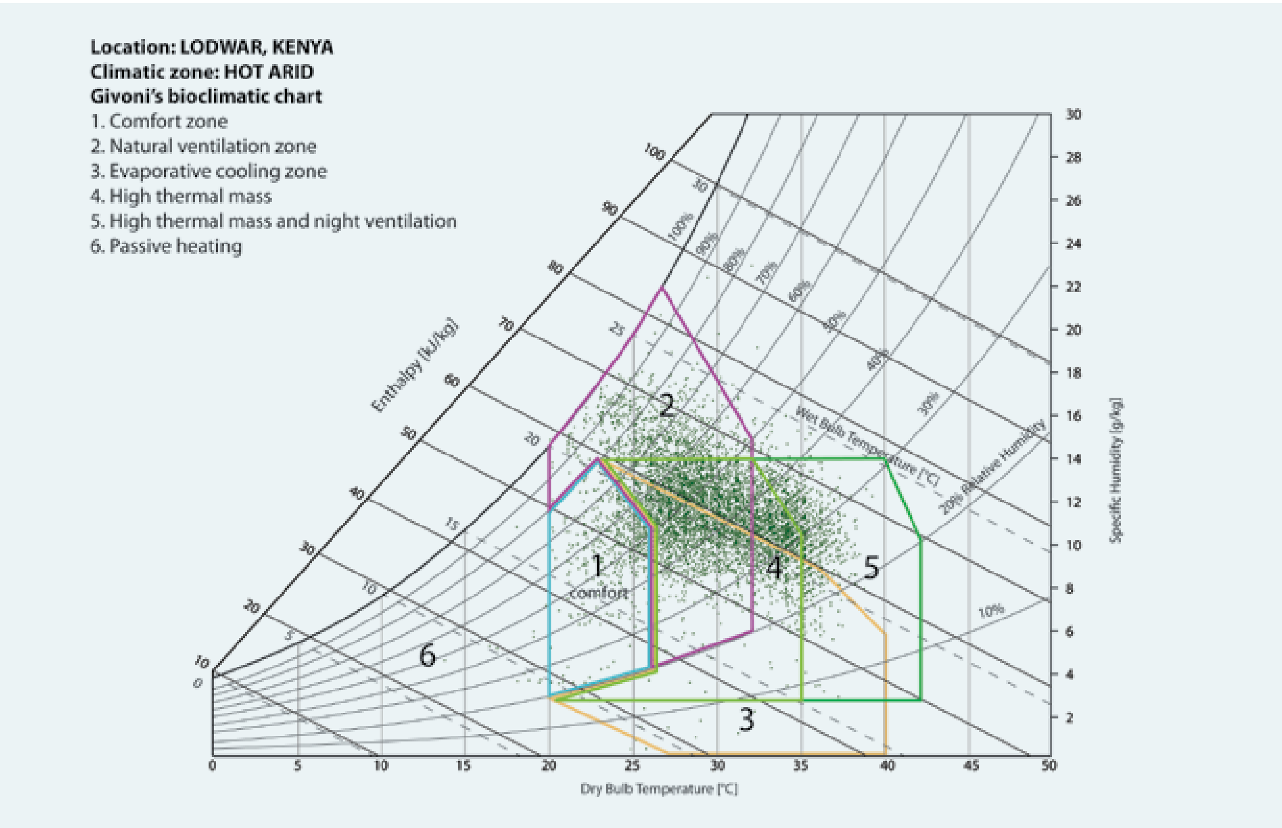


FIGURE 3.2-12 **GIVONI BIOCLIMATIC CHART FOR TABORA**

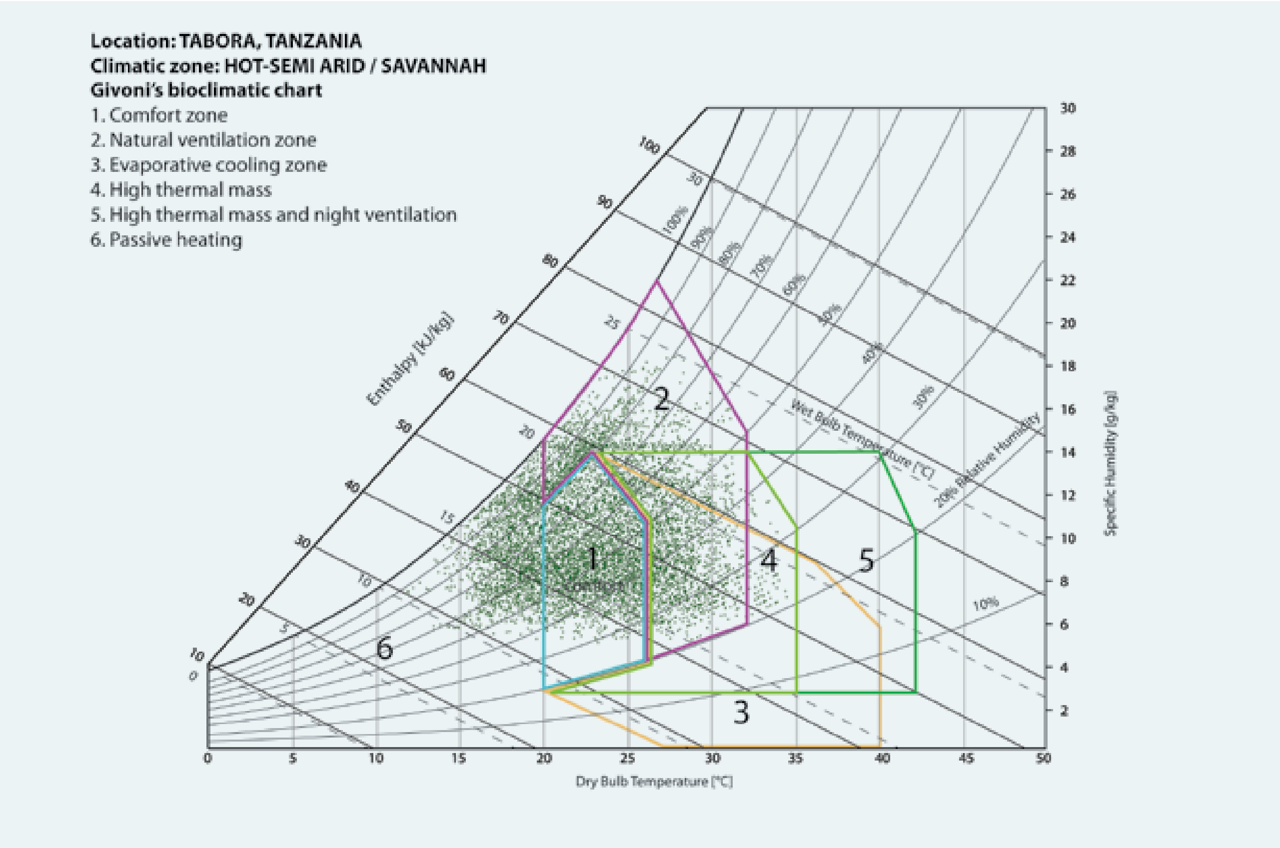


FIGURE 3.2-13 **GIVONI BIOCLIMATIC CHART FOR KAMPALA**

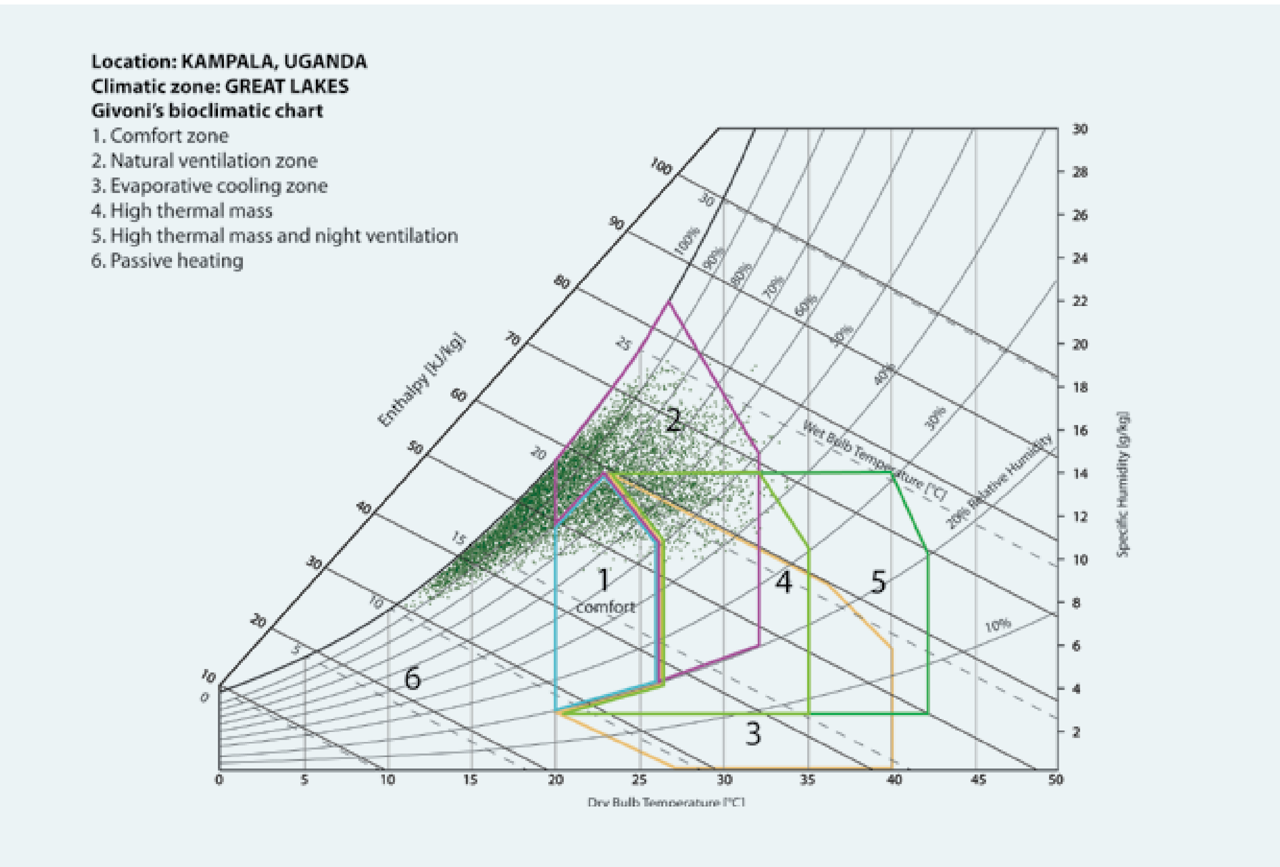


FIGURE 3.2-14 **GIVONI BIOCLIMATIC CHART FOR NAIROBI**

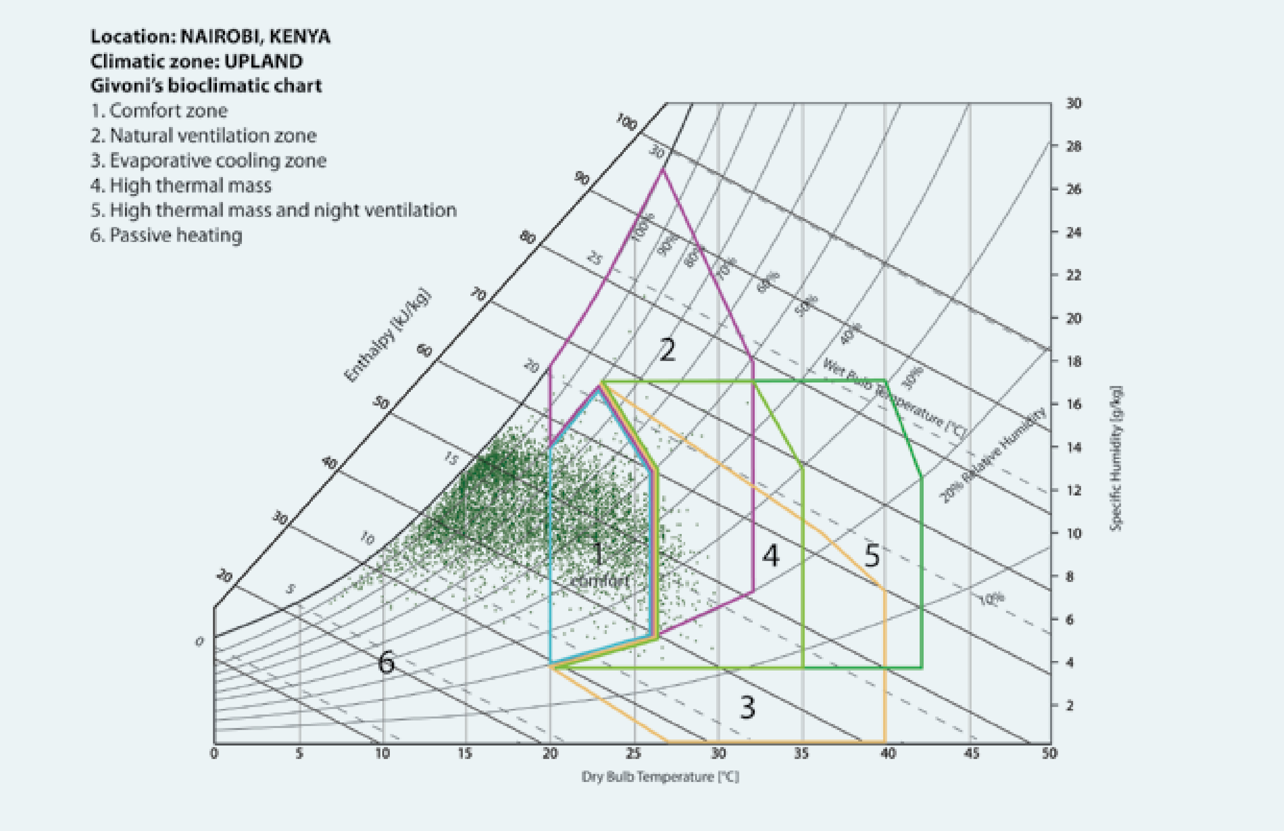
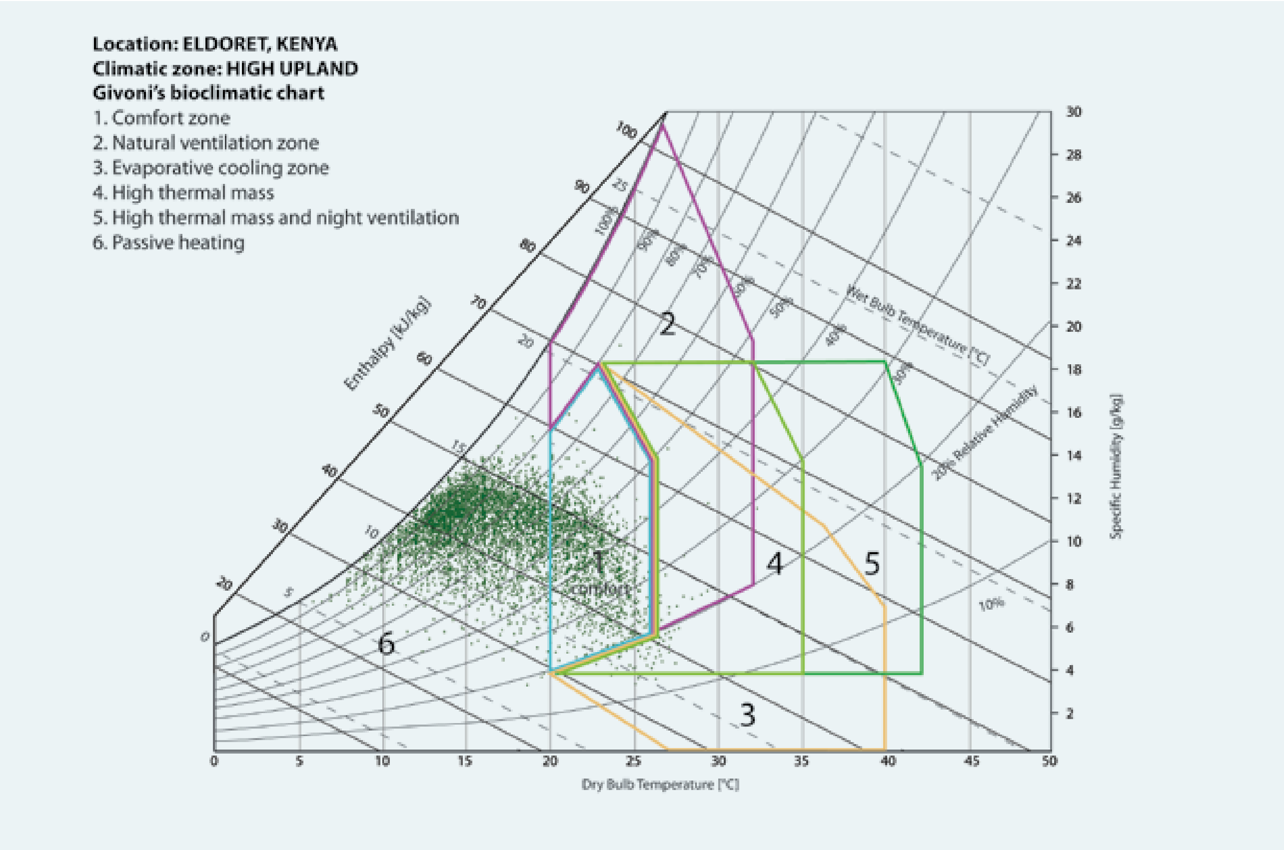


FIGURE 3.2-15 **GIVONI BIOCLIMATIC CHART FOR ELDORET**



3.3 SITE PLANNING

When urban planners start to design a new settlement, they usually look for pre-existing landmarks, such as roads, railways, rivers etc., and align the new buildings and streets accordingly. Very rarely do they look for the most ancient pre-existing landmarks: solar path and prevailing winds. However, analysis of these is very important in order to optimise the energy efficiency of the urban layout.

Low energy urban design means that shading and illumination of surfaces as well as wind must be analysed so that shape, orientation and distances between buildings can be optimised in order to control solar radiation and ventilation, with the aim of reducing the energy demands of individual buildings.

Sustainable site planning begins with an assessment of the building site in terms of its capability to provide natural resources, such as light, air, and water, and the extent to which the existing natural systems will be required to support the new development.

The process encompasses many steps, such as site selection, inventory, analysis, and development procedures.

The process is based on the concept of an interdependent natural system that links a series of interconnected geological, hydrological, topographical, ecological, climatological, and cultural attributes.

3.3.1 METHODOLOGY

The first step of energy conscious urban design is based on data collection and analysis as follows.

Data to be collected are:

- data about the macro and micro climate: detailed information about solar path, sky conditions and radiation, temperature range (seasonal minimum and maximum temperatures during night and day), humidity, precipitation, air movement etc.;
- data about the building site: topography, ventilation, orientation, vegetation, neighbouring structures, soil, water and air quality.

The analysis involves the adoption of solar diagrams, shading diagrams, comfort diagrams and tables.

Other information required is:

- data about building usage and cultural background: type of usage, period of usage, clothing, traditions and aesthetic values of occupants, traditional techniques and building materials;
- data about economic aspects: financial resources, available labour, materials and technologies.

3.3.1.1 **MICROCLIMATE**

The conditions which allow energy to flow through the building fabric and determine the thermal response of people are local and site-specific. These conditions are generally grouped under the term microclimate, which includes the wind, radiation, temperature, and humidity experienced around a building. A building by its very presence will change the microclimate by causing an obstruction to the wind flow, and by casting shadows on the ground and on other buildings. A designer has to predict this variation and take its effect into account in the design.

The microclimate of a site is affected by the following factors: landform, vegetation, water bodies, street width and orientation, open spaces and built form.

An understanding of these factors greatly helps in the preparation of the site layout plan.

The density and size of the built area affect the degree to which the microclimate can be modified in terms of wind conditions, air temperature, radiation balance, and natural lighting. This density depends on the proportion of the land covered by the buildings and the average height of the buildings (the effect of which can be modified by the relative heights of individual buildings on site).

Density also creates the heat island effect, which can be mitigated by reducing the total paved area allowed on site, and the services networks in terms of cost and technologies.

Each building type and combinations of different building types (i.e. detached/semi-detached, courtyard/patio, high rise and row buildings) form a matrix of environmental conditions that affect both macro and microclimate around and inside the building.

A correct mix of building types could help in achieving adequate sun protection and ventilation: high-rise buildings can increase ventilation in a dense development; low-rise buildings should be sited so that they avoid excessive heat exchange with the environment and utilize their link with open spaces.

3.3.1.2 **URBAN LAYOUT AND EXTERNAL SPACE**

Urban layout greatly depends on climate and should be designed differently in each climatic zone. The basic concerns are the provision of shading and air movement. The orientation of streets and the layout have a significant effect on the microclimate around buildings and on the access to sun and wind.

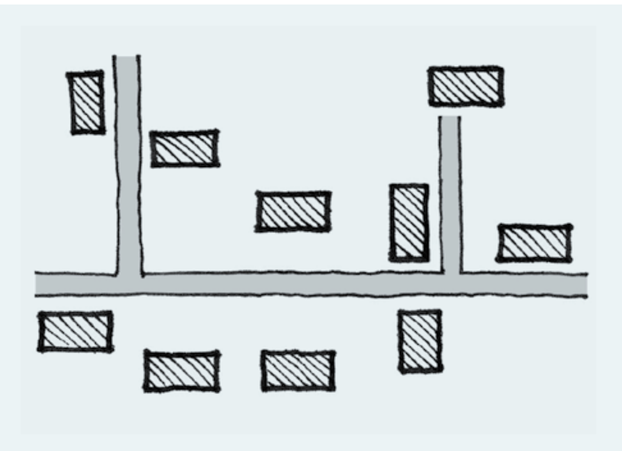
The urban form cannot change the regional climate, but can moderate the microclimate and improve the conditions for the buildings and their inhabitants.

The influence of the climate on the layout of traditional settlements around the world is clearly illustrated by the following examples:

- settlements in hot-humid areas (such as Zone I) are laid out to make maximum use of the prevailing breeze (Fig. 3.3-1). Buildings are scattered, vegetation is arranged to provide maximum shade without hindering natural ventilation;
- settlements in hot-arid climates (such as Zone II) are characterized by optimal protection against solar radiation by mutual shading (Fig. 3.3-2), which leads to compact settlements, narrow streets and small squares which are shaded by tall vegetation;
- settlements in cool areas (such as Zone VI) are generally laid out to make use of solar radiation during the coldest period and for protection from cold winds.

Although modern requirements are often in contradiction with traditional patterns, their advantages should be taken into consideration as much as possible.

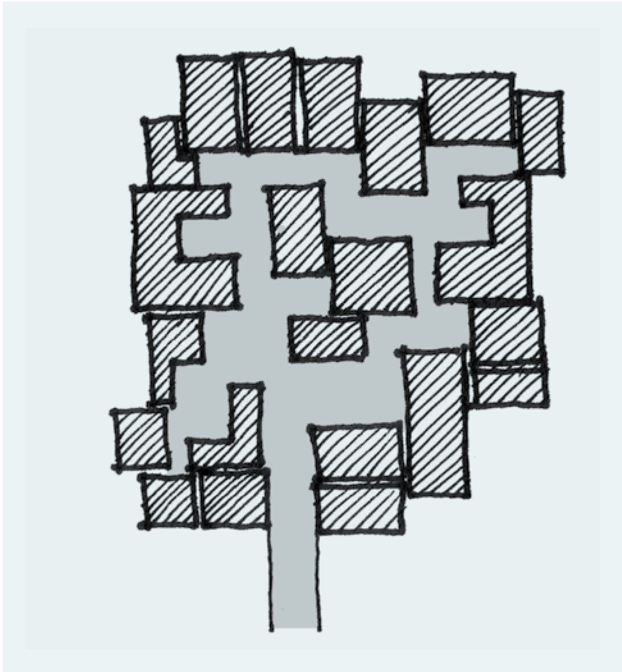
FIGURE 3.3-1 **TYPICAL SETTLEMENT FOR HOT-HUMID REGIONS**



3.3.2 RECOMMENDED URBAN PATTERNS

In tropical climates many of the activities associated with indoor spaces in moderate or cold climates (washing, cooking, eating, playing, working etc.) are most often performed outdoors. So, as the area adjoining the building becomes an extension of the indoor space, it must be treated with equal care by the designer.

FIGURE 3.3-2 **TYPICAL SETTLEMENT FOR HOT-ARID REGIONS**



Solar radiation control

Balanced urban patterns of streets and blocks can be oriented and sized to integrate concerns for light, sun and shade according to the characteristics of the local climate.

A cardinal orientation will generally cast more shade on buildings facing north-south streets than a rotated orientation, and thus do a better job of shading buildings. In contrast rotated orientations provide more shade on the streets for longer periods during the day (Fig. 3.3-3).

Depending on the climate, different combinations of strategies may be appropriate. Table 3.3-1 shows potential solutions for three basic climate zones.

Wind effects

In hot-humid climates loose urban patterns should be preferred in order to maximise cooling breezes.

Breezy streets oriented to the prevailing wind maximize wind movement in urban environments and increase the access of buildings to cross ventilation. To maximize access to cross ventilation and air movement in streets, orient primary avenues at an angle of approximately 20°-30° in either direction from the line of the prevailing summer breeze (Fig. 3.3-4).

FIGURE 3.3-3 **URBAN LAYOUT AND SHADING**

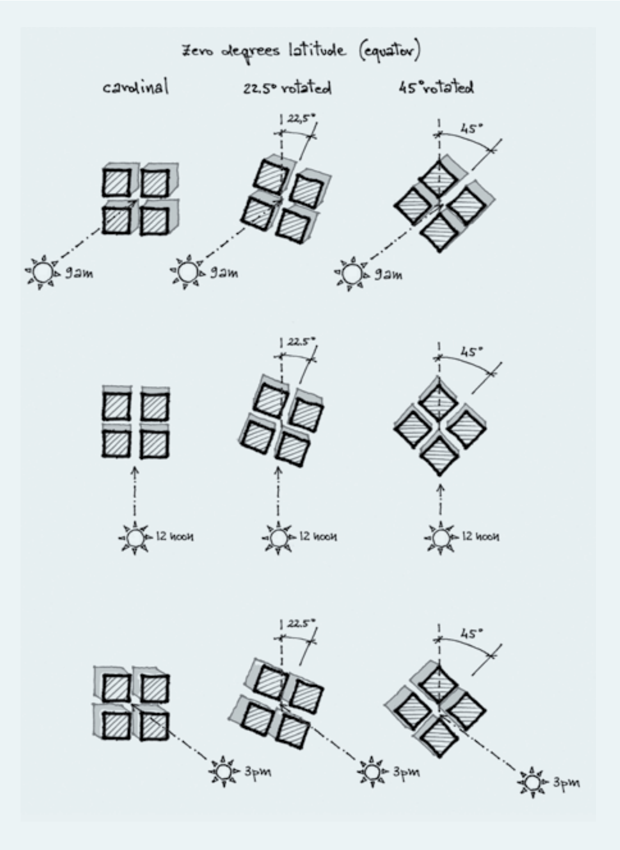
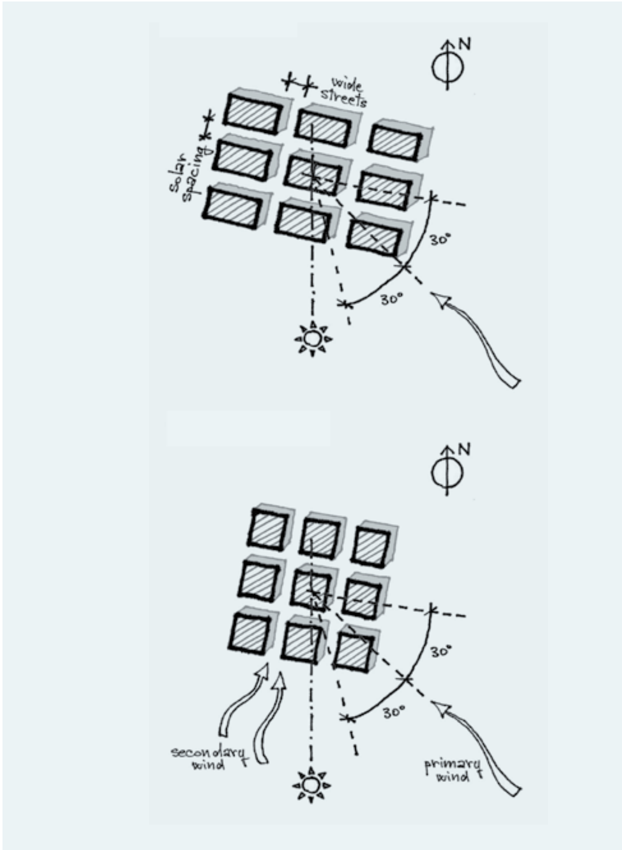


FIGURE 3.3-4 **URBAN LAYOUT AND WIND ACCESS**



Further, it should be taken into account that dispersed buildings with continuous and wide open spaces preserve each building's access to breezes.

Generally speaking, buildings in which cross ventilation is important should be separated by a distance of 7 times the building height to assure adequate airflow if they are directly behind one another[17] (Fig. 3.3-5); far less if staggered (Fig. 3.3-6).

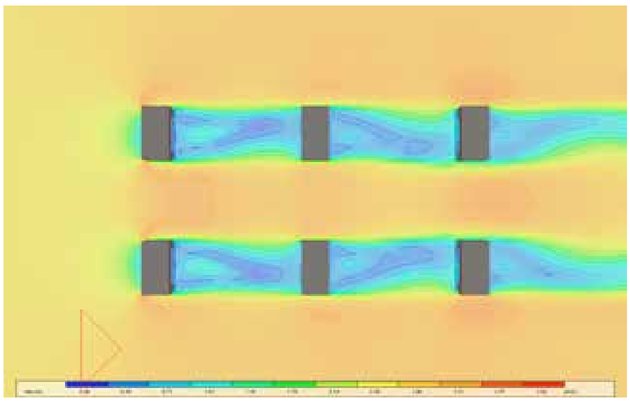
In dense urban areas this rule cannot be followed. The reduction of cross ventilation deriving from a high-density layout can be overcome by providing ventilating ducts or shafts for deeper rooms.

When cooling is the priority, windbreaks should be avoided. The unique exception is in relation to hot-arid climates, where windbreaks provide important dust and sand protection. Along tropical coasts there is usually a sea breeze. The strength of the breeze is directly proportional to the temperature difference between the land and the sea, and its speed depends on whether it is assisted or hampered by the prevailing wind, and the strength of the thermal contrast between land and sea.

Lakes may also develop similar local wind circulation patterns.

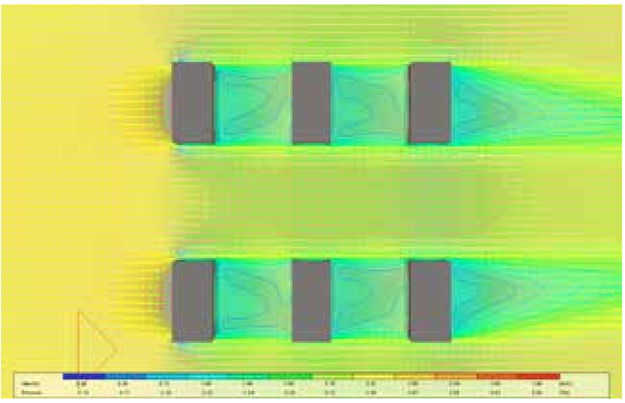
In both cases the direction of the winds is perpendicular to the coast; this effect should be taken into account in order to improve the urban layout: it could also give rise to completely different optimal urban layouts in a small region.

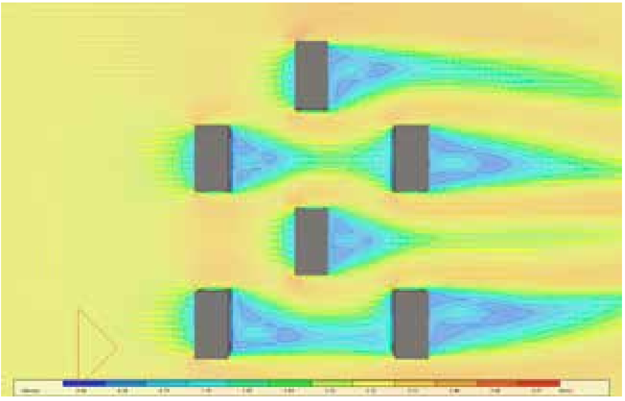
FIGURE 3.3-5 **CFD SIMULATION OF THE AIRFLOW PATTERN IN ROW ARRANGEMENT WITH A RATIO DISTANCE/HEIGHT = 7**



17 *V. Olgyay, Design with climate, Princeton University Press, 1963*

FIGURE 3.3-6 **CFD SIMULATION OF THE AIRFLOW PATTERN IN ROW ARRANGEMENT WITH A RATIO DISTANCE/HEIGHT = 3. AIR FLOW PATTERNS IN ROW ARRANGEMENT (ABOVE) AND STAGGERED (BELOW)**





In urban settlements,the optimum distance for ventilation may be in contradiction with social issues. This is the case when people living in low rise buildings are used to having social relationships in the street, which is narrow and considered as an extension of the house. If buildings are too far away, these social relationships are precluded or at least made more difficult. The use of the street as an extension of the house, at urban level, is in contradiction also with the choice of the north-south orientation of the main façades of the building, because the street would be in the sun most of the time (Fig. 3.3-3). So as to favour street life, buildings should be elongated north-south with façades facing east and west, so maximising the shading of the street. In an urban layout with narrow streets this orientation is only partially penalised, as the buildings shade them and each other (with the exception of the first building on the east and west borders of the settlement). If, as in the hot-humid climatic zones of the EAC, monsoon winds are blowing in the north-east/south-west direction, this could be the direction of the main streets which best favours their shading, but ventilation would be penalised.

Table 3.3-1 summarises the recommendations for three climates. Hot-arid, hot-humid and high uplands climates are at the vertexes of a triangle encompassing the complex variety of climates in EAC countries. These climates (hot semi-arid/savannah, great lakes and upland) are more or less close to each of the basic three, and the requirements they impose regarding settlement lay-out according to climate, are intermediate, as described more in detail in chapter 4.8.

Effects of water

Combinations of interwoven buildings and water can be used to reduce the ambient air temperature.

In hot-arid climates water evaporation can cool air temperature. This evaporation rate depends on the surface area of the water, the relative humidity of the air, and the water temperature. Since the heat transfer between air and a horizontal film of water is poor, the evaporating surface area of water should be increased by spray and fountains with very fine droplets.

Green borders

In hot-arid and semi-arid climates, green borders of irrigated vegetation can be planted to cool incoming breezes.

Planted areas can be as much as 5-8 °C cooler than built-up areas due to a combination of evaporation and transpiration, reflection, shading and storage of cold.

For this reason, the presence of vegetation of compatible height is recommended in hot regions where climatic conditions permit it to be grown.

Overhead shades

A layer of overhead shades can protect outdoor space between buildings from the high sun.

In many hot climates, both humid and arid, groups of buildings may be linked by shading pedestrian streets or pedestrians may be protected by arcades at the edges of streets and open spaces.

3.4 BUILDING DESIGN

Building shape and orientation are the first choices in the design process. They are also the most critical because they have the most impact on both thermal and visual comfort and on energy consumption. The third most important decision is related to the thermal mass and the insulation of the envelope, together with the sizing of openings. This applies to building design in any part of the world. In addition, the designer of a residential building in the EAC and in general in all developing countries with similar climates has to face a special challenge when dealing with low cost housing: the design of the kitchen. This is because of the cooking technologies used and their impact on comfort and health.

TABLE 3.3-1 **STREET ORIENTATION AND LAYOUT BY CLIMATIC PRIORITY**

		Response	Recommendations
Climate	**1st priority**	**2nd priority**	
Hot-arid	Shade	Night wind	Compact layout. Narrow N/S streets for shade. Rotate from cardinal to increase street shading. Rotate from cardinal according to prevailing night winds in hottest season. Elongate blocks E/W.
Hot-humid	Wind	Shade	Dispose buildings in a staggered pattern to favour ventilation. Orient streets 20°-30° oblique to predominant wind. Elongate blocks E/W. Wide streets for wind flow.
High upland	Solar access in cold season	Wind protection in cold season	Cardinal orientation to favour solar gains on north facing façade. Provide solar access with appropriate building height to distance ratio. Vegetation to protect from predominant wind in cold season.

3.4.1 BUILDING SHAPE

The capability of a building to store or release heat is related to its volume (and to its mass and shape), since losses or gains take place through its surfaces. Thus, the ratio of surface to volume determines the heating rate during the day and the cooling rate during the night.

At a constant volume (and therefore usable floor surface), heat losses and gains increase as we move away from the more compact form, the cube (Fig. 3.4-1). Furthermore, reducing the surface to volume (S/V) ratio also reduces the amount of material needed to make the envelope, with consequently lower construction costs and a smaller amount of embodied energy.

On the other hand, for the purposes of natural lighting and natural ventilation, a long, narrow shape is better than a square one (Fig. 3.4-2).

The optimum shape depends upon the type of tropical climate: in hot-arid zones, where the daily temperature swing is high (hot days and cool nights) a compact shape is best (low surface to volume ratio), to minimise the area of envelope exposed to the sun. By contrast, in hot-humid zones, where the daily temperature swing is small and relative humidity is high, the shape should be as open as possible in order to allow natural ventilation. At the same time, however, sun protection is essential and all possible measures should be taken to provide it.

In climates in between hot-arid and hot-humid, the choice between compactness and openness depends upon the prevailing climatic conditions, i.e. if the climate is closer to hot-arid or to hot-humid, and on the availability of wind.

High rise buildings have a lower S/V ratio than low rise ones; moreover, they expose less roof area to the sun, with the same volume, i.e. floor area (Fig. 3.4-1). Since solar gains from the roof are a critical issue in tropical countries, medium rise (4-5 floors) buildings should be preferred. We should also take into account the negative effects of urban sprawl, which is exacerbated by the use of low rise buildings.

The building's depth, i.e. the distance between the opposing façades, is another deciding factor from the conceptual point of view.

In hot-humid climates, this depth should be limited in order to promote air circulation, and the rooms should be arranged in a row and provided with large openings on the opposite exterior walls.

In hot-arid climates, however, natural ventilation should be avoided during the day, and night ventilation should be favoured for cooling the structure. The most efficient way to optimise these contrasting needs is provided by the traditional courtyard building (Fig. 3.4-3). Closely linked to the shape of the building is the distribution of the interior spaces. Layout and spacing are very important, determining dimensions, proportions and the relationship between inside and outside, and then, thermal flow, ventilation, daylight and view.

FIGURE 3.4-1 **TOP: VARIATION OF SURFACE TO VOLUME RATIO (SHAPE COEFFICIENT) FOR INCREASING VOLUME OF A CUBE. BOTTOM: EVOLUTION OF THE SHAPE COEFFICIENT FOR DIFFERENT COMBINATIONS OF A 125 M³ VOLUME**

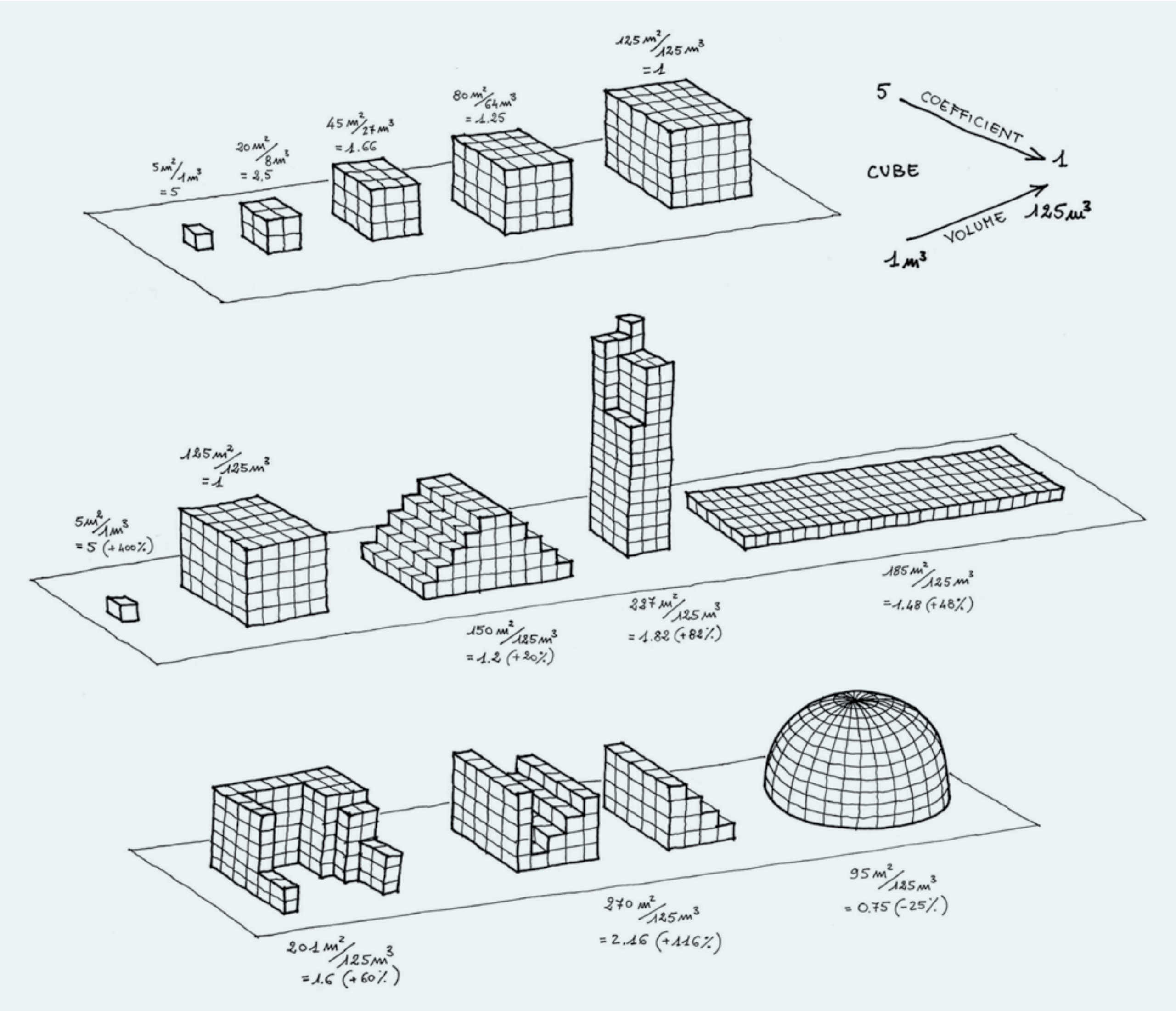
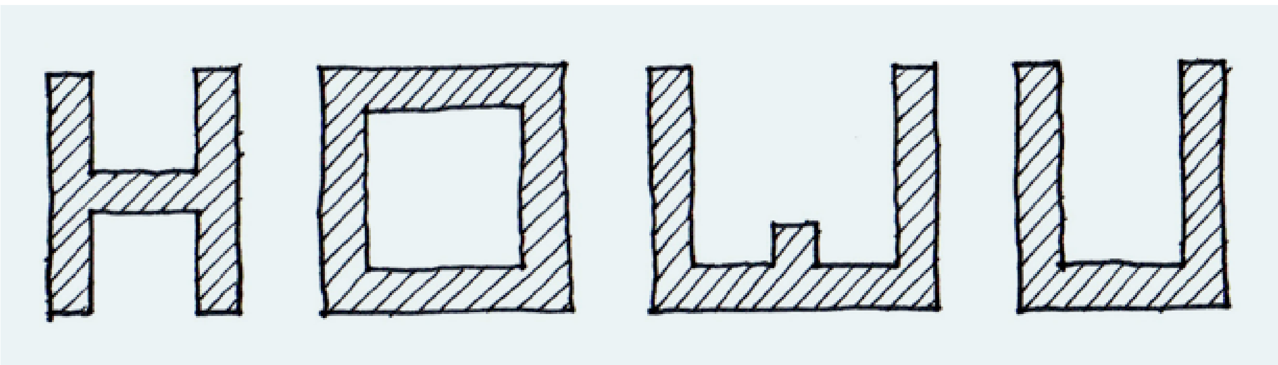


FIGURE 3.4-2 **EXAMPLES OF BUILDING PLANS WITH GOOD ACCESS TO NATURAL LIGHT AND WITH GOOD POTENTIAL FOR NATURAL VENTILATION**

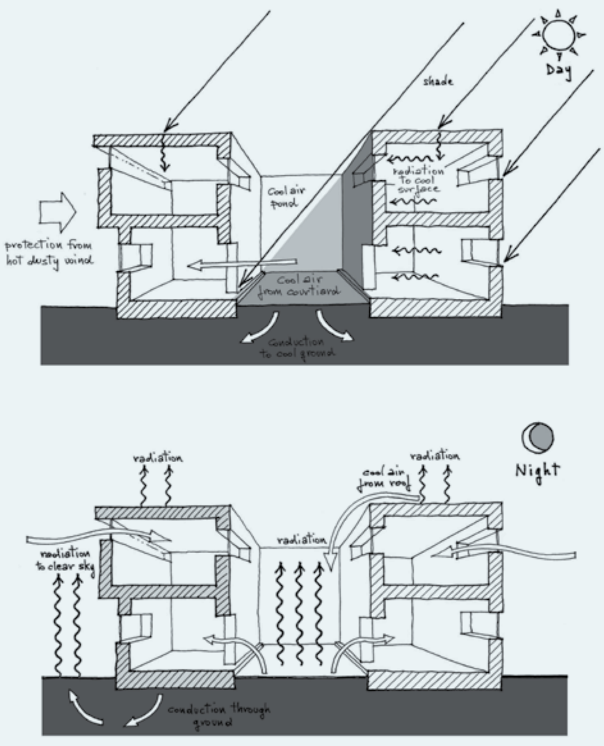


COURTYARD

In most warm climates, much of the day-to-day activity takes place outdoors. Appropriate design of comfortable outdoor spaces is therefore a critical issue in tropical regions. The best example of a well-designed outdoor space is the courtyard, which is especially suitable in hot-arid climates, where it is traditional and common. In a courtyard a pool of cool night air can be retained, as it is heavier than the surrounding warm air. If the courtyard is small (width not greater than height), breezes will leave such pools of cool air undisturbed. The small courtyard is an excellent thermal regulator. High walls cut off the sun, except for around midday, and large areas of the inner surfaces and of the floor are shaded during the day, preventing excessive heating; moreover, the earth beneath the courtyard draws heat. During the night the heat accumulated during the day is dissipated by re-radiation. Heat dissipation through the inside surfaces should be assisted during the night by adequate ventilation. Thus, the design of openings should be guided by two requirements: during the day small openings would be most desirable; during the night the openings should be large enough to provide adequate ventilation so as to dissipate the heat emitted by the walls and the floor of the courtyard.

A solution satisfying both these contradictory requirements is to use large openings, with high thermal resistance shutters, e.g. heavy, made of wood and partially glazed to let the light in. They would be kept shut during the day and open during the night.

FIGURE 3.4-3 **COURTYARD**

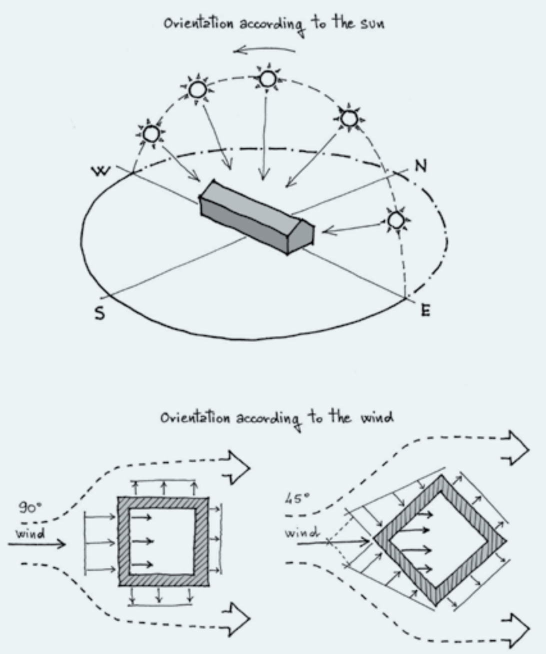


3.4.2 BUILDING ORIENTATION

Building orientation in tropical climates is very critical, and the basic rule is: minimise façades facing east and west (Fig. 3.4-4) and take into account local prevailing winds, because of their connection with natural ventilation.

The best orientation of a building with respect to the sun is common to all climates in EAC countries, because they spread over a small range of latitudes around the equator (from about + 5° N to – 10° S). In this range the solar path is such that a significant amount of solar energy can fall on east and west-facing façades, where solar protection is difficult. Therefore the most suitable building orientation and shape is that which is elongated along the east-west axis, in order to maximise the north and south-facing façades (which are easy to protect with small overhangs) and minimise the east and west-facing ones (which are difficult to protect), thus reducing heat gains to a minimum.

FIGURE 3.4-4 **ORIENTATION ACCORDING TO SUN AND WIND**



A westerly orientation of the largest façades has to be avoided, since in the afternoon both solar radiation and temperature reach their peak. The spaces that are used less frequently (such as bathrooms, storage rooms, etc.) can be an effective thermal barrier if they are located on the east or, better, west side of the building. Rooms needing better daylight conditions should be located towards the façade that requires less solar protection, according to its orientation. Bedrooms, where thermal comfort is the most important requirement, should not have a western orientation in a warm and humid climate, because solar protection is very difficult and the mass-delayed solar radiation effects on the thermal indoor environment take place in the late evening and night, coinciding with the time the bedroom is being used. Lightweight walls give more freedom in the choice of orientation.

In hot-humid climates the building should be open to the exterior, elongated (high surface to volume ratio) and oriented in such a way as to capture the slightest breeze, otherwise the air temperature inside will be higher than outside. Unfortunately, very often the best orientation from the point of view of sun is not the best from the point of view of wind. In these circumstances it is necessary to undertake the rather difficult task of optimisation, taking into account that, if natural ventilation (i.e. wind direction) is favoured, it will be necessary to provide solar protection for the windows exposed to sun, and this solar protection may be an obstacle to air circulation.

In a highlands climate, where some heating is needed, a compromise has to be found in the size of the area of east and west-facing façades, to allow some sun to enter the building in the cooler months.

3.4.3 BUILDING FABRIC THERMAL TRANSMITTANCE AND MASS

In air-conditioned buildings, a certain amount of insulation and thermal mass is always recommended, in order to reduce heat flow and to even out the effect of the changes in external energy inputs (solar radiation, temperature, wind). In the absence of an air conditioning system, or in the periods in which it is not used, the optimum amount of insulation and mass of walls and roofs depends on the type of climate.

3.4.3.1 THERMAL INSULATION

Thermal insulation in tropical climates has to be considered both in the highlands, where temperatures can be such that some heating is required, and in hot-arid lowlands, where it is necessary to reduce the heat flow entering a wall or a roof because of the intensity of solar radiation incident on it. In warm humid climates with adequate natural ventilation indoor and outdoor air temperature is the same. Insulation would have the function of reducing the heat flow due to solar overheating of external surfaces. Roofs receive far more solar energy than walls and, unlike them, cannot be shaded; thus roof insulation is most critical.

A surface exposed to the external environment is subjected simultaneously to radiative (short and long-wave) and convective heat exchanges. Particularly if the surface is dark and exposed to the sun, the surface reaches temperatures that can greatly exceed that of the air, thus affecting the heat flux through the wall, which may be very high.

The optimum insulation of a roof depends on a variety of factors; the outside temperature, the resistance and thermal inertia of the material forming the wall or the roof,the air velocity, the intensity of the incident radiation, the coefficient of absorption of solar radiation and on the emissivity in the far infrared.

A minimum requirement is that the temperature difference between air and ceiling does not exceed 1-2 °C; starting from this assumption it is possible to calculate (see Appendix 1 – Principles of building physics) the amount of insulation required. A U value of 0.8 W/m^2K for the combination roof-ceiling is a reasonable first guess.

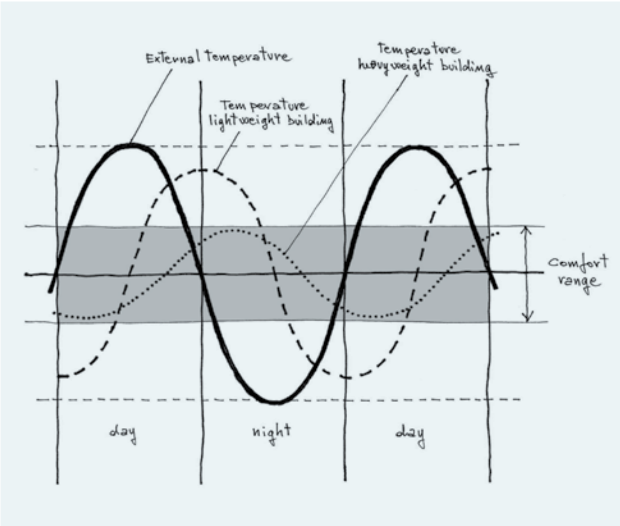
In less extreme climates and in the highlands insulated roofs are also advisable.

3.4.3.2 THERMAL MASS

In hot-arid tropical climates, where the daily temperature swing is high, thermal mass plays a crucial role, absorbing the heat during the day and returning it at night, thus maintaining the environmental conditions in the comfort range (Fig. 3.4-5); resistive insulation alone would not be effective. Thermal mass also proves to be useful, if combined with some insulation, in a tropical highlands climate, mainly because it allows storage of heat gained due to solar radiation during the day, avoiding overheating, and then releases it at night.

Thermal mass, however, is of little or no use in a humid lowland tropical climate, where the daily temperature swing is very low, because the heat stored during the day from incident solar radiation would be released at night, worsening the comfort conditions.

FIGURE 3.4-5 **EFFECT OF THERMAL MASS ON THE BEHAVIOUR OF A BUILDING WITHOUT AIR CONDITIONING. THE HIGHER THE MASS, THE SMALLER THE FLUCTUATION AND THE LONGER THE TIME WITHIN THE COMFORT RANGE.**



3.4.4 ROOF AND WALL DESIGN

Decisions about roof shape, colour and composition, and the colour and composition of walls are crucial because they determine the overall performance of a building. Design choices about the roofs in single storey buildings are especially critical, while the decisions about the walls are equally critical in both low and high rise buildings.

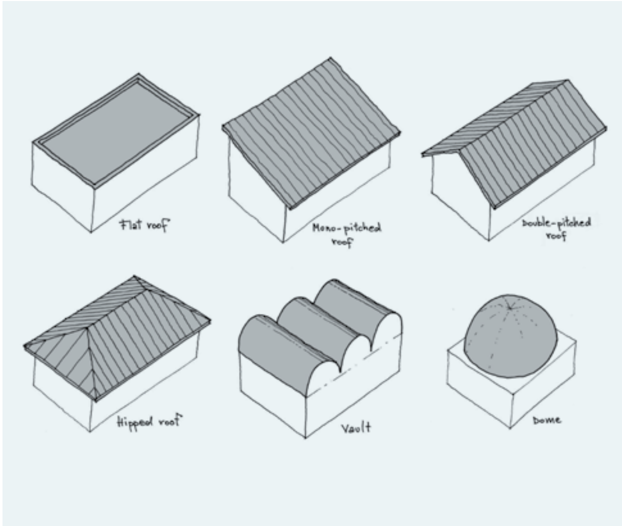
3.4.4.1 **ROOF**

The roof is the part of a building which receives the most solar radiation. The outer surface absorbs radiation and heats up; the roof then transmits this heat to its inner surface, which increases in temperature, radiating inwards, heating up the indoor air, and finally being absorbed by the occupants and objects inside. The thermal performance of the roof is critical for thermal comfort

Thermal performance depends to a great extent on the shape of the roof, its construction and the materials used. The first prerequisite is a highly reflective surface, to minimise the amount of solar energy absorbed. Polished metal sheets and light-coloured finishes are the most common technological solutions. More technologically advanced, so-called "cool roofs" are also available on the market[18].

The shape of the roof should be designed in accordance with precipitation, solar impact and utilisation pattern (pitched, flat, vaulted, etc., figure 3.4-6).

FIGURE. 3.4-6 **BASIC ROOF TYPES**



To keep roofs cool, they should be sloped towards the prevailing breeze and any obstructions that would prevent the airflow along the roof surfaces should be avoided.

Domed and vaulted roof

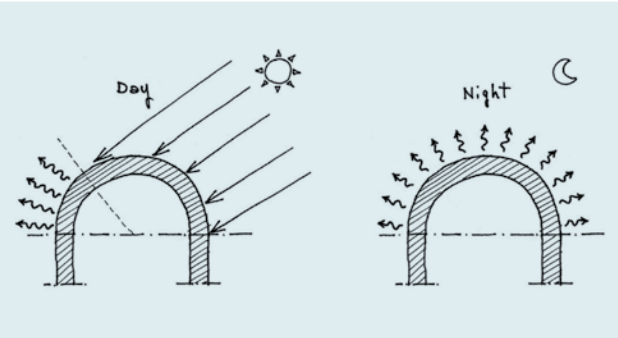
Domed roofs have been traditional in hot-arid regions for thousands of years. These roofs have small openings at the top, are made of locally available materials such as stone or brick masonry and have a plaster finish. The opening at the top provides ventilation and an escape path for hot air collected at the top. They have several advantages:

- in vaulted roofs in the form of a half-cylinder and in those domed in the form of a hemisphere, at least part of the roof is always shaded, except at noon when the sun is directly overhead;
- due to thermal stratification, all the hot air within buildings with curved roofs gathers in the space under the roof, hence creating a more comfortable feeling at floor level;
- domed and vaulted roofs also increase the speed of the air flowing over their curved surfaces due to the Bernoulli effect, making cooling winds more effective at reducing the temperature of such roofs.

18 *The term "cool roof" is typically used to describe surfaces with high solar reflectance and high far infrared emissivity. Ordinary finishes reflect the short-wave infrared of the solar spectrum much like the visible; "cool" coatings also reflect the solar infrared as well as the visible radiation.*

Even though curved roofs absorb almost the same amount of beam radiation as flat ones, they absorb more diffuse radiation. The increased input in solar radiation is offset by the greater convective heat exchange with the outside air, due to the larger surface area and to the higher convection losses; moreover, the larger surface favours heat losses during the night because of the re-irradiation in the far infrared, with the resulting cooling effect, which is especially effective in the clear nights of hot-arid climates (Fig. 3.4-7). For this reason curved roofs are suitable for areas with intense total radiation and low sky diffuse radiation e.g. hot-arid regions. To be fully effective, however, they must be appropriately designed with an opening at the top for natural ventilation at night.

FIGURE 3.4-7 **ROUNDED ROOFS GENERATE THEIR OWN SHADE THROUGHOUT THE DAY (LEFT) AND RE-EMIT THE HEAT OVERNIGHT (RIGHT)**



In some hot-arid regions the vault, the dome and the flat roof are the traditional roof shapes. The common construction method of today, a 10 to 15 cm thick exposed concrete roof, is the worst possible solution, because the inner surface temperature can go up to 60 °C and the heat remains until late in the evening. This means that the roof radiates heat towards the inhabited space, creating a very uncomfortable environment. The choice of material used and its thickness are therefore as important as the shape.

Single leaf roof

Most common in hot-humid climates, the single leaf roof should be made of lightweight materials with low thermal capacity and high reflectivity. Metallic and light-coloured surfaces have the best reflectivity. Painting the surface in light colours, e.g. a coat of whitewash applied yearly, is an economical method of increasing reflectivity. It must not be forgotten that soiling or ageing worsen the reflective properties. Regardless of the type of material used, aluminium, cement or galvanized sheet metal, the temperature difference between the underside of the sheet and the indoor air will be, in the hot hours of a clear day, about 35 °C[19]. To give an idea of the impact on thermal comfort, it can be estimated that – for a person lying down – an increase of 1 °C of the underside of the sheet has the same effect as an increase of 0.3-0.5 °C in air temperature. Thus, the lower layer of the single leaf roof should be heat insulating[19]. For these reasons, a single leaf construction without insulation will not satisfy comfort requirements.

The most suitable material for the upper roof layer is aluminium sheeting. However, this material has some drawbacks, such as the glare from dazzling sunlight and the noise from rain, wind or other materials striking it (twigs, fruit, etc.). Even the sound of animals (birds, small animals) walking across the upper roof surface can cause a noticeable disturbance.

Another problem that may arise if a roof made of light material is not insulated below is the condensation that may occur because of its cooling down during the night through re-radiation.

The roof is also important for providing shade to the walls. How much the roof should overhang depends on the local solar path and the design of the façade. Warm air rising up a façade should be able to escape through suitable vents.

Double leaf roof

The most effective roof type for all EAC climate zones is a ventilated double skin. The outer skin shades the inner layer and absorbs solar heat according to its reflectivity, which should be as high as possible.

Ventilation of the space between the roof and the ceiling is essential for comfort, as shown in Table 3.4-1, where the temperature difference between indoor air and the underside of the ceiling is given for various combinations, in the absence of ventilation.

TABLE 3.4-1 **ORDER OF MAGNITUDE OF TEMPERATURE DIFFERENCES BETWEEN CEILING UNDERSIDE AND INDOOR AIR FOR DIFFERENT COMBINATIONS OF LIGHT-WEIGHT ROOFS, AT THE TIME OF MAXIMUM SOLAR IRRADIATION ON A CLEAR DAY**

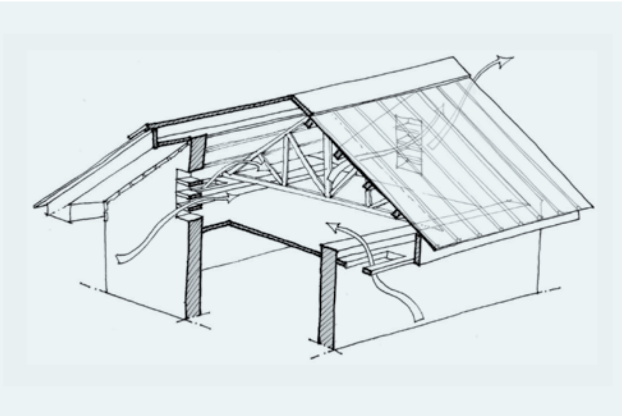
Roof	Ceiling	Temperature difference (°C)
Galvanised sheet, new	Asbestos-cement	3.5
	Insulation, 12 mm	2.5
Galvanised sheet, oxidised	Asbestos-cement	14
	Insulation, 12 mm	8
Aluminium, after some months ageing	Asbestos-cement	4
	Insulation, 12 mm	3

Source: *J. Dreyfus, Le comfort dans l'habitat en pays tropical, Eyrolles, 1960*

19 *J. Dreyfus, Le comfort dans l'habitat en pays tropical, Eyrolles, 1960*

In ventilated roofs like the ones shown in figures 3.4-8 and 3.4-9, the heat between the two skins is removed by the airflow crossing the roof space through openings facing the prevailing winds. The outlet opening should be larger than the opening for the inlet; they should also be placed at different heights in order to obtain air movement by the stack effect when the wind is not blowing. The heat load is reduced by ventilation in the daytime and rapid cooling is allowed at night.

FIGURE 3.4-8 **ATTIC VENTILATION**



In ventilated roofs of the kind shown in figure 3.4-9, roof slopes should be oriented towards the prevailing breeze.

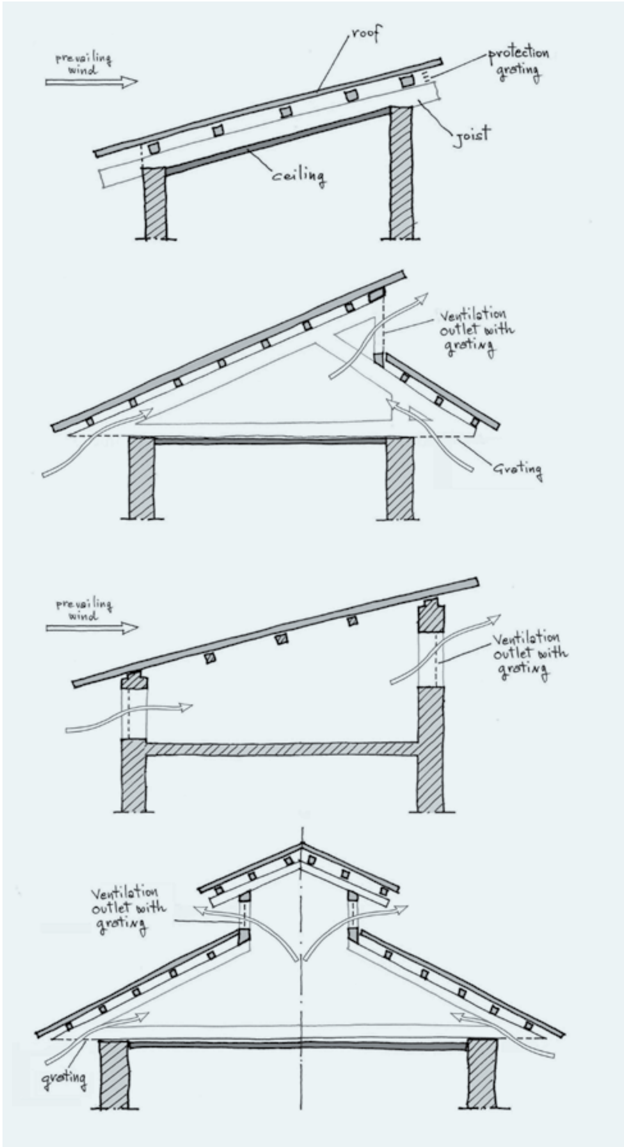
In both types of ventilated roof any obstruction which would interrupt the airflow next to the surface of the roof should be avoided.

In figure 3.4-10 some solutions for roof ventilation are shown.

A reflective surface in the cavity (e.g. aluminium foil) is highly recommended since it reduces the radiant heat transfer by reflecting the long-wave radiation emitted by the hot upper layer. This foil (called a radiant barrier) should be applied to the inner surface of the roof (Fig. 3.4-11). In this way, radiant heat is prevented and convective heat is removed by ventilation.

A simple and effective solution in hot-humid climates is a flat roof shaded by an aluminium screen (Fig. 3.4-12). The performance of the screen can be improved if the lower surface is covered with a low emission layer, or the upper surface of the flat roof is covered with a reflective layer.

FIGURE 3.4-9 **VENTILATION OF THE SPACE BETWEEN ROOF AND CEILING**



A sloping roof with wall shading overhangs and a well-ventilated space between roof and ceiling is also an appropriate solution, provided that the ceiling below the roof is massive (e.g. concrete a minimum of 10-15 cm thick, covered with 5 cm insulation, figure 3.4-13).

If, instead of aluminium, galvanised corrugated sheets are used, insulation thickness has to be increased by at least 3 cm. In both cases a reflective surface on the insulation layer or in the lower surface of the roof would improve the performance.

FIGURE 3.4-10 **VENTILATION OF THE GAP BETWEEN THE TWO ROOF LEAFS**

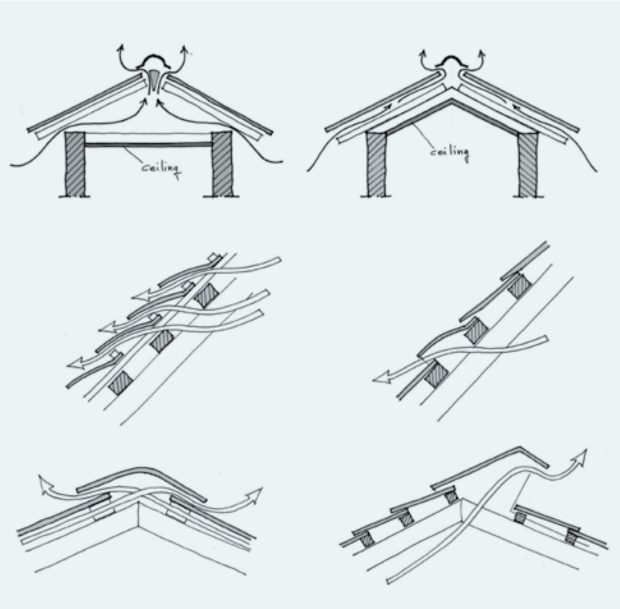


FIGURE 3.4-11 **ALUMINIUM LAYER BETWEEN THE ROOF AND THE CEILING**

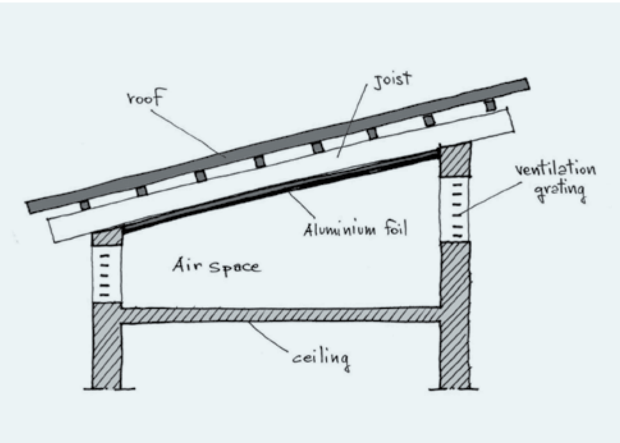


FIGURE 3.4-12 **ALUMINIUM SUN SCREEN ABOVE A FLAT ROOF**

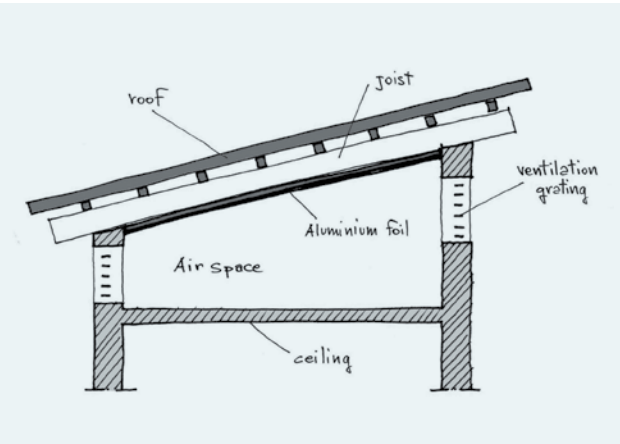
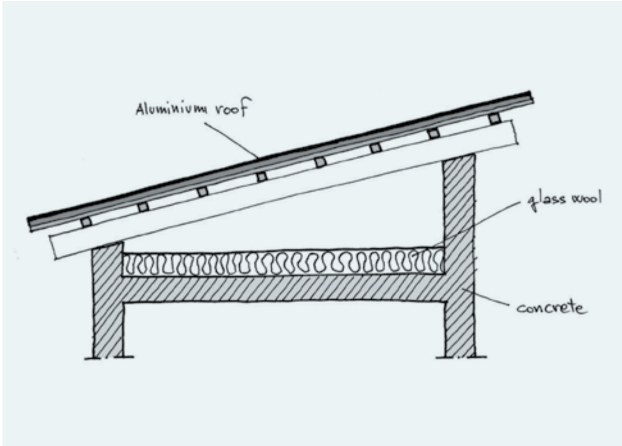


FIGURE 3.4-13 **ALUMINIUM ROOF; CONCRETE CEILING AND INSULATION**



Flat roof

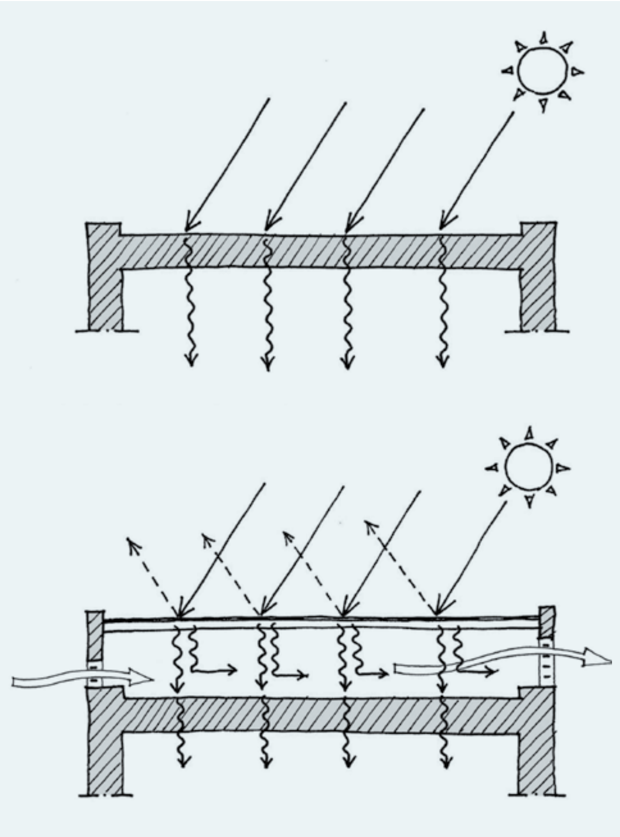
The flat roof is practical in areas where it seldom rains. It is also a good reflector and re-radiates heat efficiently, especially if it consists of a solid, white painted material. High solid parapet walls along the edge of the roof can provide daytime shade and privacy, but can also have the disadvantage of creating an undesired stagnant pool of hot air. The construction and exact placement of parapet walls should therefore be carefully examined.

The performance of a flat roof can be improved by separating roof and ceiling with a ventilated cavity (Fig. 3.4-14). If this technique is used, the material of the roof should be light and the ceiling material should be massive. Aluminium foil between the cavities is recommended for improving the roof's performance, as in pitched roofs.

GENERAL RULES FOR ROOF DESIGN BY CLIMATIC AREA

The roof in a tropical climate should be, as far as possible, reflective, insulated and ventilated. In hot-arid climatic zones the roof should also be massive; in hot-humid zones, however, it should be lightweight. Both insulation and thermal mass can be moved to the ceiling, with similar results. In the highlands roof ventilation may not be necessary, but insulation is necessary and some thermal mass is helpful.

FIGURE 3.4-14 **TOP: FLAT ROOF; BOTTOM: VENTILATED DOUBLE ROOF WITH HEAVY CEILING**



3.4.4.2 **WALLS**

Walls constitute the major part of the building envelope. A wall which is not protected from the sun heats up and transmits heat to the inside. The thickness and material of a wall can be varied to control heat gain. The resistance to heat flow through the exposed walls may be increased in the following ways:

- increase the thickness of the wall;
- adopt cavity wall construction;
- use walls made of suitable heat insulating material;
- fix heat insulating material on the inside or outside of the exposed wall;
- use radiant barriers;
- apply light coloured whitewash on the exposed side of the wall.

Appropriate wall thickness varies with the material used. Regardless of the material used, it can be expected that while thick walls will produce both minimum and maximum temperatures at different times of day than thin walls, due to the additional time it takes heat to be conducted, their capacity for assimilating and radiating heat will also be much greater.

North and south-facing walls receive moderate radiation because of the steep angle of incidence. At certain times of day, when the sun is low, east and west-facing walls receive a much greater heat load, against which it is very difficult to achieve effective solar protection by using roof overhangs or horizontal lamellae.

Wall Insulation

The use of multi-layered construction has to be seriously considered for east and – especially – west-facing walls; in many cases the decision depends on economic factors. Where the resources are available, it should be used; however, a careful assessment of its thermal performance is needed.

Placing a lightweight insulating material on the outside of a massive wall will give a time lag and decrement factor greater than that of the massive wall alone; on the other hand it prevents heat dissipation to the outside at night, thus making internal ventilation imperative.

Placing insulation on the inside will result in an indoor climate performance similar to that in a lightweight structure with a highly reflective outer skin, because the balancing effect of the thermal mass of the outer wall is cut off. As with external insulation, heat dissipation at night is prevented.

Thermal mass of walls

What really counts is not the mass of the wall but the combination of mass and thermal resistance and the ability of this combination to attenuate and delay the external heat wave. Except in hot-arid climates, where thicker walls are recommended, to go above a thickness of about 30 cm of a heavy material (concrete, clay) is of little use for attenuating daily temperature variations.

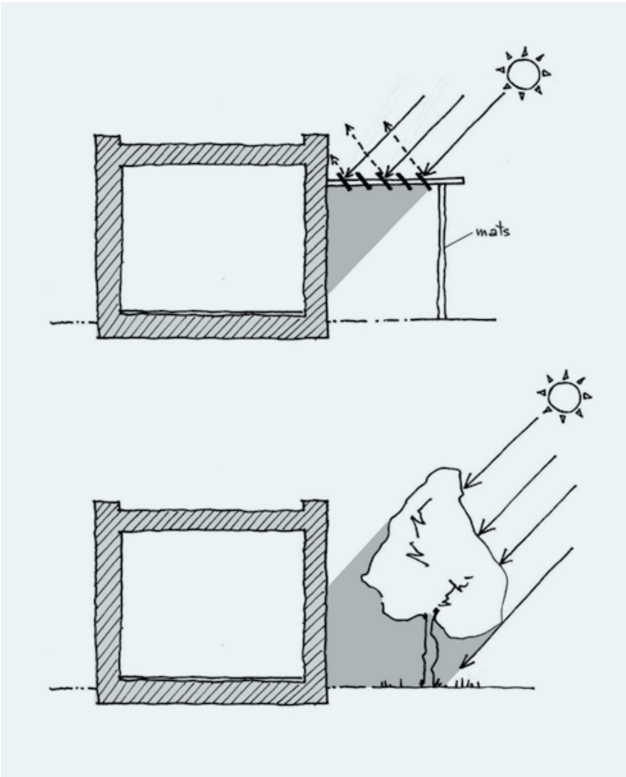
Brick, cement and earth walls provide thermal mass, which adds to energy efficiency by slowing heat transfer through the wall. They can also be efficiently used in hot humid areas if a thickness of only 10 cm is used without plastering.

However, the optimum thickness for a given material, type of insulation and climate should possibly be derived from a parametric analysis carried out by means of computer simulations.

Solar protection of walls

East and west-facing walls especially should be shaded, by pergolas or other means, as shown in figure 3.4-15.

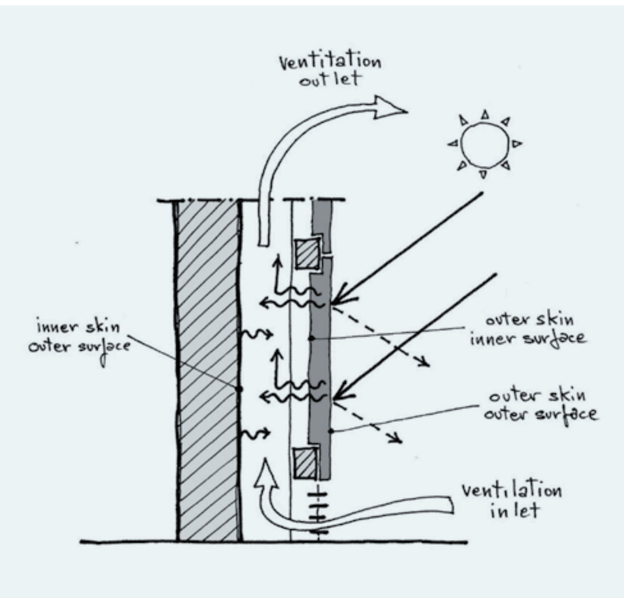
FIGURE 3.4-15 **WALLS SOLAR PROTECTION**



Ventilated wall

A ventilated and reflective outer skin is an efficient, although expensive, solution to the problem of reducing radiant daytime heat (Fig. 3.4-16). Heat dissipation at night is more efficient than with a structure using outside insulation.

FIGURE 3.4-16 **DIAGRAMMATIC SECTION OF DOUBLE-SKIN WALL**



One way of reducing the radiant heat transfer between the two skins is the use of a low emission surface on the inside of the outer skin (radiant barrier). Bright aluminium foil can be used.

GENERAL RULES FOR WALL DESIGN BY CLIMATIC ZONE

In hot-arid climates, walls of daytime living areas should be made of heat-storing materials; walls of rooms for nighttime use should have low heat storage capacity. East and west-facing walls should preferably be shaded. Highly reflective finishes are desirable.

In climates with a less extreme diurnal temperature range and where the night temperature does not fall below the comfort zone, such as in the savannah zones, the internal walls and intermediate floors should have little thermal mass, whilst the outer walls and roof need highly resistive insulation and reflectivity. Double walls with insulation in between are a suitable solution.

In climates with large diurnal temperature ranges and night temperatures below comfort level, such as Great Lakes and upland zones, inner and outer walls should possess a large thermal capacity with an appropriate time lag to balance temperature variations. To achieve this they must be constructed of heavy materials. The use of exterior or interior insulation has to be considered carefully and its suitability depends on the particular requirements and technical possibilities.

These considerations point to double-walled construction, especially for the hot-arid zones. Their effectiveness depends primarily on the surfaces of the materials enclosing the air gap. It is improved considerably if the surfaces are reflective, such as aluminium foil. Part of the radiation between the walls is converted into heat; therefore, the warm air should escape through high vents to permit an inflow of cooler air lower down. The less reflective the material used, the greater the heat penetration in the air space, and the faster the airflow needs to be.

The usually thin, outer leaf of a cavity wall can be of brick-work, concrete or suitable panels fixed to a framework.

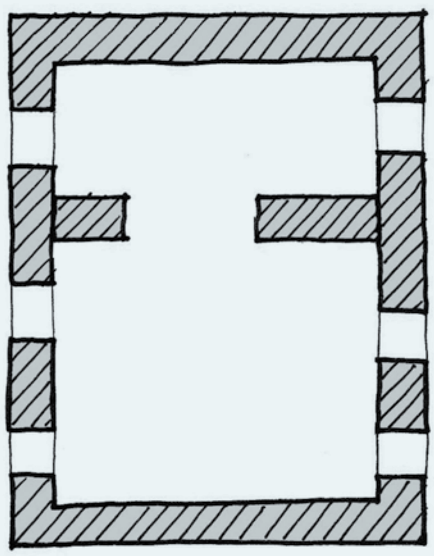
All types of clay, stone and brick are traditionally used for such walls in the hot-arid savannah, Great Lakes and upland zones. Concrete blocks have more recently replaced these materials. Where the storage of coldness is required, solid blocks are more effective than hollow blocks.

It is not only external walls that play a role in thermal comfort inside a building: heat is also absorbed and released by internal partitions. Nor is the effect of the volume of spaces negligible: in small volumes, air temperature during the day, when windows are closed, increases more than when the volume is large.

These two considerations mean that it is preferable to use high ceilings and internal layouts that are not too regular, in order to increase the amount and the total surface of internal partitions as shown in the example in figure 3.4-17. The thickness of internal partitions does not need to be more than 15 cm.

In hot-humid climates, walls - both external and internal - should be as light as possible with minimal heat storage capacity: the diurnal temperature swing is small and for buildings occupied at night thermal mass is a disadvantage since the heat stored in the structure will contribute to discomfort by overheating the space when the occupants are sleeping.

FIGURE 3.4-17 **INCREASING THE SURFACE AREA OF INTERNAL PARTITIONS IN A LARGE ROOM**



Walls should obstruct the airflow as little as possible and should reflect radiation, at least in places where solar radiation strikes the surfaces. The outer surface should be reflective and light coloured.

Walls should be shaded as much as possible. If, however, they are exposed to the sun, they should be built in the form of a ventilated double leaf construction, the inner leaf having a reflective surface on its outer side (or on the inner side of outer leaf). Some thermal insulation could also help. In the absence of a double leaf wall, thermal insulation would be necessary.

Light, thin materials such as timber are recommended. Other materials forming light panels can be used, together with a frame structure to take care of the structural requirements.

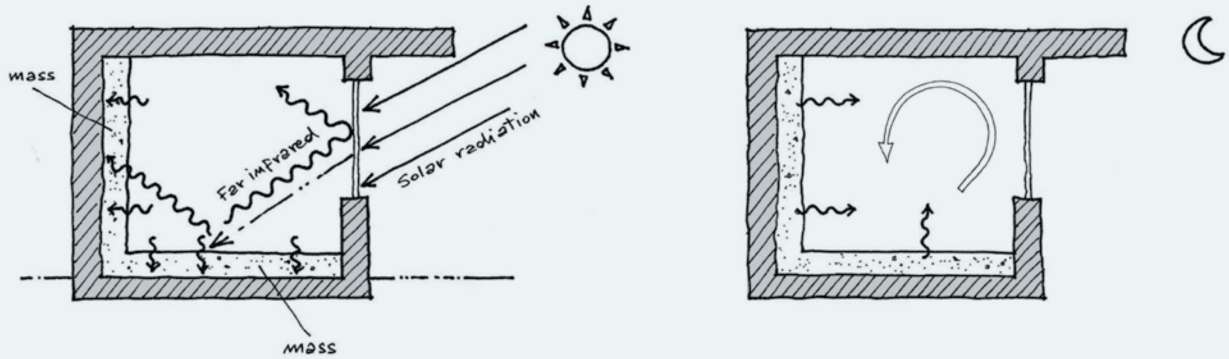
In an upland climate, solar radiation can be used in such a way as to improve comfort and reduce, or even eliminate, any need for a heating system.

There are rules of thumb that can be followed regarding thermal mass, insulation and solar gains.

These rules, however, are dependent on the design of openings, for the following interrelated reasons:

- the amount of solar energy that enters the building (which in turn depends on the orientation, on the size of the window, the type of glass and on its shading);
- the thermal mass of the room, which influences the amount of excess heat accumulated during the hours of sunshine and its return during the other hours (Fig. 3.4-18).

FIGURE 3.4-18 **SOLAR ENERGY DURING THE DAY IS TRAPPED AND STORED IN THE MASS DUE TO THE GREENHOUSE EFFECT; THE ENERGY STORED IN THE MASS IS RELEASED DURING THE NIGHT**



If the window is too large, the building is well insulated and the thermal mass is insufficient, there will be overheating in some hours of the day as a result of the excessive incoming solar energy. In addition, if a window is large, the losses will be large, even though they may be mostly offset by gains during the hours of sunshine; when there is no sun, the window loses more heat than it gains.

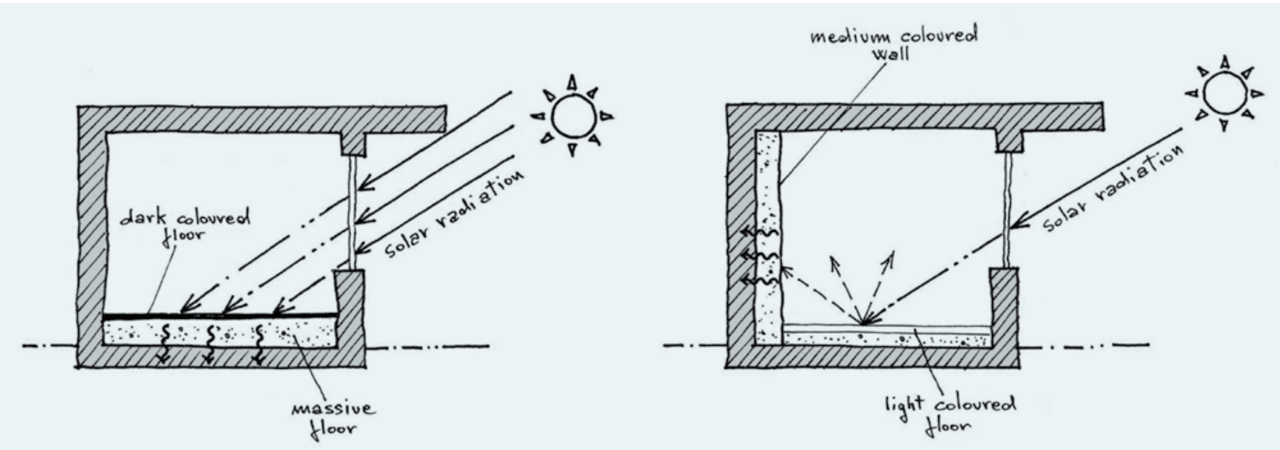
If the window is too small, on the other hand, its contribution of solar gains to the overall energy balance of the building is also small.

Optimization is a process which should be performed with the aid of appropriate calculation tools.

In relation to thermal mass, a few rules of thumb can be followed as a starting point for more accurate evaluations. It is intuitive that the best place to create thermal mass is the floor, on which most of the solar radiation is incident; it is also intuitive that to take full advantage of this, it is advisable to use a dark colour, and to avoid rugs or carpets, which act as a thermal resistance. The mass, however, can also be placed on the walls, if the floor is lightweight, but in this case it is necessary for the latter to be light-coloured (Fig. 3.4-19). For concrete, brick or stone, a thickness of just 10-15 cm is sufficient if they receive direct radiation, 5-10 cm if they receive reflected radiation. Thicker walls do not help.

Another potential way to exploit solar radiation in a highlands tropical climate is the sunspace. The sunspace is very critical in terms of comfort and energy, and its design must be accurate, with careful analysis of energy and comfort, to avoid its proving counterproductive (for example, during the hot season, overheating may occur). A mandatory rule, however, is that sunspaces can be fully opened in warm periods.

FIGURE 3.4-19 **FLOORS SHOULD BE DARK-COLOURED IF MASSIVE; LIGHT-WEIGHT FLOORS SHOULD BE LIGHT COLOURED, TO REFLECT THE SOLAR RADIATION ONTO MASSIVE SURFACES.**



3.4.5 OPENINGS

Roughly 40% of the unwanted heat that builds up in a house comes in through windows: their protection from the sun is thus imperative.

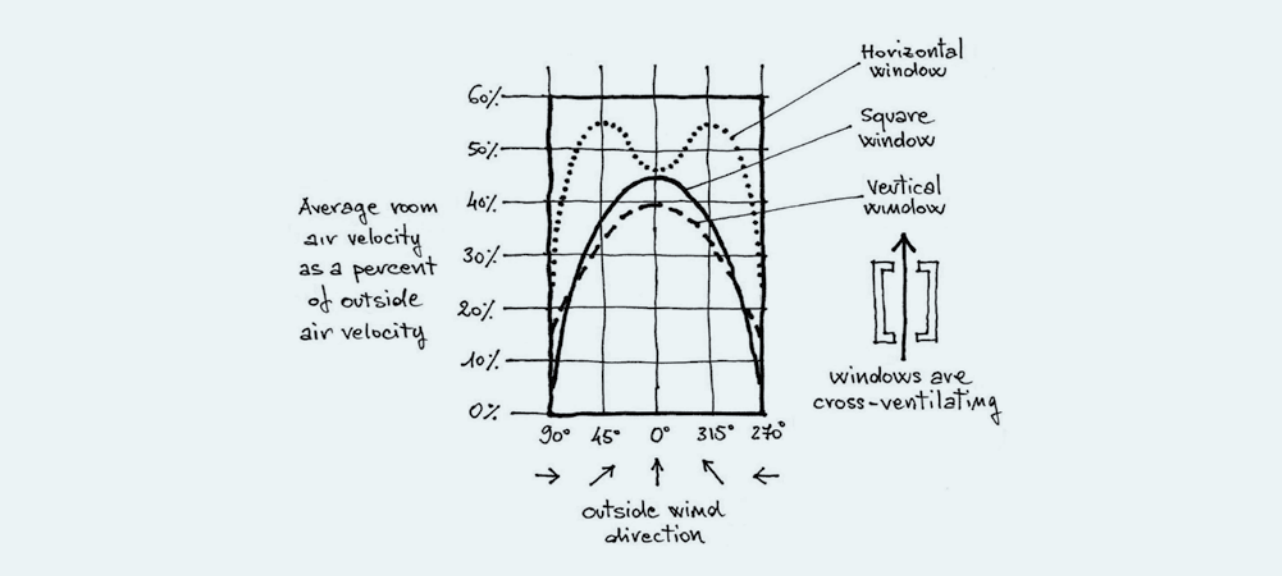
Sunscreens are an effective means of reducing undesirable solar light. Louvres are an effective shading system only if they reflect light towards the ceiling.

Openings should be large, in order to allow natural ventilation. It is best to expand them horizontally (Fig. 3.4-20). Not all types of window favour natural ventilation to the same extent (Fig. 3.4-21). The best ones are those which permit the maximum adjustable effective open area (also called permeability), such as the casement, jalousie and awning types. In hot-arid climates the casement type is the most advisable, as it allows for good airtightness during the day and has the largest effective open area for ventilation at night.

THERMAL MASS OF THE ENVELOPE IN AIR-CONDITIONED NON-RESIDENTIAL BUILDINGS

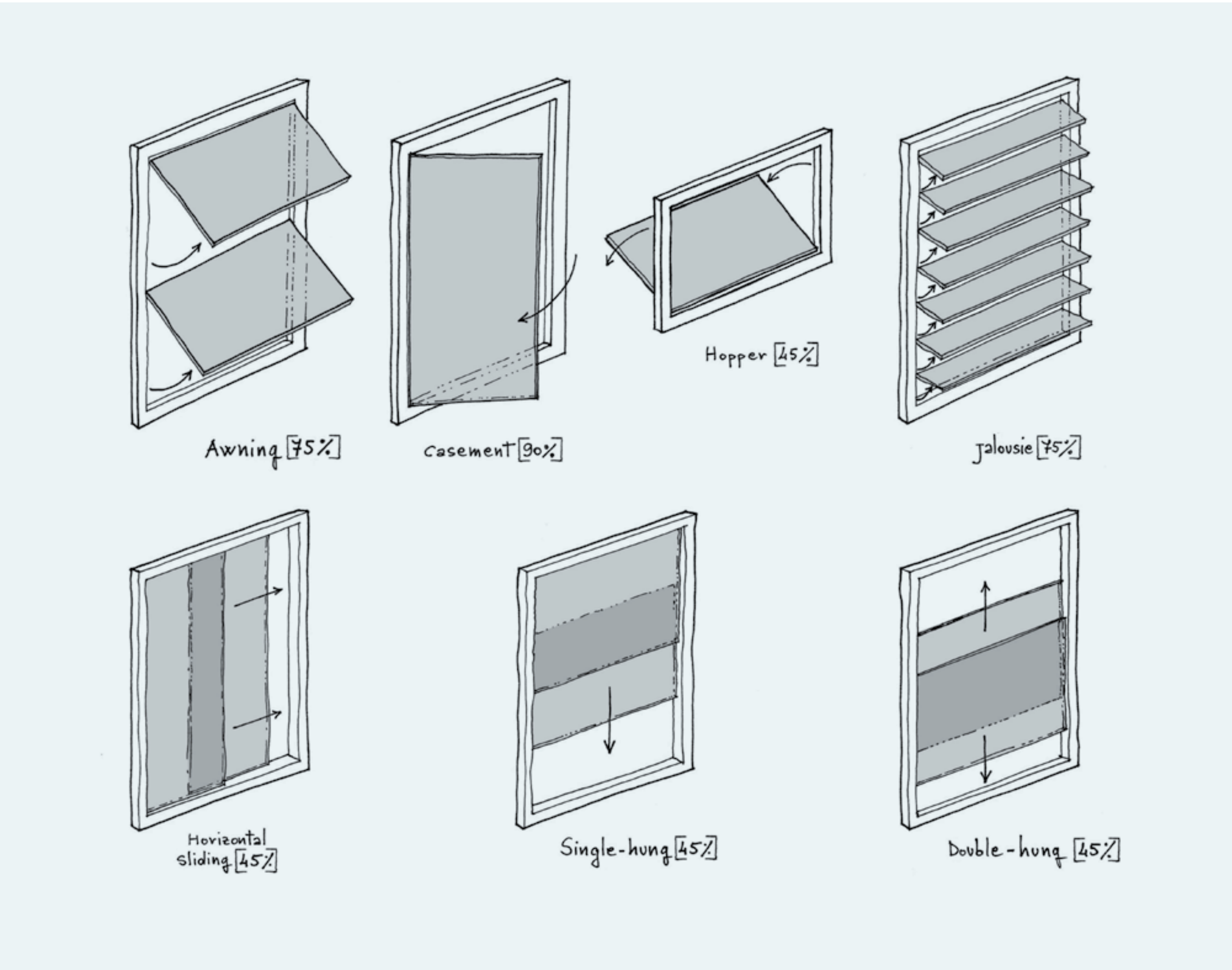
The above rules apply to residential buildings which are not air-conditioned. However, in air-conditioned non-residential buildings, thermal mass plays a different role, especially in hot-arid climates. This derives from the different use of the building, from the fact that, during the time when it is occupied, indoor temperature is kept at a constant value which is lower than outdoor temperature, and from their intermittent use (only during working hours and days). In such buildings it is always better to use a low or medium weight envelope, even in hot-arid climates. In order to determine the optimum weight of the walls and roof, it is necessary to carry out computer simulations.

FIGURE 3.4-20 **IMPACT OF WINDOW SHAPE ON AIR VELOCITY**



Source: *Chandra, Subrato, Philip W. Fairey, and Michael M. Houston. 1986. Cooling with ventilation, Solar Energy Research Institute. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1658-86.pdf*

FIGURE 3.4-21 **DIFFERENT WINDOW TYPES; IN BRACKETS THE EFFECTIVE OPEN AREA (PERMEABILITY) AS PERCENTAGE OF THE OPENING AREA**



In an upland climate, openings should be sized according to the orientation, to optimise the balance between solar heat gains and heat losses.

Whatever the window used, it should be able to accommodate a flyscreen in all the climates in which the incidence of air borne diseases - such as malaria - is high, as in almost all EAC countries. Mosquito nets help keep mosquitoes away from people, and thus greatly reduce the transmission of malaria. Insect screens may be made either of metal or nylon mesh. Metal mesh corrodes easily due to the high salt content of the air, while nylon mesh disintegrates due to exposure to ultra-violet from the sun.

As flyscreens are not a perfect barrier, because some damage may occur and because of weathering, they are often treated with an insecticide designed to kill the mosquito before it has time to search for a way past the net. Insecticide-treated nets are estimated to be twice as effective as untreated nets, and offer greater than 70% protection compared with no net.

3.4.6 THE KITCHEN

The current use of biomass for cooking in developing countries adversely affects health and the environment, because of the use of three-stone open fires and of charcoal, the latter mainly because of the deforestation that it creates.

The well-known disadvantages of the open fire are: smoke; the slow pace of cooking; health risks; and high fuel consumption. All of these can be eliminated or reduced with the use of improved stoves.

On the other hand it should be remembered that some of these inefficiencies are also welcomed due to their positive side effects:

- smoke can chase away mosquitoes in malaria-infested areas;
- open fires burn slowly and do not require frequent attention. This is welcome if other household tasks have to be carried out at the same time;
- open fires emit heat, which is welcome in cold areas.

Thus, additional solutions must be provided to complement the introduction of the improved cooking stoves:

- an extra space heater for the cold season, where appropriate ;
- openings equipped with fly screens.

However, in spite of the availability of new, more efficient, safe and healthy improved stoves, switching away from the use of traditional biomass is not feasible in the short term. One reason is the cost of new equipment; the other is that households do not simply substitute one fuel for another as income increases, but instead add fuels in a process of "fuel stacking". The most energy-consuming activities in the household – cooking and heating – are the last to switch. Use of multiple fuels provides a sense of energy security, since complete dependence on a single fuel or technology leaves households vulnerable to price variations and unreliable service. Some reluctance to discontinue cooking with fuelwood may also be due to taste preferences and the familiarity of cooking with traditional technologies. As incomes increase and fuel options widen, the fuel mix may change, but wood is rarely entirely excluded. Improving the way biomass is used for cooking is, however, an important way of reducing its harmful effects. This can be achieved either through transformation of biomass into less polluting forms or through improved stoves and better ventilation. Adding chimneys to stoves is the most effective improvement that can be made from the point of view of health. Increasing household ventilation is also a very cost-effective measure.

In order to design the kitchen to minimise the negative effects on health and on the environment arising from the use of biomass for cooking, the architect should reject the common approach in which the kitchen is neglected, even in newer houses, and left to the occupants to design, especially when we consider that the kitchen is[20]:

- where most household energy is used in developing countries;
- where cooking and related activities are carried out. It is one of the main workplaces in the home, but the one with the worst indoor environment - air pollution from smoke, high temperatures and humidity, and in general a messy and dirty place;
- a hazardous and often unhealthy place where many children are burned;
- an integral part of most homes, with a significant impact on the overall indoor environment if it is not in a kitchen-house;
- a workplace where most activities are carried out by women and children. Thus the kitchen should be designed with the aim of making it a safe and healthy workplace and, possibly, a place for the family to meet and for the children to do their homework.

The location of activities (i.e. indoors or outdoors) is a basic question for architects. It is the starting point for design and for giving activities a physical form and expression. For the kitchen, the location of the stove and its type is crucial, since it has a great impact on the overall kitchen environment and influences kitchen design. The kitchen should be defined from the user's perspective, the culinary activities, and the use of water and the cooking stove/energy/fuel involved in the process. These factors

20 B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995 define how much space is needed in the kitchen. Their effects on the kitchen environment, indoor climate and indoor air quality as well as function interact and should determine the design of the kitchen and its relationship to indoor and outdoor space.

Whatever the kind of fuel – firewood or charcoal – and the stove used – traditional or improved – the main aim should be to design the kitchen in such a way as to maximise natural ventilation. This kind of approach can be found in some vernacular architecture examples in Europe, before fossil fuels were available and affordable, and for some time after that. These examples could still be used as valuable examples, as shown in figure 3.4-22, where the kitchen ceiling is shaped to act as a hood, inducing vigorous air movement by the stack effect and removing the smoke even if an open fire is used. At the same time the kitchen becomes a gathering place for the family. Another common solution to the problem of smoke was a hood above the cooking stove (Fig. 3.4-23).

FIGURE 3.4-22 **A KITCHEN-IN-CHIMNEY ONCE USED IN TRADITIONAL HOUSES IN THE ITALIAN ALPS**

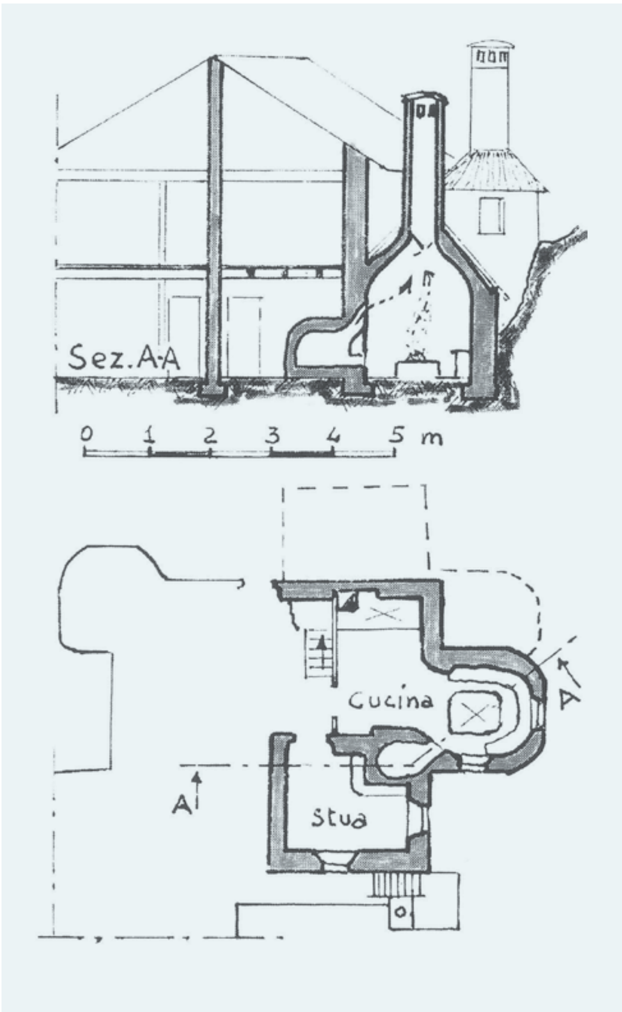


FIGURE 3.4-23 **A WOOD OR CHARCOAL COOKSTOVE AND A HOOD TO EXTRACT SMOKE IN AN OLD TRADITIONAL KITCHEN IN SICILY**

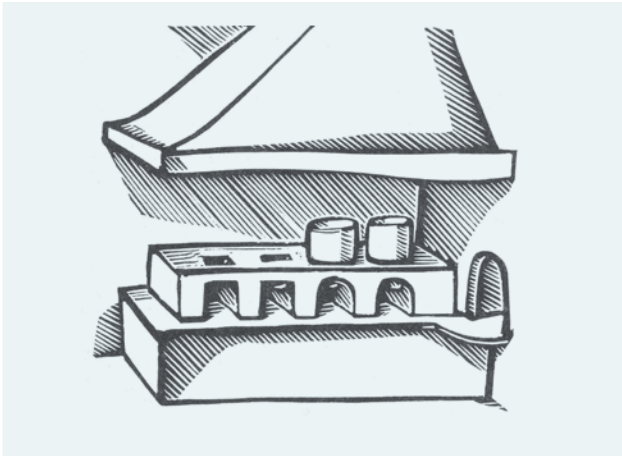
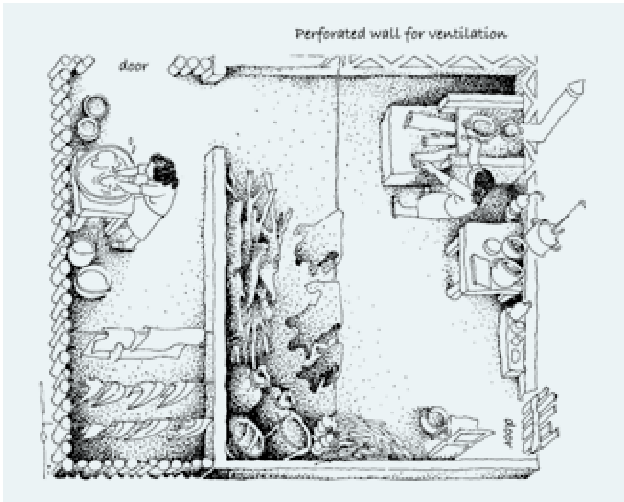


FIGURE 3.4-24 **A KITCHEN IN PARAGUAY.**



Source: *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*

In climates where the cool season is mild, the approach shown in figure 3.4-24, where natural ventilation is enhanced by perforated walls, can be considered.

3.5 NATURAL VENTILATION

The term *natural ventilation* is used to indicate the intentional airflow through windows, doors or other openings designed for the purpose, obtained without the use of fans; it is created by pressure differences caused by the wind and/or by temperature differences between the inside and the outside.

Natural ventilation affects three issues: health, the energy balance of the building and thermal comfort.

It affects health because of the relationship between air changes and air quality. It affects the energy balance of buildings because the flow of external air subtracts heat from or adds it to the internal space: it subtracts heat if the outdoor air temperature is lower than the indoor air temperature and adds it if it is higher (see Appendix 1 – Building physics). Thermal comfort is also indirectly affected as a consequence of the change in indoor air temperature due to ventilation,

It directly affects thermal comfort because air velocity affects the body's energy balance through convective exchange and perspiration: the higher the air velocity the greater the body's heat loss (see Appendix 2 – Thermal and Visual Comfort).

Because of the effects on the energy balance of the building and on thermal comfort, natural ventilation strategies differ according to the local climate. A high air flow rate, and hence air velocity, is beneficial all day in hot-humid climates, whereas in hot-arid climates with a significant daily temperature variation, only night ventilation should be used (a high ventilation rate during the day would warm up the building structure, which would release the heat at night, leading to an uncomfortable indoor environment; night ventilation, on the other hand , because of the low air temperature during the night, cools the building structure down, creating a more comfortable indoor environment the following day, provided that the windows are kept closed). In upland climates, by contrast night ventilation should be kept to the minimum compatible with the needs of air quality, and day ventilation should be modulated according to outdoor temperature.

3.5.1 BASIC PRINCIPLES OF NATURAL VENTILATION

Natural ventilation is driven by some basic principles, which we recall below:

1. Air always moves from a higher pressure zone to a lower pressure one;
2. An air flow is called laminar when the speed is low and the fluid streamlines all move in parallel (Fig. 3.5-1a); When the speed increases or there is a pronounced change of direction, the motion becomes turbulent, and fluid streamlines cease to move in parallel, giving rise to significant changes in direction and to eddies (Fig. 3.5-1b);
3. Air, as all fluids, is subject to the Bernoulli effect, because of which there is a reduction of pressure when speed increases; this effect is exploited in the wing of an aeroplane, whose shape is such that it forces air passing above it to follow a longer path, resulting in greater speed than that of the air flowing beneath it (Fig. 3.5-2); the pressure at the top is then lower than at the bottom and there is a push from the bottom upwards: the lift;
4. Because of the Venturi effect, when an air stream is forced through a smaller section (Fig. 3.5-3) there is an increase in speed and a decrease in the pressure in correspondence to the narrowing;

FIGURE 3.5-1 **LAMINAR AND TURBULENT FLOW**

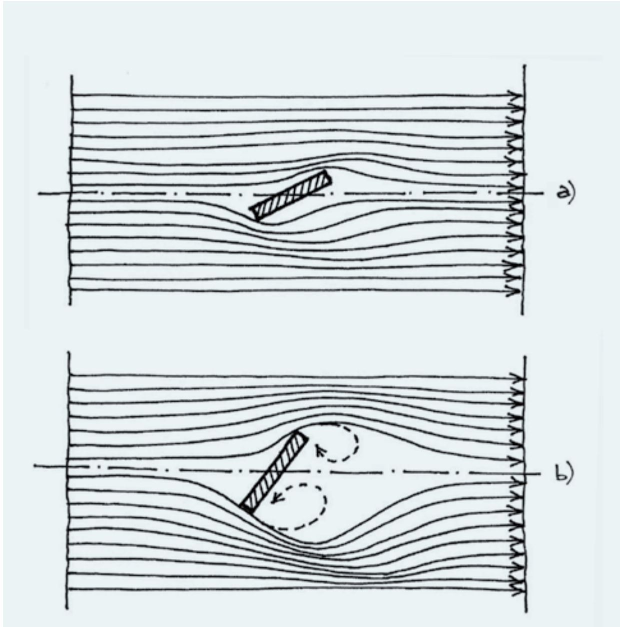


FIGURE 3.5-2 **BERNOULLI EFFECT**

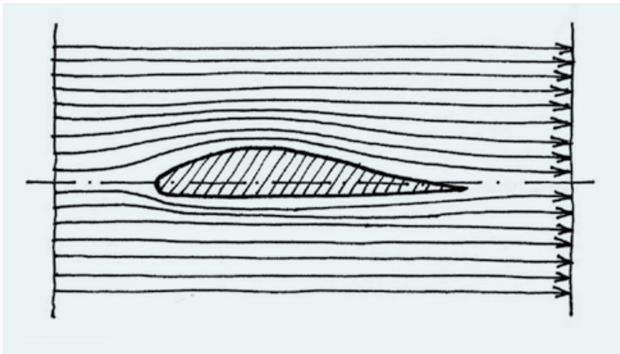
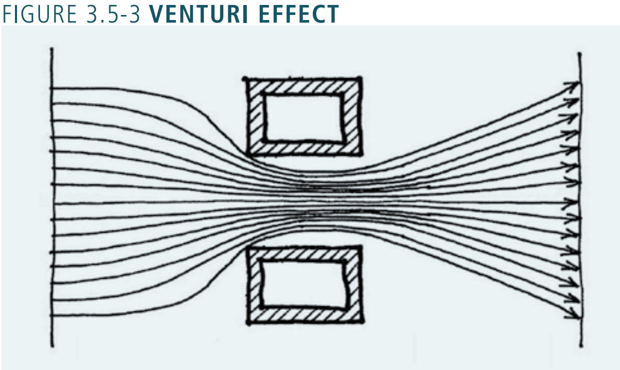
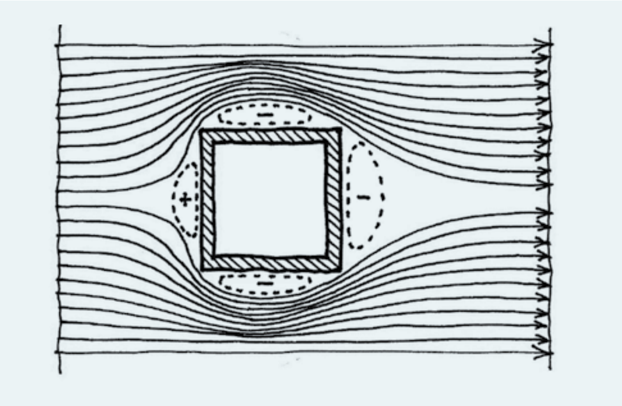


FIGURE 3.5-3 **VENTURI EFFECT**



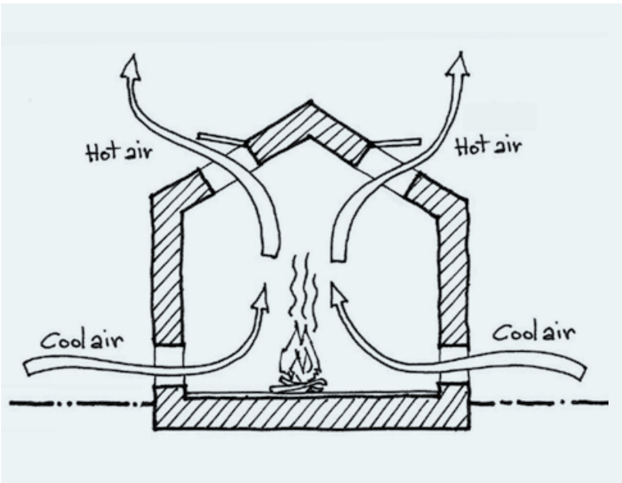
5. As an effect of a combination of the factors described above, when the wind hits a building it causes areas of low pressure to be created along the sides parallel to its direction and on the leeward side (Fig. 3.5-4);

FIGURE 3.5-4 **PRESSURE DISTRIBUTION AROUND A BUILDING**



6. When the air inside a room or building is warmer than the outdoor air, it triggers the stack effect (Fig. 3.5-5): the pressure inside is lower than it is outside due to the lower density of warmer air.

FIGURE 3.5-5 **STACK EFFECT**

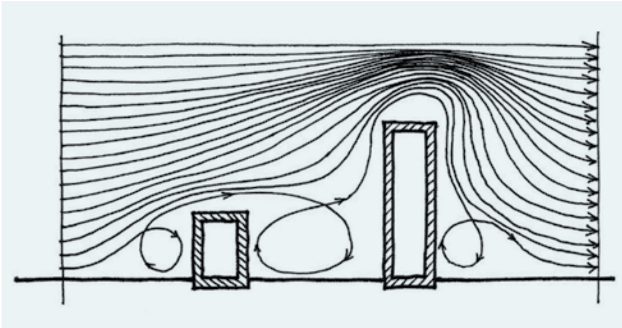


3.5.2 WIND DRIVEN AIR MOTION

Although the physical laws that cause the phenomena are known and well defined, it is not an easy task to predict the flow of air around and through buildings, especially with regard to the path of the fluid streamlines. In the past, knowledge in this field was mainly built up with scale models, smoke tests and wind tunnels. More recently Computerised Fluid Dynamics allows designers to predict with very good accuracy the effects of their choices. A large set of general rules were derived from these studies:

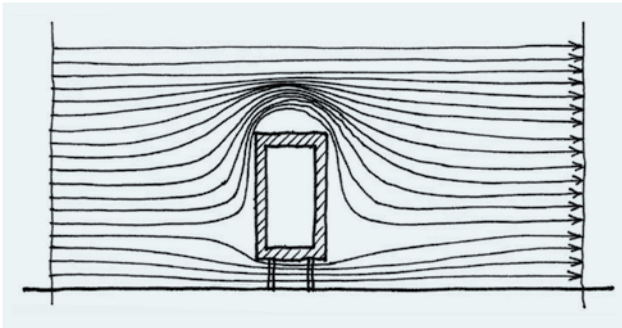
- When a low-rise building is to windward of a higher one, considerable turbulence is created between the two, figure 3.5-6;

FIGURE 3.5-6 **LOW-RISE BUILDING TO WINDWARD OF A HIGH-RISE ONE**



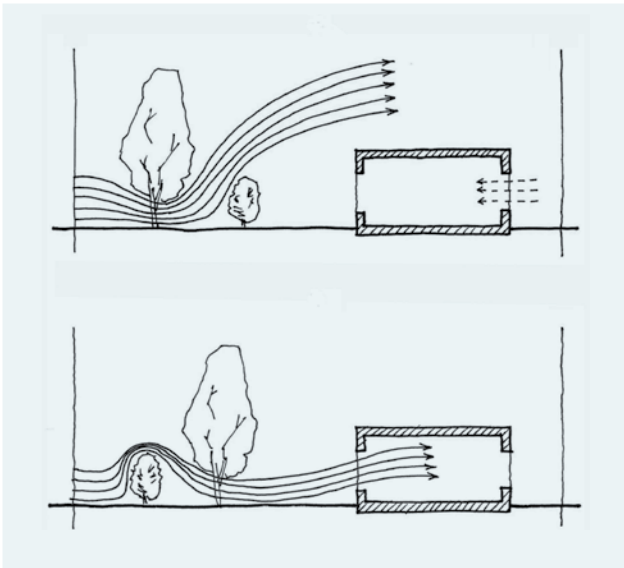
- In a building on stilts leeward pressure is reduced and in correspondence to the stilts wind speed significantly increases, figure 3.5-7;

FIGURE 3.5-7 **BUILDING ON STILTS**



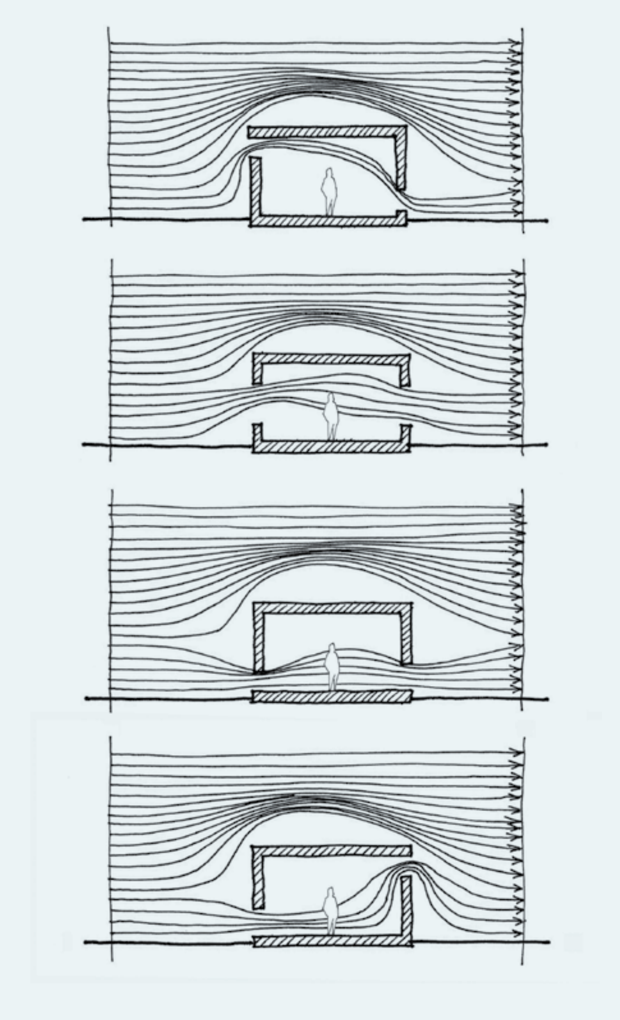
- To maximise the cooling effect of wind, trees with high canopies should be used and bushes should be kept away from the building, figure 3.5-8;

FIGURE 3.5-8 **EFFECT ON WIND OF TREES WITH HIGH CANOPIES AND OF BUSHES**



- The air flow pattern due to the wind depends on the relative position of the openings. The best conditions are created when the outlet opening is higher and wider than the inlet (the ideal is to have them of equal area), figure 3.5-9;

FIGURE 3.5-9 **AIR FLOW PATTERN, ACCORDING TO THE RELATIVE POSITION OF THE OPENINGS**



- A horizontal overhang above the opening deflects flow upwards. If the overhang is spaced away from the wall, the flow is deflected at half height, figure 3.5-10;
- When inlet and outlet openings are aligned, cross ventilation is activated by wind. If the openings are aligned in the direction of the wind, the air flow passes right through the space influencing a reduced part of it and giving rise to modest induced air movements. If the wind blows obliquely, however, the ventilation involves a wider zone and more air movement is induced. If the wind blows parallel to the openings, there is no significant air movement in the space, figure 3.5-11;

FIGURE 3.5-10 **EFFECT OF A HORIZONTAL OVERHANG ABOVE THE OPENING**

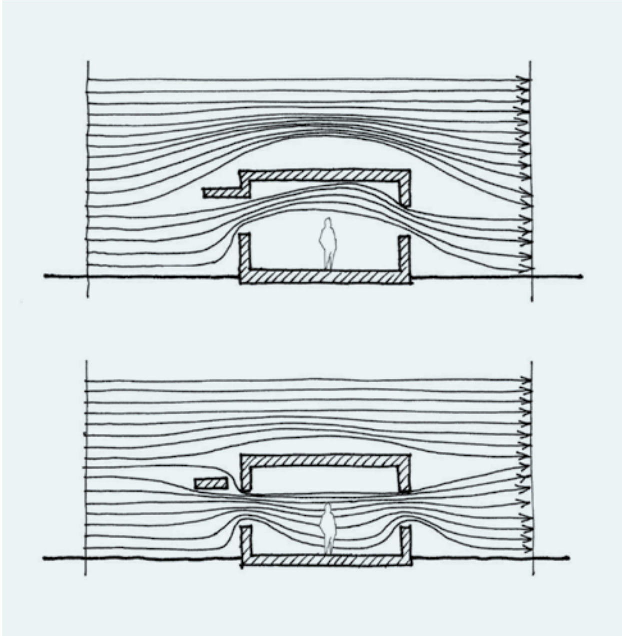
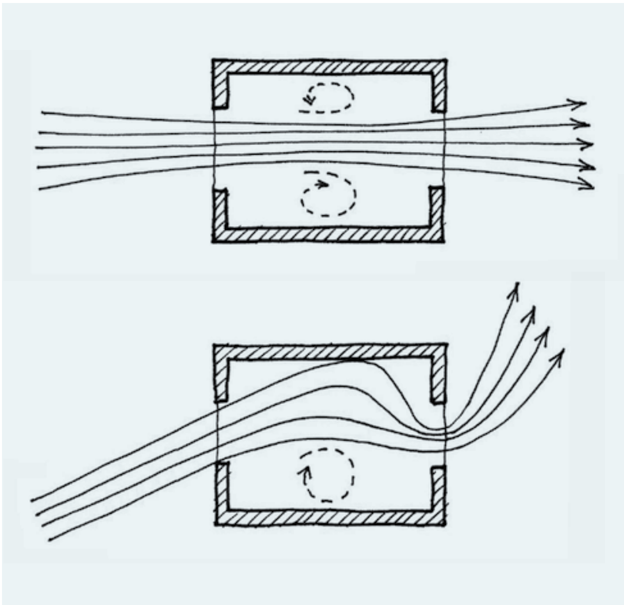


FIGURE 3.5-11 **EFFECT OF ALIGNMENT OF OPENINGS ON CROSS VENTILATION**



- If the room has openings on adjacent walls, wing walls can significantly increase the effectiveness of natural ventilation, figure 3.5-12.

In most cases rooms have only one wall facing outside and a single opening; ventilation is derived only from the turbulence induced by wind fluctuations and the resulting air movement is quite poor (if the window is on the windward side, the available wind velocity is about 10% of the outdoor velocity at points up to a distance one sixth of the room width; beyond this, the velocity decreases rapidly and hardly any air movement is produced in the leeward portion of the room[21]). This situation can be improved by splitting the single opening into two, positioning the parts as far apart as possible; if the wall is to windward, a further improvement is obtained by constructing a vertical fin (wing wall, figure 3.5-13).

FIGURE 3.5-12 **IMPROVING VENTILATION WITH OPENINGS ON ADJACENT WALLS, AND WING WALLS**

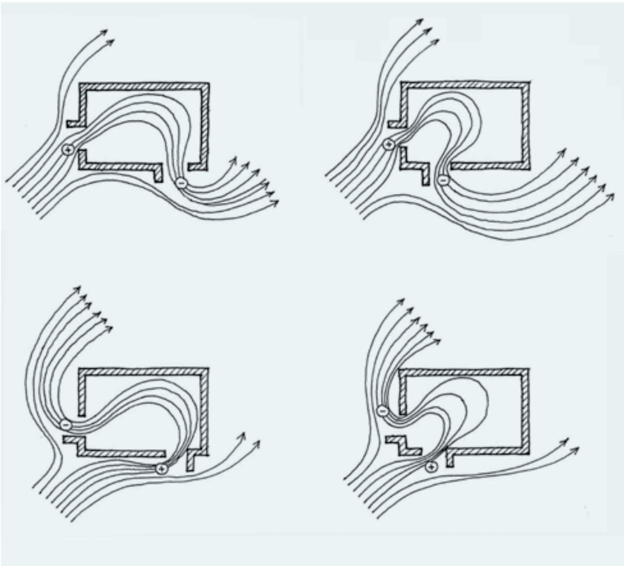
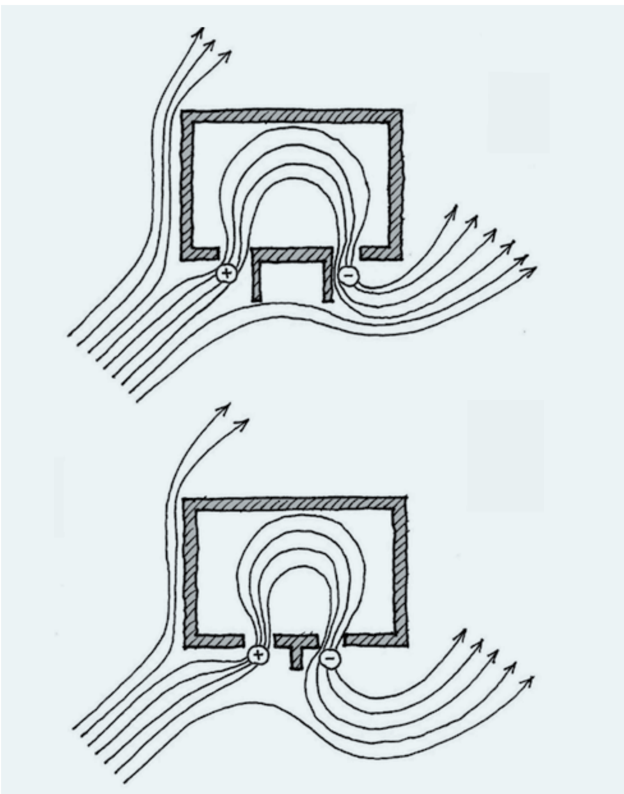


FIGURE. 3.5-13 **VENTILATION, WITH WING WALLS, IN ROOMS WITH ONLY ONE WALL FACING OUTSIDE AND TWO OPENINGS**



21 *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

3.5.2.1 **SIZING OPENINGS FOR CROSS-VENTILATION**

To estimate the size of the openings (opposite) in the case of cross ventilation, the following equation can be used[22]:

$$V = KAv \tag{3.5-1}$$

where:
V = air flow rate [m³/s];
K = coefficient of effectiveness;
A = net free area of inlet openings, equal to outlet [m²];
v = outdoor wind speed [m/s].

The coefficient of effectiveness depends upon the direction of the wind relative to the opening, and on the ratio between the areas of the two openings. It is maximum when the wind blows directly onto the opening and it increases with the relative size of the larger opening.

For opposite openings of equal area, K = 0.6 for wind perpendicular to opening (or 0°) and K = 0.3 for wind at 45°.

Changes in wind direction up to 30° on either side of the normal to the window wall have little effect on the values of K. For wind directions outside these limits, the value of K may be considered to change linearly with wind direction.

According to the type of window (jalousie, sash, casement, etc. - see figure 3.4-21), the net free area of an opening is different and it is obtained by multiplying the gross opening area by the window permeability.

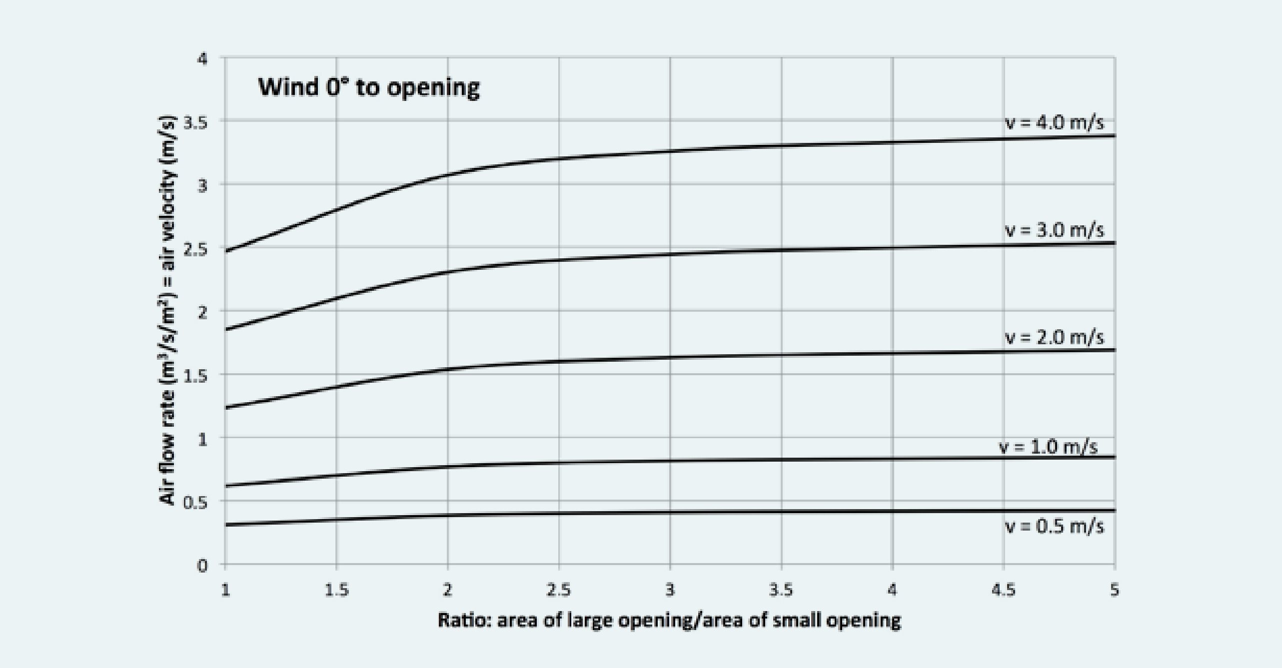
The air flow rate can also be obtained using the graphs of figure 3.5-14 (wind 0° to opening) and figure 3.5-15 (wind at 45° to opening), providing the air flow rate per square meter through the smaller opening (coincident with the air velocity in m/s) with different wind speed.

3.5.2.2 **INDOOR AIR VELOCITY**

When we know the air flow rate, combined with the outdoor and indoor temperature, it is possible to calculate the amount of heat added to, or subtracted from, the internal space, i.e. the thermal load deriving from ventilation: this is information related to the energy balance of the building (see Appendix 1 – Building physics). But ventilation also has a beneficial effect on thermal comfort, this effect being linked to the air velocity in the place where the subject is situated (see Appendix 2 – Thermal and Visual Comfort). As seen previously, local values of air velocity depend on many factors (wind velocity and direction, size and position of openings, etc.) and they can only be accurately predicted with CFD simulations or experimental evaluation.

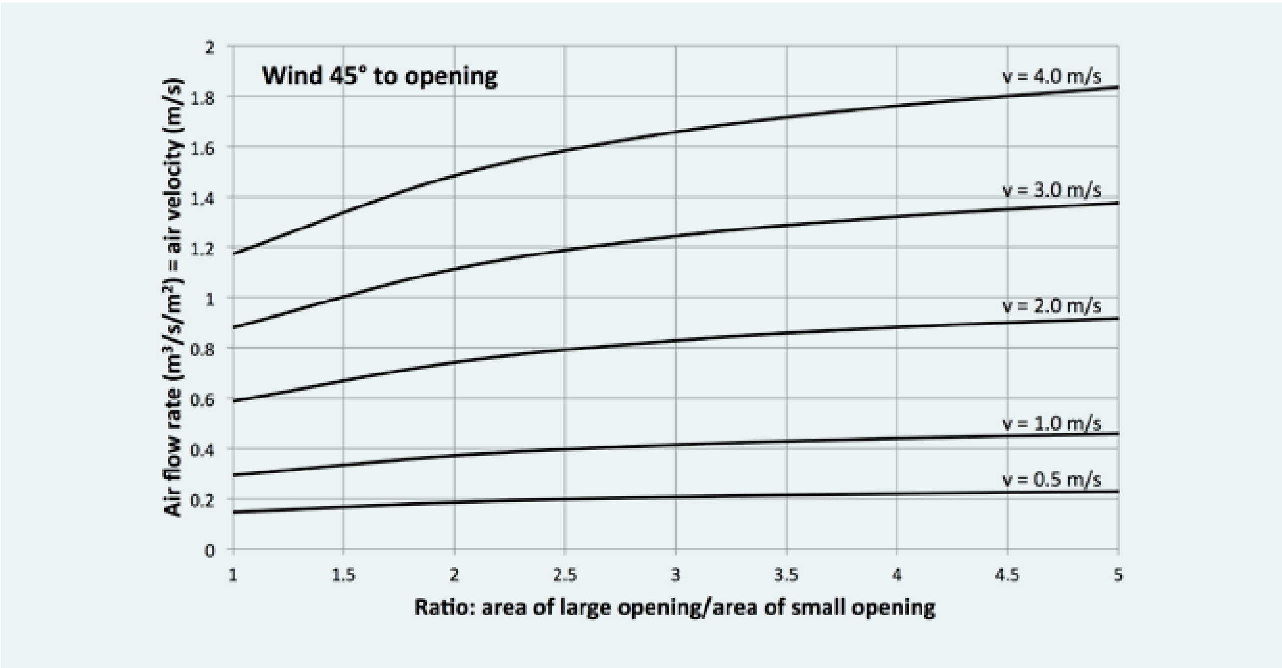
22 *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

FIGURE 3.5-14 **AIR FLOW RATE PER SQUARE METER THROUGH THE SMALLER OPENING (OR AIR VELOCITY IN M/S) WITH DIFFERENT WIND SPEED – WIND INCIDENT AT 0°**



***Adapted from:** N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

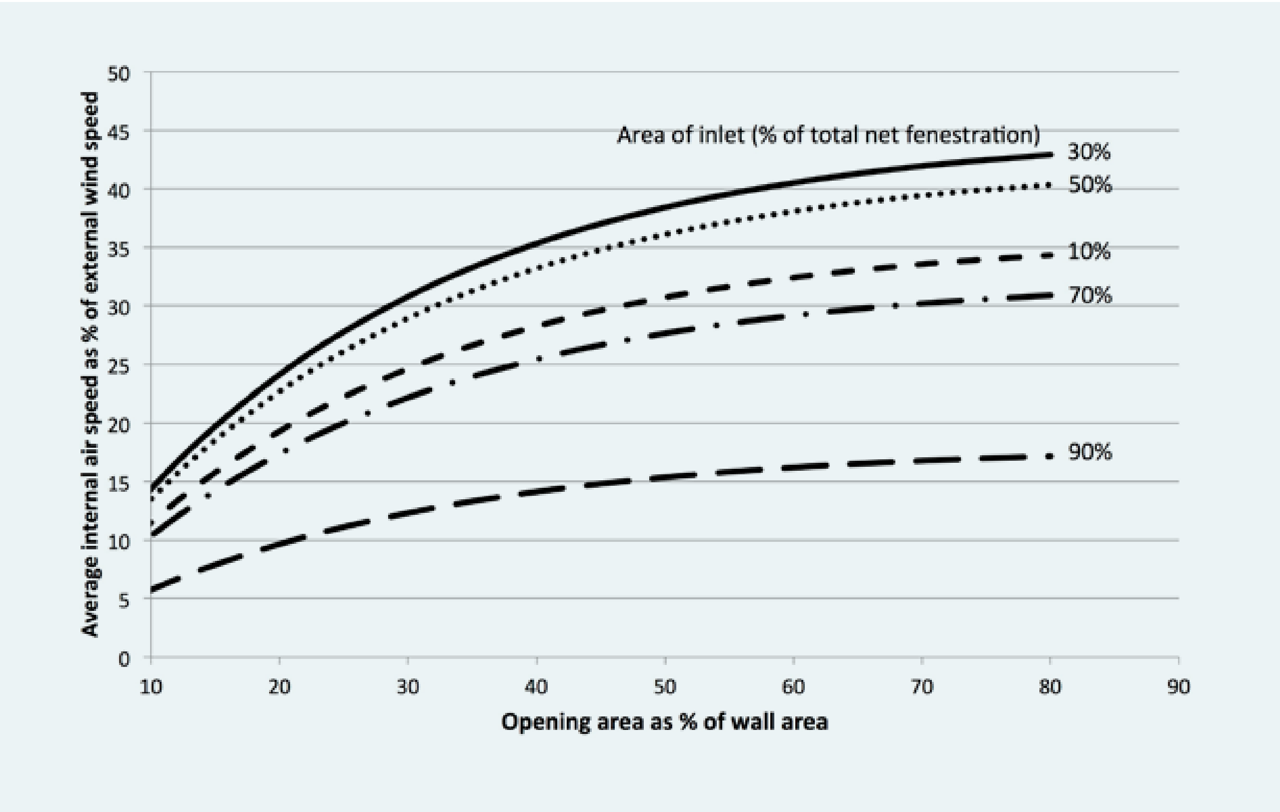
FIGURE 3.5-15 **AIR FLOW RATE PER SQUARE METER THROUGH THE SMALLER OPENING (OR AIR VELOCITY IN M/S) WITH DIFFERENT WIND SPEED – WIND INCIDENT AT 45°**



***Adapted from:** N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

A compromise between the absence of information about air velocity and the detailed knowledge of the values of air velocity in each part of the internal space, is an evaluation of the average wind velocity. From the average wind velocity it is possible to derive, as a first approximation, an indication of the effect of the airflow on comfort. The relationship between the area of the openings and the internal air velocity as a percentage of external wind speed, for a cross ventilated room with centred opposite openings, is plotted in figure 3.5-16, for different values of inlet area expressed as % of total (inlet + outlet) net fenestration, to take into account the effect of different inlet and outlet sizes.

FIGURE. 3.5-16 **AVERAGE INTERNAL AIR SPEED FOR DIFFERENT AREAS OF THE OPENINGS FOR CROSS VENTILATION**



Adapted from: *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

The values of internal air speed deriving from figure 3.5-16 change if the location of windows is changed, i.e. if they are not centred and opposite. For a given external wind velocity, the value of the average internal air velocity must be corrected according to Table 3.5-1.

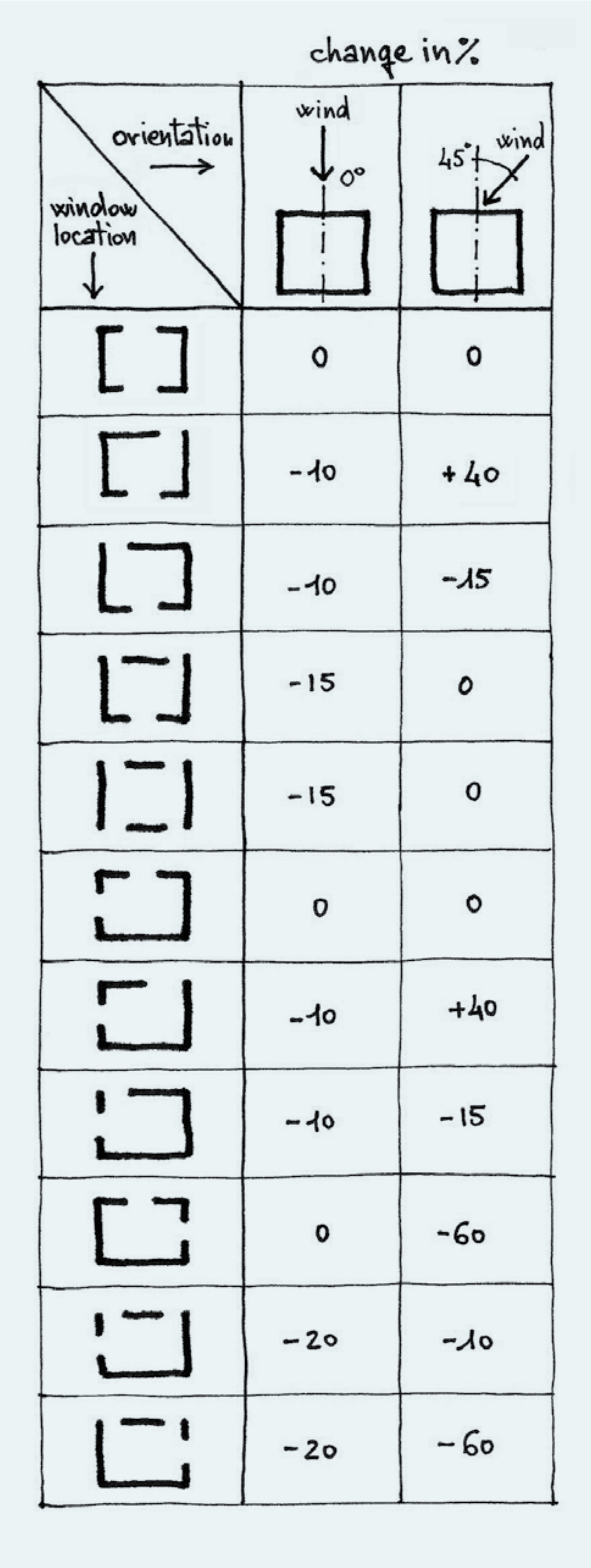
Effect of louvers

Louvers used for protection against direct solar gains significantly affect the average indoor air speed and the airstream pattern. Table 3.5-2 summarizes the effect of some simple types of louvers on room air motion, giving the corrective factors to be applied to the average indoor air velocity obtained with the figure 3.5-16.

Effect of verandas

The presence of a veranda on the windward or leeward side of a room influences the air motion. The correction factor to be applied to the average indoor air speed obtained with figure 3.5-16 is given in Table 3.5-3.

TABLE 3.5-1 **EFFECT OF WINDOW LOCATION ON INDOOR AIR MOTION**



Source: *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

TABLE 3.5-2 **EFFECT OF LOUVERS ON INDOOR AIR MOTION**

Type of louver	% change of average internal air speed
	0°
Horizontal (sunshade)	-20
L-type (horizontal and vertical)	+5
Multiple horizontal	-10
Multiple vertical	-15

Source: *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

TABLE 3.5-3 **EFFECT OF VERANDAS ON INDOOR AIR MOTION**

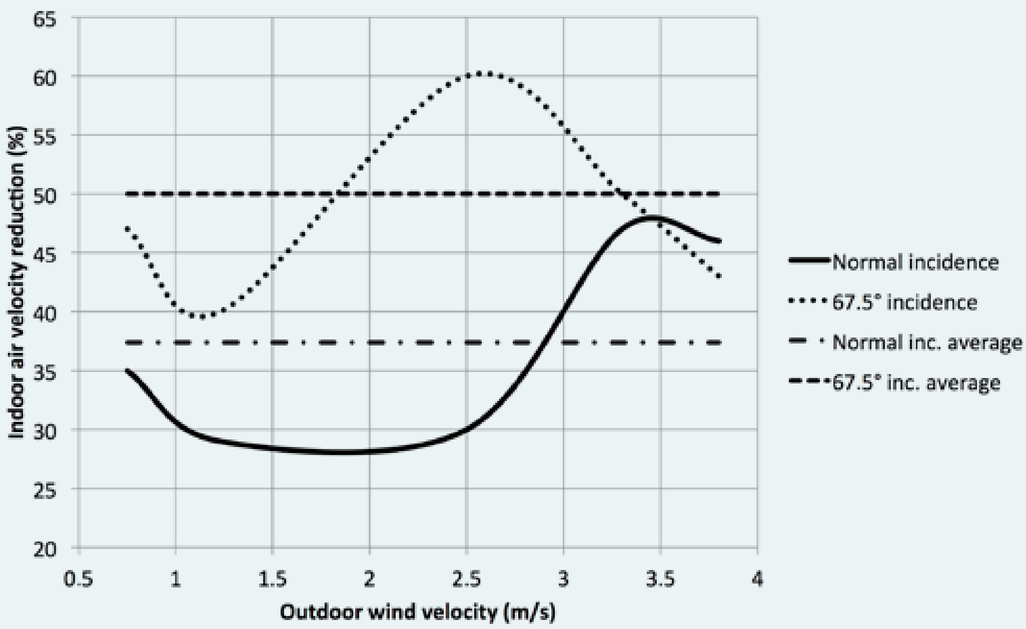
Type of veranda	Location	% change of average internal air speed
		0°
Open on three sides	Windward	+15
	Leeward	+15
Open on two sides	Windward	0
	Leeward	0
Open side parallel to the room wall	Windward	-10
	Leeward	0
Open side perpendicular to the room wall	Windward	-50
	Leeward	0

Source: *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

Effect of flyscreens

Flyscreens or mosquito nets are an absolute necessity not only in malaria infested areas but also if any kind of lamp is used indoors at night, to prevent large amount of insects entering, attracted by the light. Such screens and nets substantially reduce the air flow. A cotton net can give a reduction of 70% in air velocity. A smooth nylon net is better with a reduction factor of about 40% of the air flow rate and about 35% of average indoor air speed. The reduction of the latter increases, but not dramatically, with outdoor wind speed, and it is also affected by the wind's angle of incidence, as shown in figure 3.5-17.

FIGURE 3.5-17 **FLYSCREEN. REDUCTION OF WIND VELOCITIES WITH THE INCIDENT ANGLE**



Adapted from: *O.H. Koenisberger, T.G. Ingersoll, A. Mayhew, S.V. Szoklay, Manual of tropical housing and building, Longman, 1975*

3.5.3 STACK EFFECT

Heated by internal loads (people, lights, equipment) air entering a building that is not air-conditioned tends to rise, because it warms up and its density, and therefore its weight, is lower than that of the outside air. If there is an opening at the top, the warm air escapes through it, and is replaced by the outer, colder and heavier air, which enters from the bottom.

In the absence of wind, if internal resistance to flow is not significant, the air flow rate *V* crossing two equal size openings at different heights through the stack effect, depends on the difference between the internal average temperature T_i and the external one T_o [K], on the height difference H [m] between the openings and on their net equal area A [m^2], figure 3.5-18 ($A_1 = A_2$), and can be calculated with[23]:

$$V = 2.88A\sqrt{H\frac{T_i - T_o}{T_i}} \quad (3.5\text{-}2)$$

If the inlet and outlet areas are not equal, the air flow is first determined using the smallest of the two areas and then, according to the ratio of outlet to inlet, or vice versa, the percentage of the flow increase is provided by the graph of Figure 3.5-19.

Where appropriate, the same correction factors for louvers and fly screen, as for cross ventilation, should be applied.

23 *ASHRAE Handbook of Fundamentals, 1993*

Since the air flow increases with the stack height and the temperature difference, the height difference H between the openings should be increased as much as possible, as should their size.

To enhance the flow rate, an effective solution is to increase the temperature difference between inside and outside, using the solar chimney, exploiting solar energy to heat the rising air flow (Fig. 3.5-20).

3.5.4 VENTILATION DUE TO COMBINED EFFECT OF WIND AND THERMAL FORCES

The actual air flow in a building results from the combined effect of thermal (stack effect) and wind forces. The two forces may either reinforce or oppose each other, depending on the direction of the wind and on whether the internal or the external temperature is higher. When acting simultaneously, the resulting air flow rate through the building can be calculated as[24]:

$$V = \sqrt{V_w^2 + V_s^2} \quad (3.5\text{-}3)$$

where:
V = resultant air flow rate [m^3/s];
V_w = air flow due to wind [m^3/s];
V_s = air flow due to stack effect [m^3/s].

24 *N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994*

FIGURE 3.5-18 **AIRFLOW DUE TO THE HEIGHT DIFFERENCE BETWEEN THE OPENINGS AND THE TEMPERATURE DIFFERENCE BETWEEN INSIDE AND OUTSIDE, IN THE ABSENCE OF WIND**

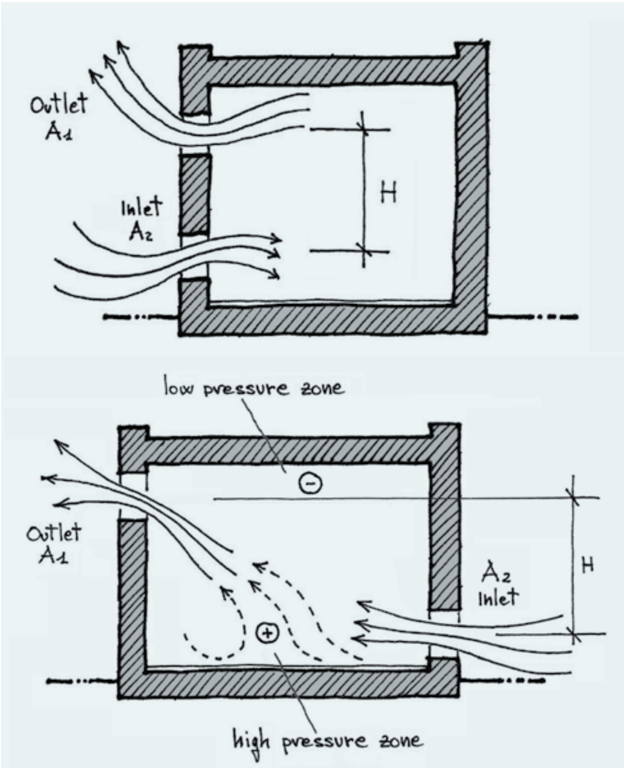


FIGURE 3.5-19 **INCREASE IN STACK FLOW RATE DUE TO DIFFERENTIAL OPENING SIZES**

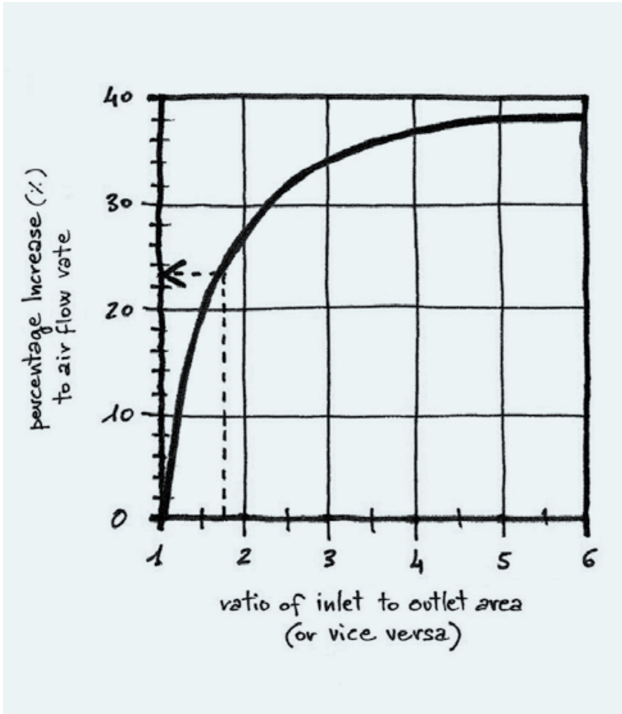
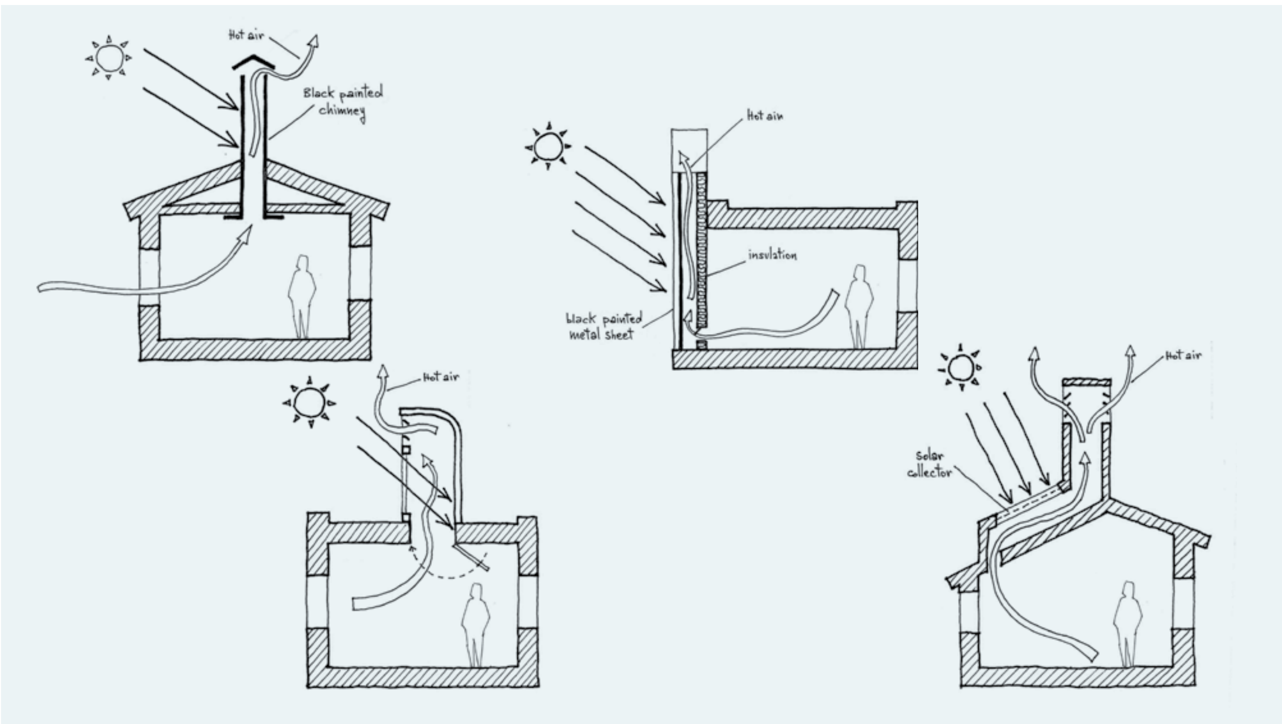


FIGURE 3.5-20 **DIFFERENT TYPES OF SOLAR CHIMNEY**



3.5.6 ROOM ORGANISATION STRATEGIES

When designing so as to profit as much as possible from the benefits of natural ventilation, both cross and stack, organisation of the rooms plays an important role. The best strategies are shown in figure 3.5-21.

3.5.7 WIND CATCHERS

There are cases in which it is difficult to provide adequate ventilation even if the location is fairly windy. This is the case in low-rise, high density settlements, where it is difficult to get good wind access, because upwind buildings block breezes, or when conflict between the best orientation for shade and wind forces sun protection to be favoured, or when the shape of the plot does not allow the building to be oriented to take advantage of the prevailing wind direction.

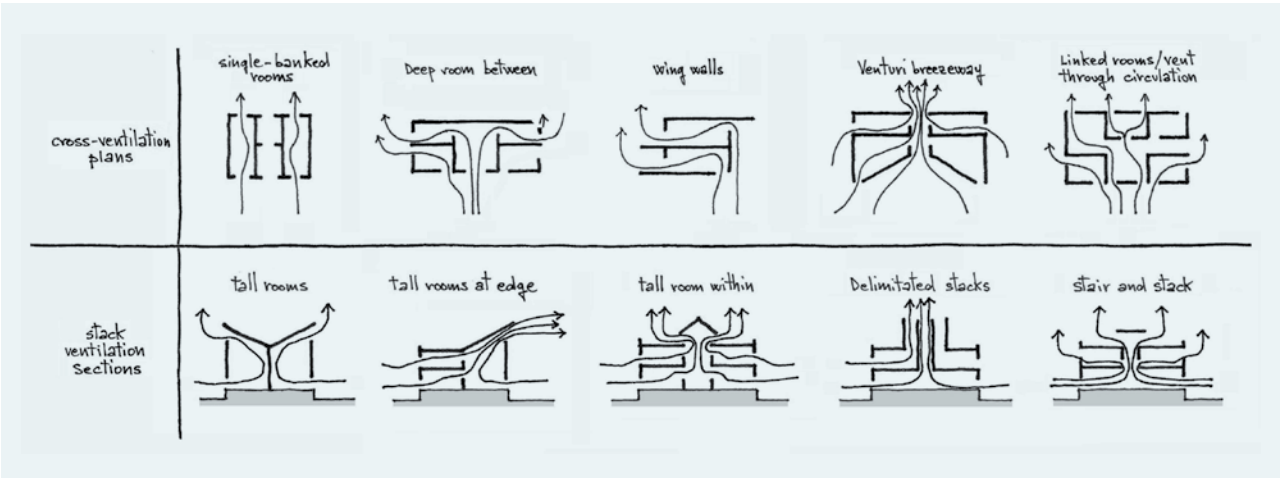
In some countries, a traditional solution to this kind of problem is the wind catcher: a tower capable of capturing winds above the building, bringing in fresh air from outside (Fig. 3.5-22). A prerequisite for using a wind catcher is that the site should experience winds with a fairly good consistent speed.

Windcatchers can be categorized in two groups: vernacular windcatchers (Fig. 3.5-23) and modern or commercial windcatchers (Fig. 3.5-24). The foundation of these three types of windcatchers is almost the same.

Wind catcher inlets, in order to rise above the layer of turbulence and drag, should be at least 2.4 meters above the height of surrounding buildings and obstructions.

The size of the wind catcher opening required to attain a given airflow rate, as a percentage of floor area can be determined from the graph of figure 3.5-25.

FIGURE 3.5-21 **ROOM ORGANISATION STRATEGIES FACILITATING BOTH CROSS AND STACK VENTILATION**



Source: *G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001*

FIGURE 3.5-22 **UNIDIRECTIONAL (LEFT) AND MULTIDIRECTIONAL (RIGHT) WIND CATCHER**

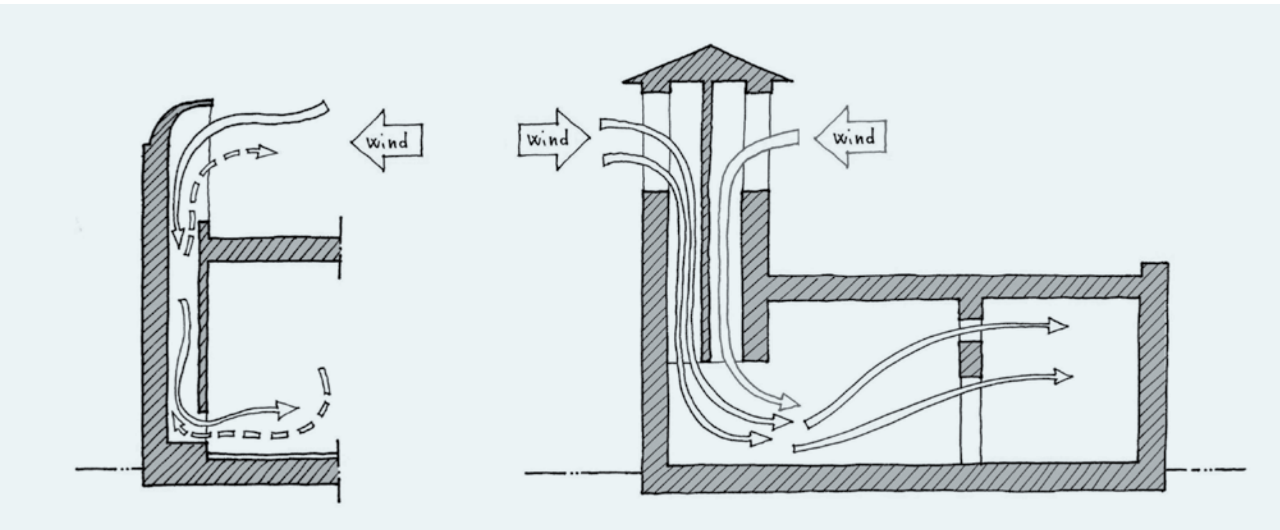


FIGURE 3.5-23 **CATCHING EFFICIENCY FOR DIFFERENT WIND CATCHER DESIGN**

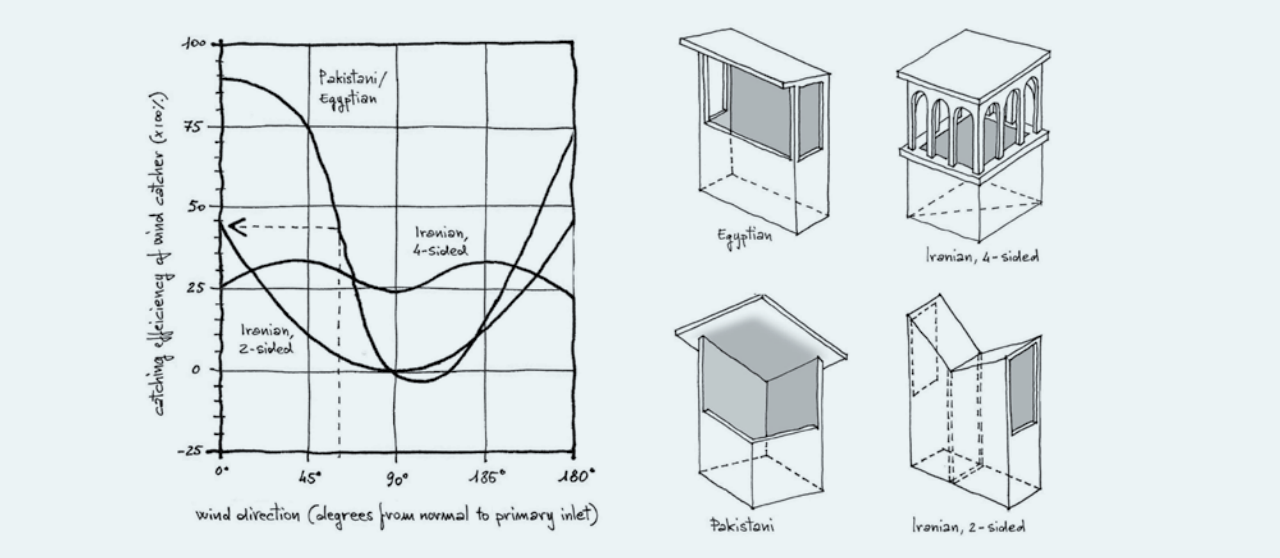
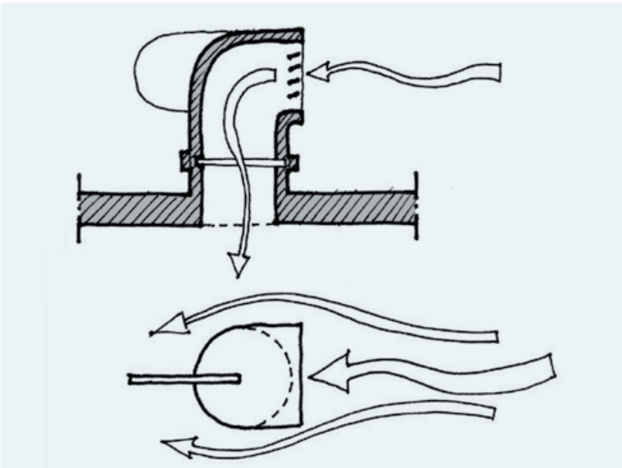


FIGURE 3.5-24 **SPINNING WIND CATCHER**



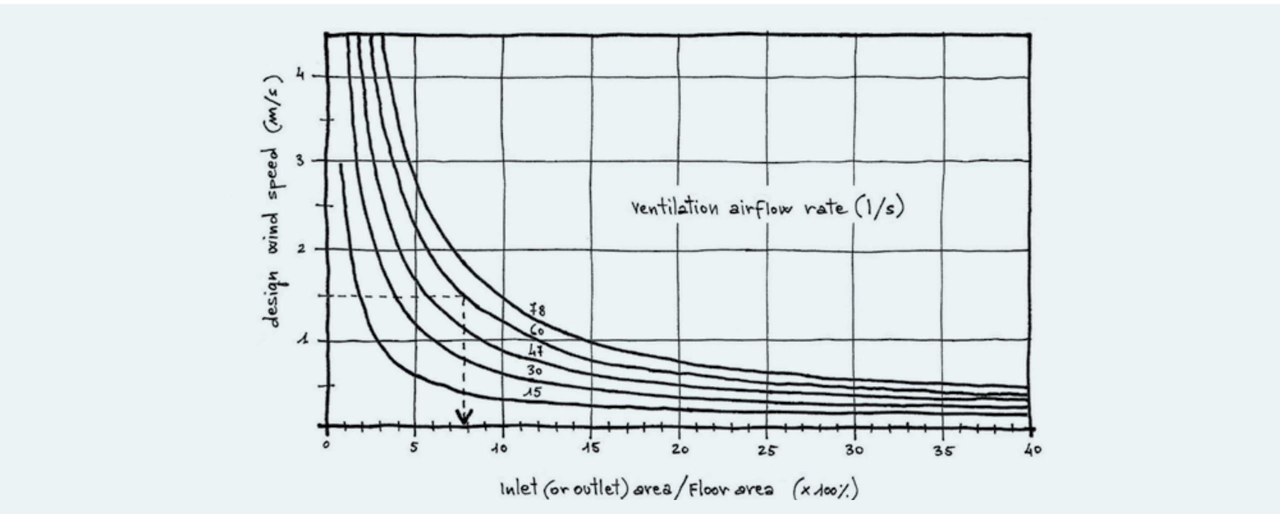
Source: *G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001*

Enter the design wind speed on the vertical axis of the graph, move horizontally until the curve for the required ventilation airflow rate is intercepted; then drop to the horizontal axis to read the size of inlet as a percentage of floor area.

The graph is based on an incident wind angle of between 0° (normal) and 40° to the wind catcher opening.

For wind catcher designs with openings in multiple directions, the opening in each direction should be sized to meet the airflow rate required. The inlet from a single direction should be no larger than the cross sectional area of the tower, while operable windows used for outlets should be about twice as large as the inlets.

FIGURE 3.5-25 **SIZING WIND CATCHERS FOR COOLING**



Source: *G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001*

Despite all the advantages of a windcatcher, an argument against using it is that it is a place that insects and dust may enter easily. This problem is greater in Africa where dengue fever and malaria kill thousands of people every year. Flyscreens must thus be used at the inlet or outlet, with the consequent reduction in the air flow (about 50%).

Another weakness of a windcatcher is that control of the volumetric flow rate is almost zero, unless adjustable dampers are used.

Wind catchers, in hot-arid climates, should be used only for night ventilation but, if water is available, their effectiveness can be extended to daytime by exploiting the principle of evaporative cooling (see paragraph 3.8 – Natural cooling systems).

3.5.8 INDUCED VENTILATION

Induced ventilation can be very effective in hot and humid climates as well as in hot and dry climates. Ventilation can be induced in three ways. One way involves heating air in a restricted area through solar radiation, thus creating a temperature difference and causing air movements, as in solar chimneys. The draught causes hot air to rise and escape outdoors, drawing in cooler air and thereby causing cooling (Fig. 3.5-26).

The second way exploits wind velocity, either by channelling the airflow inside (Fig. 3.5-27) or by creating a depression with a rotating device moved by wind to extract air from the building (Fig. 3.5-28).

The third way exploits the Venturi effect as depicted in figure 3.5-29, where air is extracted from the building because of the low pressure created by the wind on top of a shaft. In windy areas it could be an effective alternative to wind catchers.

FIGURE 3.5-26 **INDUCED VENTILATION: STACK EFFECT**

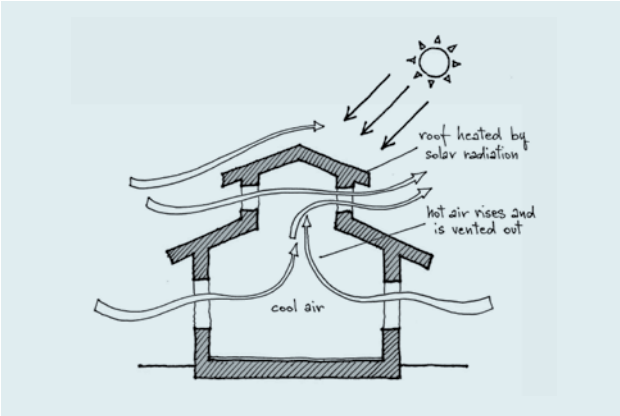


FIGURE 3.5-27 **INDUCED VENTILATION: CHANNELLING AIRFLOW**

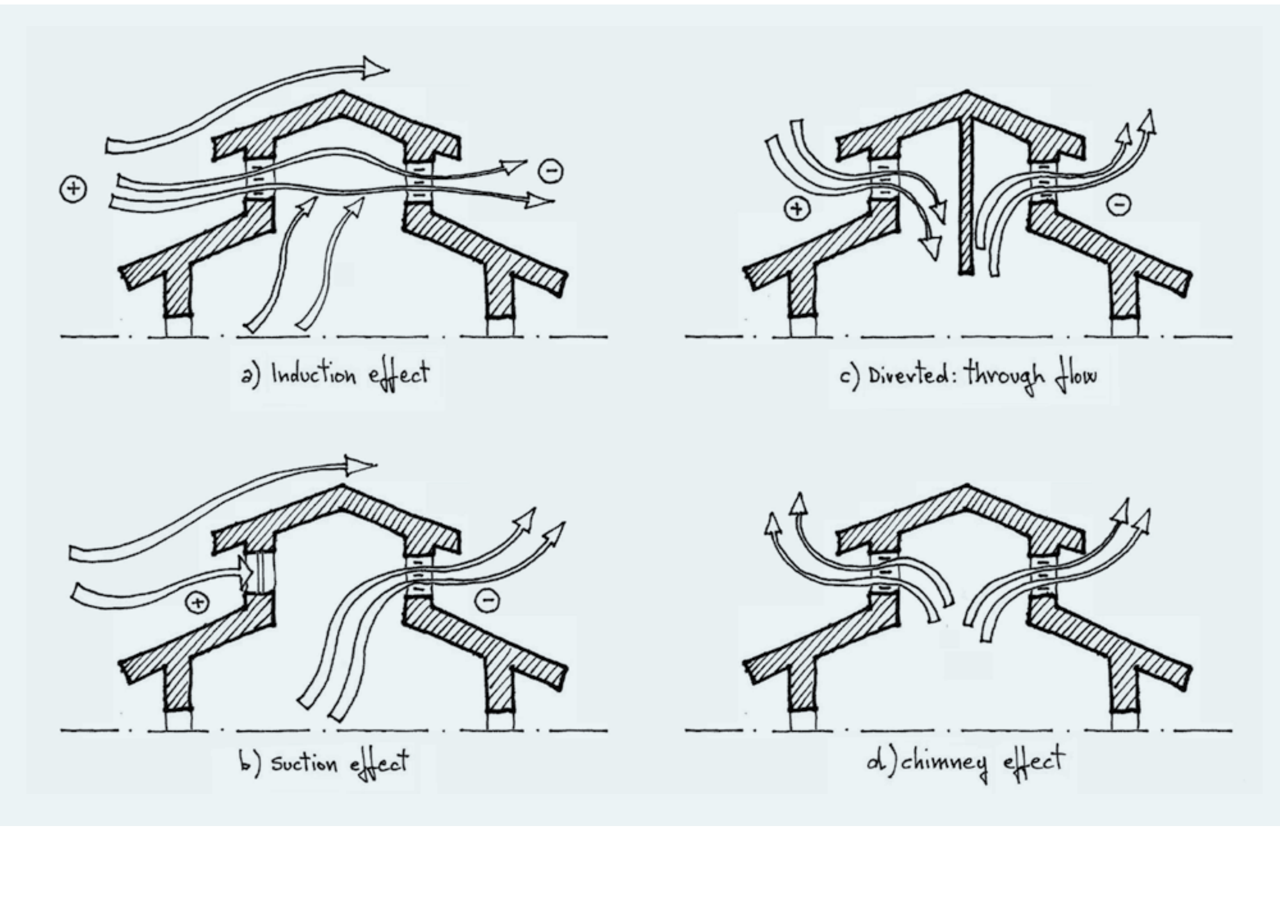


FIGURE 3.5-28 **INDUCED VENTILATION: ROOFTOP AIR VENTILATOR**

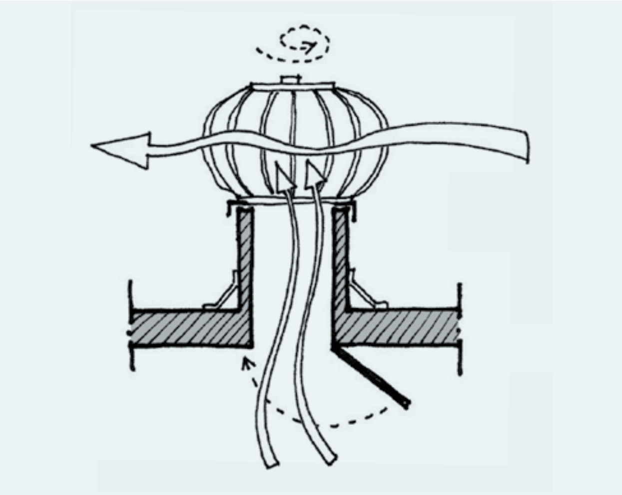
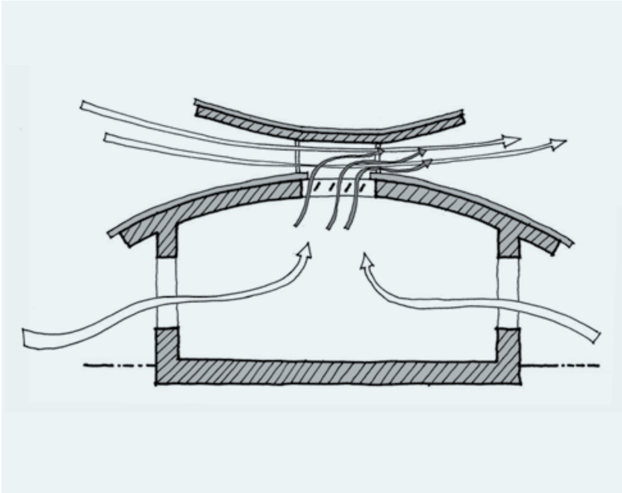


FIGURE 3.5-29 **VENTURI PASSIVE VENTILATOR WITH ADJUSTABLE LOUVERS**



3.5.9 RECOMMENDATIONS FOR BEST EXPLOITATION OF NATURAL VENTILATION

- Orient the building to maximize surface exposure to prevailing winds. However, a building does not necessarily need to be oriented perpendicular to the prevailing wind. It may be oriented at any convenient angle between 0 – 30 degrees without losing any beneficial aspects of the breeze.
- Consider, in the orientation of the building and in sizing the windows, the different needs according to the climate: day ventilation in a hot humid climate; night ventilation in a hot -arid climate with significant daily temperature variation; moderate ventilation in a cool upland climate.
- Raising the building on stilts is an advantage: it catches more wind.
- Hedges and shrubs deflect air away from the inlet openings and cause a reduction in the indoor air motion. These should not be planted inside a distance of about 8 m from the building because the induced air motion is reduced to a minimum in that case. However, air motion in the leeward part of the building can be enhanced by planting low hedges at a distance of 2 m from the building.
- Trees with large foliage mass, with trunks bare of branches up to the top level of the window, deflect the outdoor wind downwards and promote air motion in the leeward portion of buildings.
- An effective cross-ventilation design starts with limiting the depth of the building to facilitate inward air flow from one facade and outward flow from the other. Architectural elements can be used to harness prevailing winds: architectural features like wing walls and parapets can be used to create positive and negative pressure areas to induce cross ventilation.
- Air speed inside a space varies significantly depending on the location of openings. The most effective strategy is to provide staggered openings on opposite walls. Limit room widths if openings cannot be provided in two walls.
- Large openings, doors, and windows are an advantage provided they are effectively protected from the penetration of solar radiation.
- Inlet and outlet openings at a high level would only clear the air at that level without producing air movement at the level of occupancy. Maximum air movement at a particular plane is achieved by keeping the sill height of the opening at 85% of the critical height (such as head level). The following levels are recommended according to the type of occupancy.
  - For sitting on chair = 0.75 m
  - For sitting on bed = 0.60 m
  - For sitting on floor = 0.40 m
- Greatest flow per unit area of openings is obtained by using inlet and outlet openings of nearly equal areas at the same level.
- In rooms of normal size which have identical windows on opposite walls, the average indoor air speed increases rapidly by increasing the width of window by up to two-thirds of the wall width. Beyond that the increase in indoor air speed is in much smaller proportion to the increase in window width.
- In the case of rooms with only one wall exposed to the outside, provision of two windows on that wall is preferred to a single window.
- A single-side window opening can ventilate a space up to a depth of 6-7 m. With cross-ventilation, a depth up to 15 m may be naturally ventilated. Integration with an atrium or chimney to increase the stack effect can also ventilate deeper plan spaces.

- Provision of horizontal sashes inclined at an angle of 45 degrees in an appropriate direction helps promote indoor air motion. Sashes projecting outwards are more effective than those projecting inwards.
- Roof overhangs help promote air motion in the working zone inside buildings. A veranda open on three sides is to be preferred as it increases room air motion with respect to the outdoor wind, for most orientations of the building.
- Air motion in a building is not affected by the construction of another building of equal or smaller height on the leeward side, but it is slightly reduced if the building on the leeward side is taller than the windward block.

3.6 DAYLIGHTING

Taking advantage of daylight is essential for sustainable architecture in any climatic conditions, in order to provide visual comfort, reduce the amount of conventional energy used and, at the same time, to diminish thermal gains indoors caused by artificial lighting.

Sky luminance and thus passive design strategies are different in hot-humid and hot-arid climates. In the clear skies typical of hot-arid climates, brightness is not uniform, diminishing from the horizon to the zenith, with a sharp increase at the sun’s position. In the overcast skies characteristic of hot-humid climates, sky luminance is more uniform, but by contrast increases from the horizon to the zenith.

Daylight requirements are usually classified as quantitative and qualitative. Quantitative requirements refer to the illumination level indoors and qualitative requirements are related to the distribution of luminance in the visual field.

Daylight level

The quantity of light or illuminance level indoors varies depending mainly on the distance from the opening through which light is coming in. Illuminance level at any point of a room is the sum of the direct light coming from the sky, the light reflected from the surfaces of the nearby buildings or from the ground, and the light reflected from the internal surfaces of the room (ceiling, walls and floor).

As the sky luminance varies during the day and the year and, consequently, indoor daylight is also variable, an index, the *daylight factor,* was developed (see Appendix 2 – Principles of thermal and visual comfort). The daylight factor expresses the ratio of the illumination level at a point indoors to the illumination outdoors on a horizontal plane, without obstructions. The daylight factor is regulated by set standards and its compliance with these depends on the dimension of the windows, the depth of the room, the shape, location and type of windows and shading devices, the obstruction provided by the context, and the colour of the external and internal surfaces.

Light colours outside contribute to indoor daylight, because they increase the reflected light coming in, thus the required window area is less when the surfaces of the surrounding buildings are light coloured. Light coloured interior surfaces increase the illumination level indoors, allowing smaller windows. The appropriate size of windows is usually estimated according to the prescribed standards. It is related to the floor area of the room and its depth, since deeper spaces require larger windows for the same floor area. The proportions and location of the windows also influence interior daylight. Horizontal windows or two windows separated in the same wall are more effective for daylight than only one with the same area but vertical in shape, stretching from floor to ceiling. Finally, the window frame also influences daylight, depending on the reduction coefficient, which expresses the ratio of the real area available for light penetration and the total area of the opening.

Daylight quality

Besides the quantitative requirements for the minimum indoor illumination level, qualitative requirements are related to the uniform distribution of daylight indoors. The ratio of minimum to maximum illumination levels indoors has to be controlled to avoid high luminance differences in the visual field. Another impact on the qualitative requirements for visual comfort is caused by direct sunlight indoors, whose reflection may cause glare.

In hot-arid and savannah climates, because of the glaring nature of light when it is reflected from the ground or from light coloured buildings, openings should be shaped in such a way that the view is directed towards the sky rather than towards the horizon or the ground. Thus, windows should be located above the visual level or protected by Venetian blinds, avoiding a direct view to outdoors but allowing indirect light reflected from the ground outside to penetrate through the blinds and be reflected on the ceiling, producing uniform indirect daylight. The colour of the blinds should not be very light in this case, to avoid glare from them.

Since internally reflected light is the best for natural lighting, a window positioned high, i.e. above eye level for example, will have the effect of reflecting the light towards the ceiling. A ceiling painted white will, in turn, provide adequate diffusion of light inside, even if the openings are relatively small (Fig. 3.6-1). Low windows are also acceptable if they face a shaded courtyard or non-glaring surfaces.

In hot-humid and Great Lakes climates, since the sky and not the ground is the main source of glare, views from the interior spaces directly to the outdoors are suitable, but openings should be positioned in such a way that the sky is not directly seen. Overhanging roofs or large verandas can be used for obstructing the direct view of the sky (Fig. 3.6-2).

FIGURE 3.6-1 **OPENING TYPES ALLOWING THE REDUCTION OF GLARE IN A HOT-ARID CLIMATE**

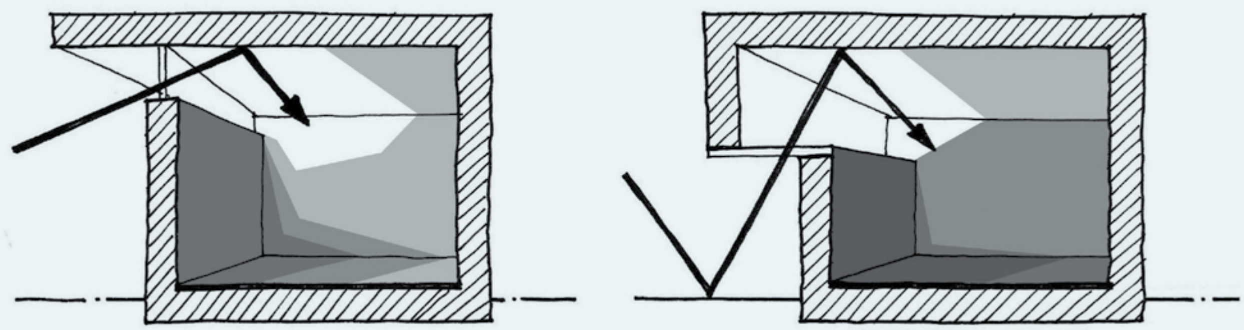
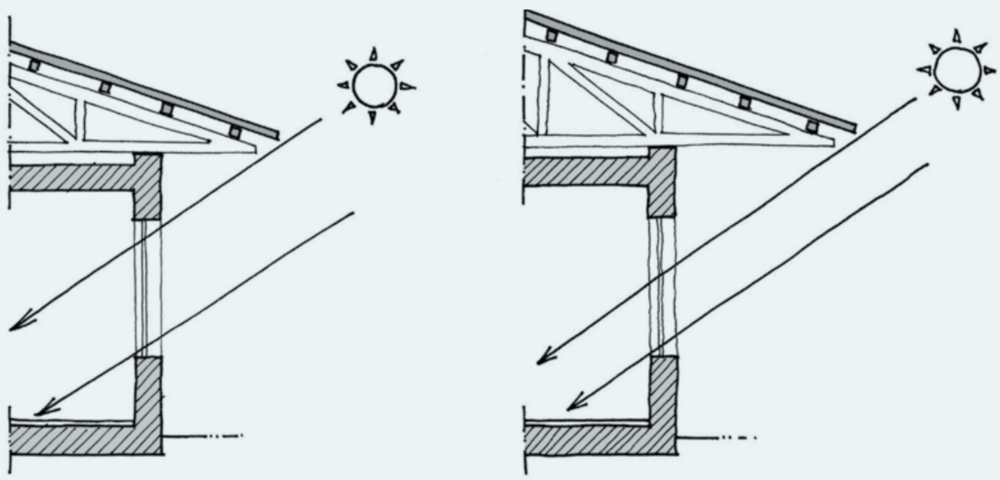


FIGURE 3.6-2 **IN A HOT-HUMID CLIMATE OVERHANGING ROOFS HELP TO REDUCE THE GLARE FROM THE SKY**



3.6.1 WINDOW DESIGN AND VISUAL COMFORT

Often, in current design practice, the only constraint taken into account for the sizing of windows is the one that derives from the health regulations that stipulate a minimum area. When this has been complied with, the size and shape of the windows are generally based more on aesthetic than functional criteria, in spite of the fact that window design involves choices that have a great impact on energy consumption and on visual comfort.

The first concern of the architect, therefore, should be to size the windows according to the primary function of providing natural lighting, and then check if the fulfilment of this requirement is consistent with the other important function that windows have: to provide an external view for the building's occupants.

3.6.1.1 A FIVE STEP METHOD TO USE IN THE EARLY PHASES OF THE DESIGN PROCESS

The method[25] allows a first, approximate, sizing of windows - at the earliest stages of the design process - to obtain a reasonable illumination level.

The method, being based solely on the contribution of diffuse and reflected radiation, is strictly applicable to: i) windows not hit by direct radiation (as when they are protected by an efficient sunscreen), ii) all cases in which obstructions prevent the entry of direct radiation most of the time.

25 *C. F. Reinhart, V. M. Loverso, A Rules of Thumb Based Design Sequence for Diffuse Daylight, http://www.gsd.harvard.edu/people/faculty/reinhart/documents/DiffuseDaylightingDesignSequence.pdf*

In sunny climates, therefore, in the case of windows without obstructions or not completely shaded, rooms will be over-lit (thus subject to glare and overheating); it is necessary, in this case, to use simulation models allowing the designer to take into account the effect of direct radiation on average annual illuminance values, on glare, and on the energy balance of the zone.

Even if the windows are always protected from direct sunlight, the method may overestimate the window size in tropical climates, because of the high outdoors illumination level and the number of clear days. Thus the designer should bear clearly in mind the fact that the fine-tuning of the optimization process, carried out with simulation tools, may lead to a smaller area of glass. In any event, even if the subsequent refinements will not take place because of time or economic limits, it is always preferable to use this simple method than not to use any.

The steps:

1. Assess how much natural light the space receives, by calculating the effective sky angle;
2. Assess how much lighting the space needs, by setting the target mean daylight factor desired (DF_m);
3. Calculate the window to wall ratio (WWR) required to achieve the set daylight factor;
4. Evaluate the dimensional constraints imposed by the target DF_m chosen in step 2, by calculating the appropriate depth of the space and the colour of the walls;
5. Determine the required glass area.

Step 1 – *Calculate the effective sky angle*

The sky angle is determined graphically as shown in figure 3.6-3, or analytically:

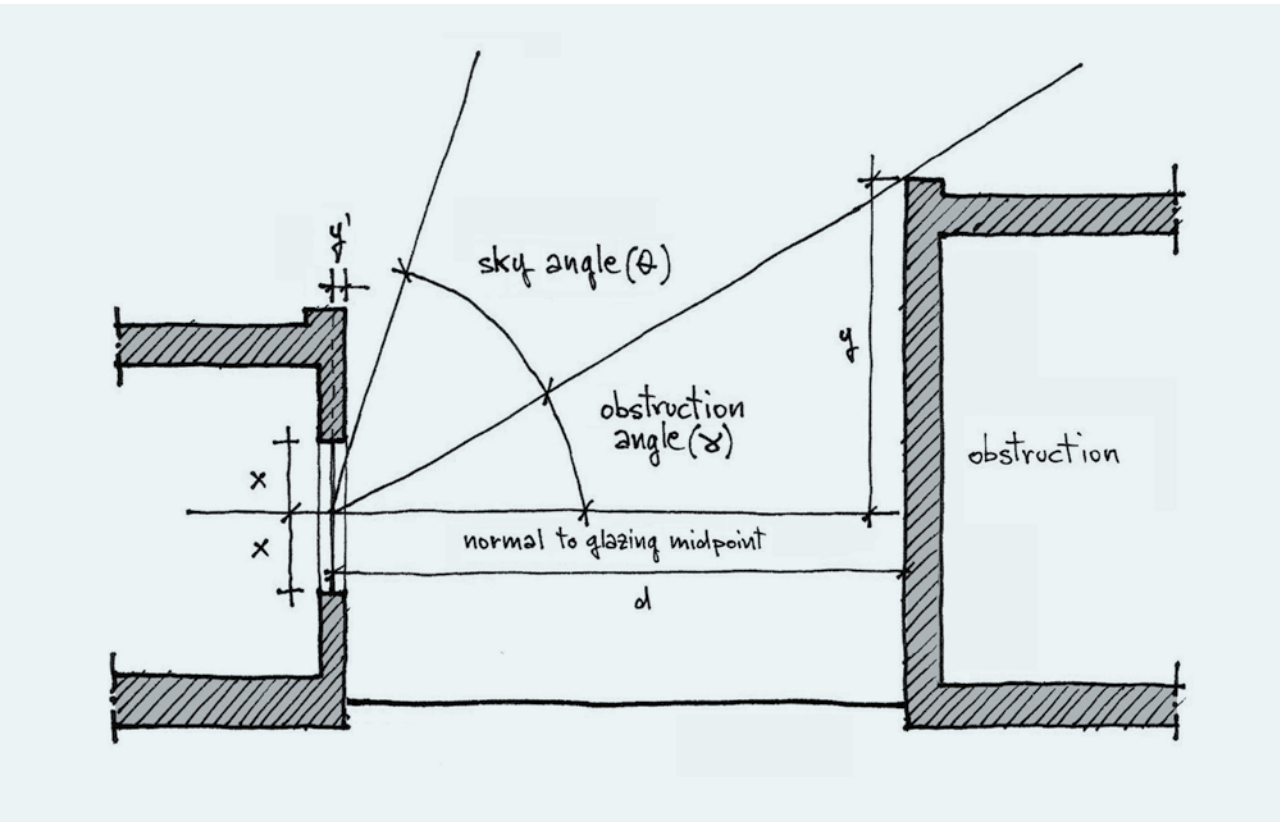
$$(\theta) = 90° - \arctan(y'/x) - \arctan(y/d) \qquad (3.6\text{-}1)$$

In cases when it is not yet known where to place the window, just pick the centre of the façade for your sky angle calculation. More complex obstruction conditions can be analysed using a 3D model and a ray-tracer.

Step 2 - *Determine the value of DF_m*

According to the outdoors average illumination levels in EAC countries on cloudy days, a space with a mean daylight factor of between 1% and 2% can be considered well lit, and requires little or no additional lighting during daytime. A reasonable first guess of the value is $DF_m = 1.5\%$

FIGURE 3.6-3 **SKY ANGLE EVALUATION**



Step 3 – *Calculate the window to wall ratio (WWR) required*

The window to wall ratio (WWR) corresponds to:

$$WWR = \frac{\text{Area of Exterior Openings (excluding mullions and window frames)}}{\text{Total Wall Area of Exterior Façade (width x floor-to-ceiling height)}} = \frac{A}{A} \quad (3.6\text{-}2)$$

The minimum WWR required for a side-lit space, taking into account external obstructions, glazing type and target mean daylight factor is given by:

$$WWR = \frac{0.088 \cdot DF_m}{\tau_{vis}} \quad (3.6\text{-}3)$$

where:
DF_m = targeted mean daylight factor in %;
θ = sky angle in °;
τ_{vis} = glazing visual transmittance.

The maximum value of WWR is 0.8, since about 20% of the opening area has to be taken into account for mullions and window frames.

Step 4 - *Calculate the maximum depth of the room and the surfaces reflectance required*

In addition to the daylight factor requirement, three factors limiting room depth should be considered in daylight design:

- daylight uniformity (distance at which the uniformity of daylighting levels throughout the space drops);
- no sky line depth (distance away from the windows at which the sky is no longer visible);
- depth of daylight area (distance to which 'meaningful' levels of daylight extend throughout the space).

The mean daylight factor becomes a poor representation of the daylighting levels in spaces under overcast sky conditions in the case of deep rooms, since they have very high daylight levels near the windows and very low values at the rear. Therefore a maximum room depth has to be established. A first approximation of the maximum acceptable depth of a space as far as daylight uniformity is concerned can be calculated by:

$$\textit{Limiting depth} = \frac{2/(1-\rho_m)}{1/l + 1/h} \quad (3.6\text{-}4)$$

where:
ρ_m = Mean surface reflectance, weighted on areas. If data are not available, ρ_m = 0.5 can be used as first approximation[26];

l = room width [m];
h = window-head-height [m].

26 *Desirable reflectances" to have a well daylit environment : ceiling > 80%, walls > 50-70%, floor > 20-40%, furniture > 25-45%*

Spaces with depth lower than this limiting depth usually exhibit relatively uniform levels of daylighting throughout.

To increase the value of the limiting depth very light colours for the walls can be used, thus increasing the average reflectance of surfaces.

The room depth (at the height of the working plane) past which there is no direct view of the sky is defined as (Fig. 3.6-4):

$$\textit{No skyline depth} = h' \tan(\alpha) \quad (3.6\text{-}5)$$

Where:

$\alpha \approx \theta$, when h>>x

Daylight penetration in a space varies linearly with window head height. The relationship factor varies depending on whether or not a shading device (curtains, blinds, etc.) is used

The limiting depth beyond which the natural light is insufficient, is given by (Fig. 3.6-5):

Limiting depth = 2.5 h without shading elements
Limiting depth = 2 h with shading elements

Considered together, the three limiting factors yield the following equation for determining the constraint on room depth:

Room depth < minimum	**No skyline depth** = h' tan(α) **Limiting depth** = 2.5 h without shading elements **Limiting depth** = 2 h with shading elements

The greatest room depth that can be used for daylighting is the smallest of the three values prescribed by the daylight uniformity, no sky line depth and the depth of daylight equations.

FIGURE 3.6-4 **EVALUATION OF THE ROOM DEPTH PAST WHICH THERE IS NO DIRECT VIEW OF THE SKY**

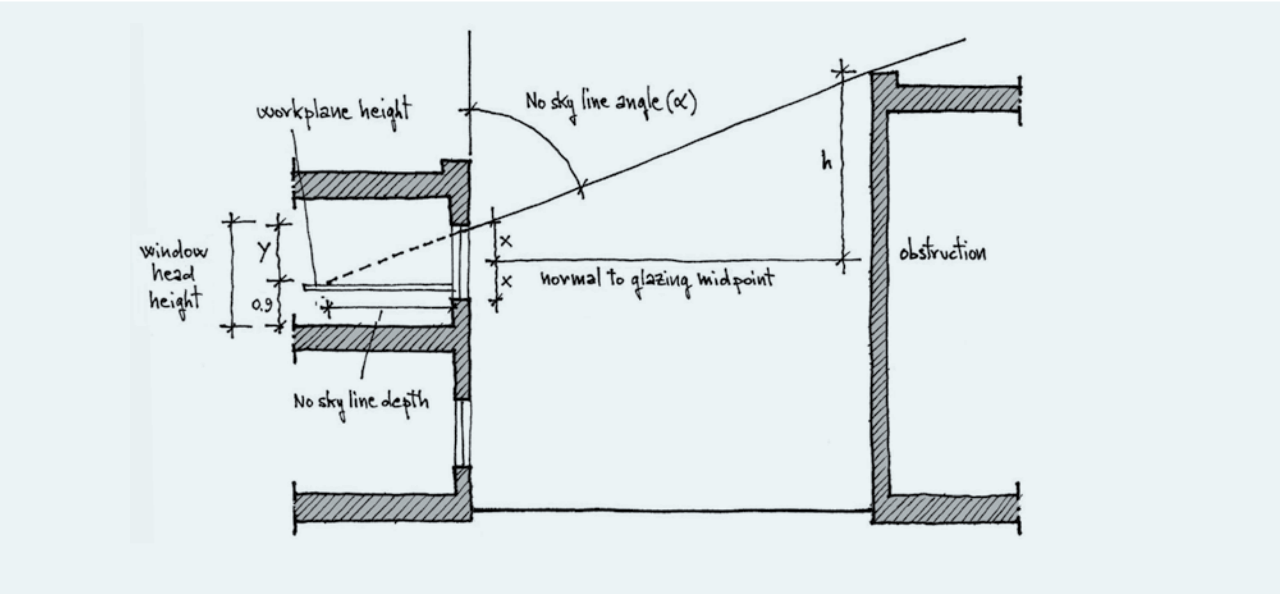
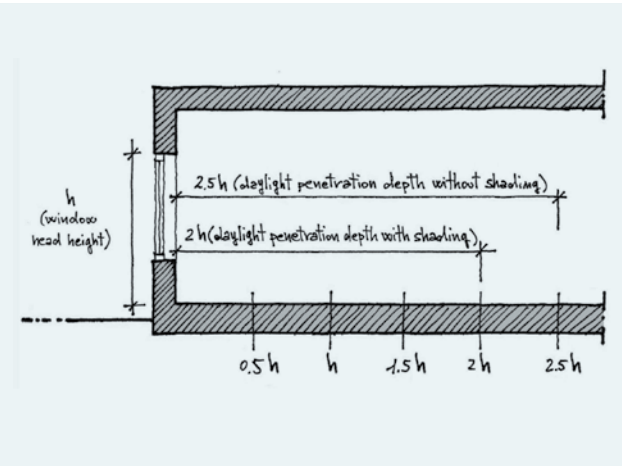


FIGURE 3.6-5 **LIMITING DEPTH**



Step 5 – Determine the required glazed area

In order to calculate the minimum required glazed area, $A_{glazing}$, required for each daylight space, the room depth of the zone may be assumed to be the depth of the daylight zone calculated in step 4. Calculate the total interior surface area (including windows), A_{total}, according to this 'virtual room depth' and derive $A_{glazing}$ using:

$$A_{glazing} = \frac{DF_m \cdot 2A_{total}(1-\rho_m)}{\tau_{vis} \cdot \theta} \qquad (3.6\text{-}6)$$

Where A_{total} is the total area of all interior surfaces, including windows; if the actual room depth is greater than the maximum calculated in step 4, use the latter to calculate A_{total}.

To obtain the total area of the window, including frames and mullions, in a first approximation multiply by 1.20.

The net glass area can be lowered by increasing the light transmission τ_{vis}, appropriately selecting the type of glass, or by increasing the sky angle, changing the shape and position of the openings, or by choosing very light colours for walls and ceiling.

3.6.1.2 **CHECK LIST**

If minimization of energy consumption is not a priority

1. Minimize the glass surfaces in the east, and, especially, in the west façades.
2. Keep WWR factor around 0.3 - 0.4.
3. If you do not know who will occupy the building, use ribbon windows.
4. Provide light-coloured interior walls and finishing.

If minimization of energy consumption is a moderately important parameter

In addition to the above:

1. Revise the size of the windows with the help of an energy calculations expert.
2. If expert advice is not available, explore alternative envelope designs that can incorporate shading devices or light shelves.
3. By means of a simple model (physical or virtual, by computer) check the quality of light and control glare.

If minimization of energy consumption is among the priorities

In addition to the above:

1. Use a more accurate model, and refine the choices in relation to the results of the analysis.
2. Ask the energy expert to perform a parametric analysis in order to optimize the façade both from the point of view of the quality of natural lighting and energy consumption, using simulation models.

3.6.2 SYSTEMS TO ENHANCE NATURAL LIGHTING

Even if windows are sized to make the most of natural light, it may be insufficient or poorly distributed. When it is not possible to obtain the desired natural lighting or light penetration due to obstructions or to glare caused by the excessive size of the glass surface or due to a conflict with solar gains, solutions can be adopted that allow better control of natural lighting.

3.6.2.1 LIGHT SHELF

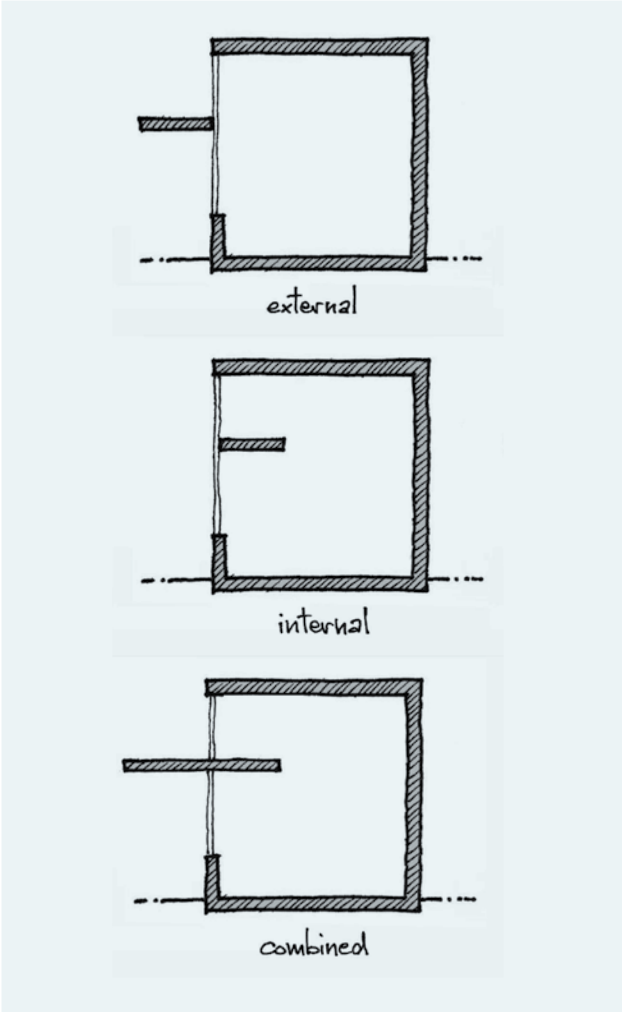
The "light shelf" is a well established way to facilitate the penetration of light into a room, and has been known and used since the times of the ancient Egyptians; it is designed to provide shade, to diffuse light more evenly in the room and to protect from direct glare.

The light shelf is generally made of a horizontal or nearly horizontal shelf arranged on the outside and/or inside of the window, in its upper part. The light shelf must be positioned so as to avoid glare and maintain the view outside; in general, the lower the light shelf, the greater the glare.

Light shelves have a considerable impact on the architectural design of the building and must be taken into account at the early stages of the design process, because, to be effective, they also require relatively high ceilings; they should be designed specifically for each orientation of the window, room configuration and latitude. They are especially suitable for climates with high sunshine levels on windows facing south or north in near equatorial latitudes.

Orientation, position, type (only internal, only external or a combination, figure 3.6-6), and depth of a light shelf is always a compromise between the needs for natural light and sun protection. A light shelf that is only internal reduces the total amount of light that is received in the space.

FIGURE 3.6-6 **POSSIBLE POSITIONS OF A LIGHT SHELF**



The minimum depth of an external light shelf is determined by the shading requirements; the deeper the shelf, the better it shades the window below, preventing the penetration of direct radiation, which causes glare and solar gains. For the interior light shelf, the limiting factor is still the glare; i.e. it is necessary to prevent the penetration of direct radiation.

The depth required is greater in the case of east and west-facing façades, and it varies with the orientation. In façades oriented within ± 20° off south or north in near equatorial latitudes), the external light shelf should have a depth of between 1.25 to 1.5 times the height of the ribbon window above; for more than ±20° off south/north the depth should be extended to between 1.5 to 2.0 times.

For rooms facing south or north, depending on the solar path, the depth of the internal light shelf may be roughly equal to the height of the ribbon window above (Fig. 3.6-7). In fact, to get a good result the window height, the depth of the light shelf and the height of the glazed ribbon above should be calculated in relation to the specific latitude, climate and orientation, using appropriate calculation tools.

If the optimum depth of the external light shelf is excessive in relation to other needs, the same result can be obtained by recessing the window below (Fig. 3.6-8); with this type of solution the contribution of natural light can be further increased by appropriately tilting the sill.

The depth of the internal light shelf can be extended so as to always intercept the direct radiation through the window above; in the case of east or west-facing windows it may happen that direct radiation is able to penetrate the space between the light shelf and the ceiling, and then it becomes necessary to provide some means of shading.

FIGURE 3.6-7 **SIZING THE LIGHT SHELF**

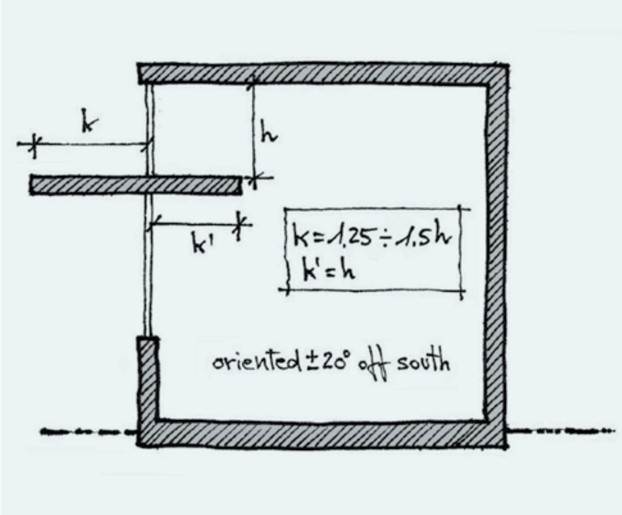
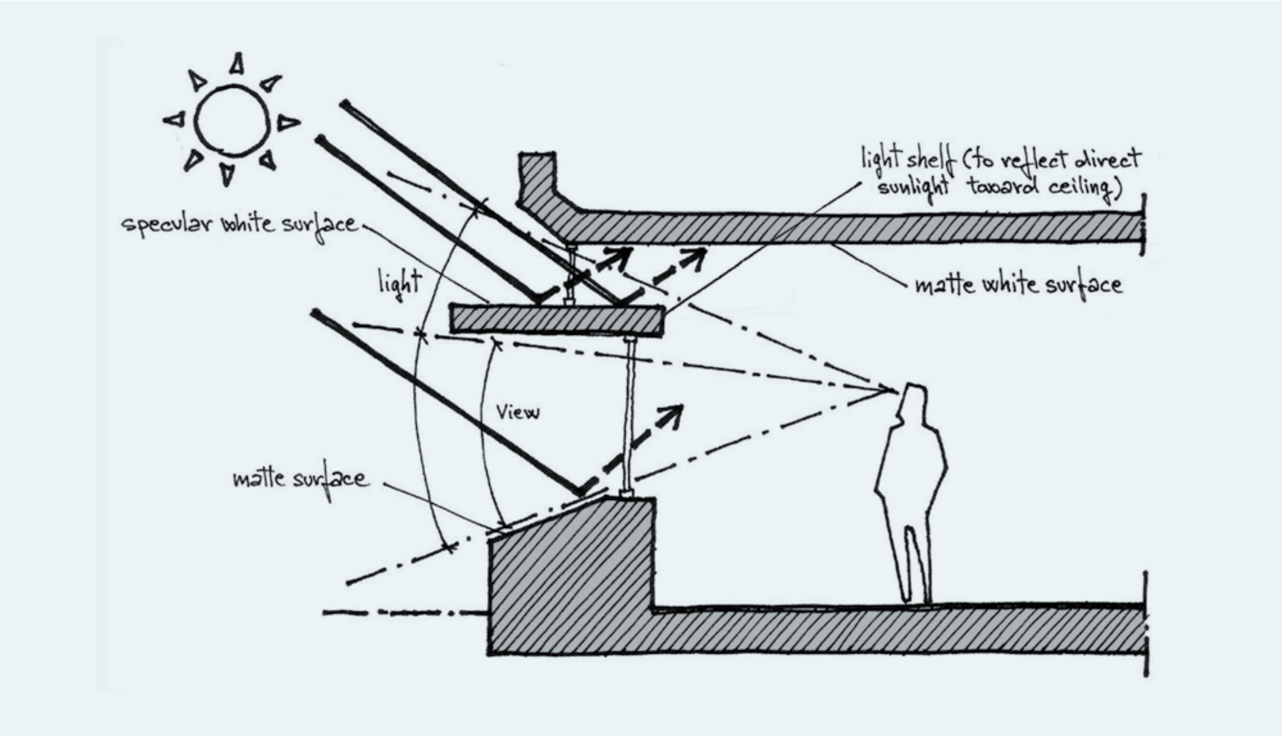


FIGURE 3.6-8 **LIGHT SHELF WITH RECESSED WINDOW**



At low latitudes, if the south or north-facing light shelf is tilted upwards (Fig. 3.6-9), the contribution of natural light increases, but the exterior part must be extended to provide satisfactory window shading. The optimum tilt angle, at latitudes near the equator depends on the ratio of X/H, according to figure 3.6-10.

The use of a light shelf - if the glass ribbon above it is appropriately sized and the depth of the internal shelf is such that it prevents direct radiation into the space - allows natural lighting to be ensured even when, to avoid glare, the glass area below is protected with a sunscreen. For south-east or south-west (north-west or north-east) facing façades, the resulting depth of the inner shelf may be excessive; in this case a series of smaller shelves, properly spaced, can be used, (Fig. 3.6-11).

FIGURE 3.6-9 **TILTED LIGHT SHELF**

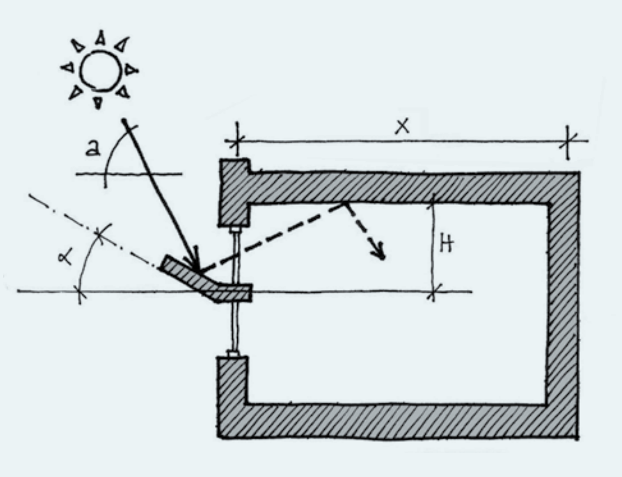


FIGURE 3.6-10 **LIGHT SHELF OPTIMUM TILT ANGLE VS, X/H**

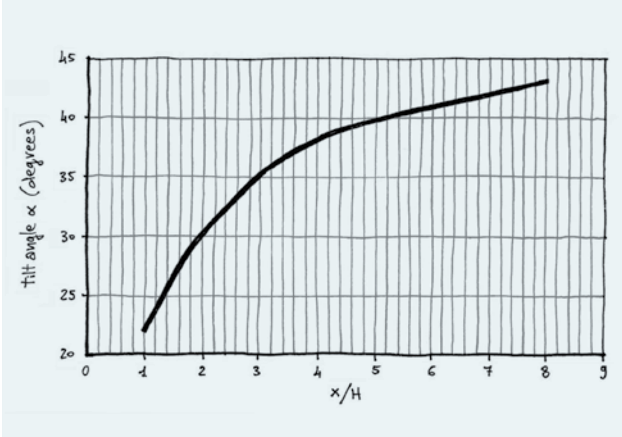
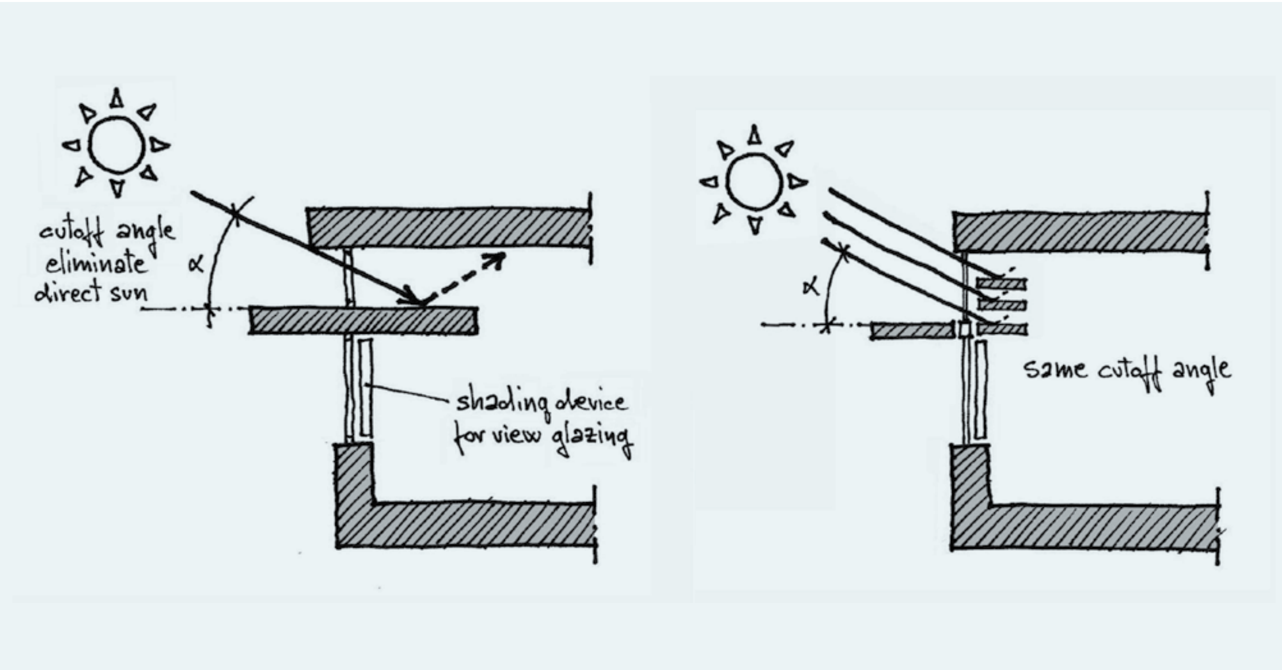


FIGURE 3.6-11 **REDUCING THE DEPTH OF THE LIGHT SHELF**



An alternative solution consists of a Venetian blind with reflective, fixed or mobile, slats on the inside (Fig. 3.6-12) or outside of the glass strip. In this case the outer shelf has the sole function of solar protection for the underlying glass.

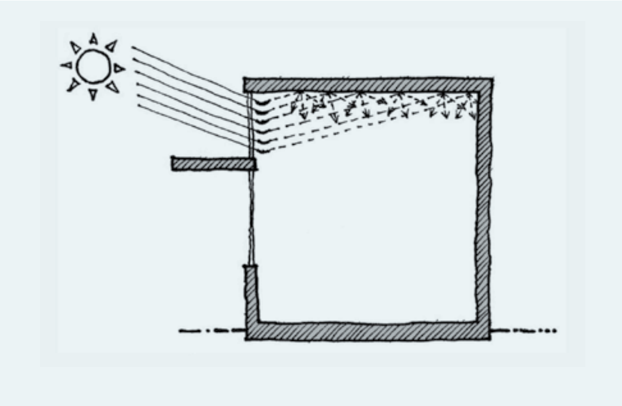
The effectiveness of natural lighting with the light shelf can be increased appropriately by curving the surface hit by sun's rays (Fig. 3.6-13). The characteristics of the upper surface of the light shelf determine its effectiveness, both in this and in all other configurations. The surface must be white or reflective, and periodic maintenance is necessary to avoid losing its features.

Tips on using the light shelf

The use of light shelves should be considered as they improve the distribution of the illumination and reduce glare, bearing in mind that not only are they useful for natural lighting, but they also serve as sunscreens.

The glass used in the ribbon above the shelf should be clear.

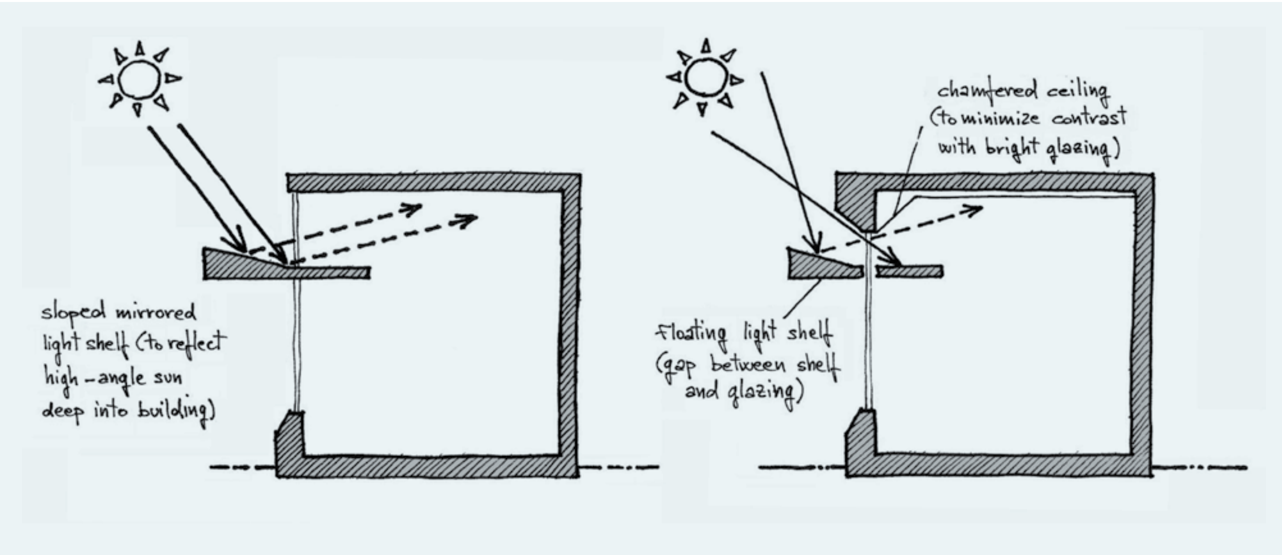
FIGURE 3.6-12 **REFLECTING BLADES INSTEAD OF INTERNAL LIGHT SHELF**



Light shelves and louvres may be opaque or translucent. If opaque light shelves are not combined with a lower view window, there may be a dark space on the wall directly under them. To address this problem, leave a gap between the light shelf and the wall. Translucent shelves provide a soft light below them but must be designed carefully so that occupants with a view of their underside are not bothered by glare.

After an initial preliminary design it is advisable to optimize the light shelf using simulation models, which is the only way to predict their effect and performance with reasonable accuracy.

FIGURE 3.6-13 **LIGHT SHELF WITH PROFILED SURFACE**



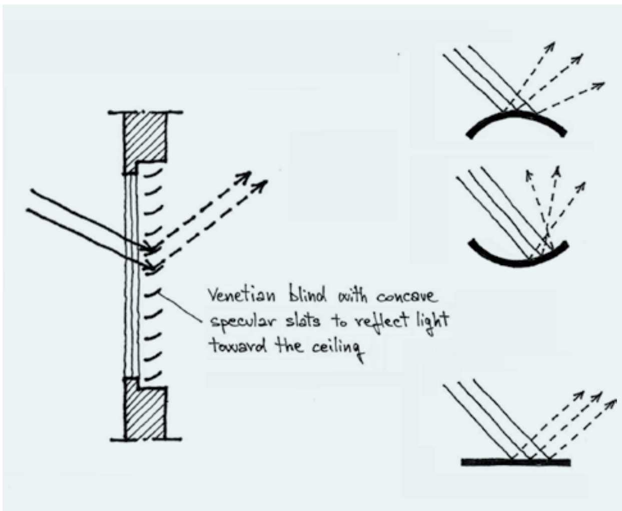
3.6.2.2 **VENETIAN BLINDS WITH REFLECTIVE SLATS**

Venetian blinds are a classic system for controlling sunlight, but they can also be used to redirect it. In some cases, the slats have sophisticated shapes and surface finishes.

The slats may be flat or curved (Fig. 3.6-14), and can be placed outside, inside or in the cavity of double glass (not recommended, since they become very hot and re-radiate towards the inner pane, which warms up). In any of these positions, they must be reflective in order to redirect light.

There are several types of slats that are able to redirect light: fixed or mobile, solid or micro perforated. The simplest system is the classic Venetian blind, whose slats are reflective on the upper surface; when the inclination is adjusted according to the position of the sun, they reflect the rays onto the ceiling (light-coloured) obtaining a diffuse illumination. Slats perforated with small holes,

FIGURE 3.6-14 **VENETIANS WITH REFLECTIVE BLADES TO REDIRECT THE LIGHT**



permit a reasonable level of inside illumination,and some view outside, even if they are completely shut (Fig. 3.6-15).

3.6.2.3 **SYSTEMS WITH ANIDOLIC CEILINGS**

Systems with anidolic ceilings are based on non-imaging optics and take advantage of the optical properties of CPC (Compound Parabolic Concentrator) to collect the diffuse light from the sky and convey it to the less illuminated area part of the room (Fig. 3.6-16). Outside the building an optical anidolic concentrator captures and focuses the scattered light coming from the highest part of the sky, which is the brightest on overcast days; a light pipe arranged in the ceiling, carries the light into the back of the room. Corresponding with the outlet of the pipe in the back of the room, a parabolic reflector distributes light into the lower parts of the room. On a clear day, the penetration of direct sunlight can be controlled by a roller blind that unfolds above the outer glass of the opening.

FIGURE 3.6-15 **ADJUSTABLE REFLECTIVE PERFORATED SLATS**

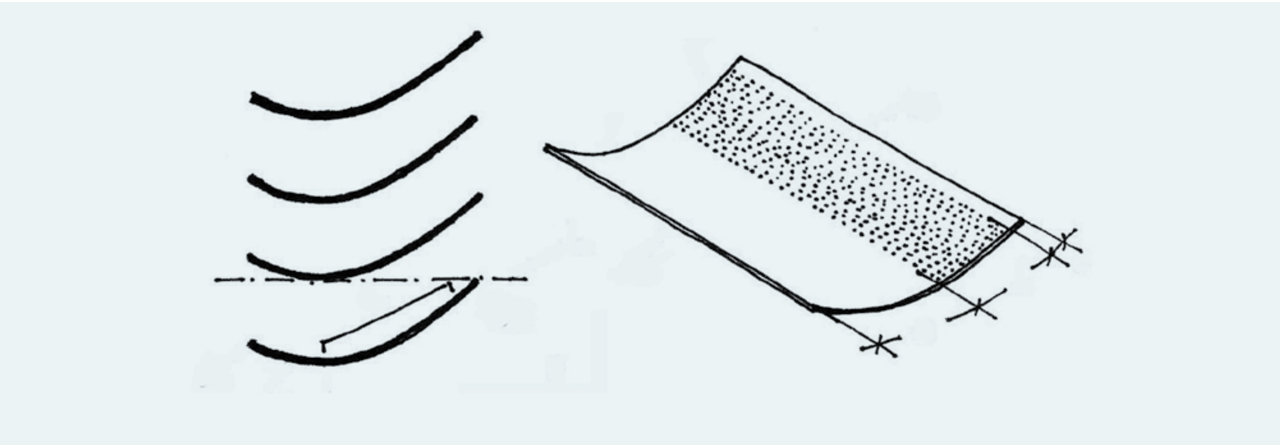
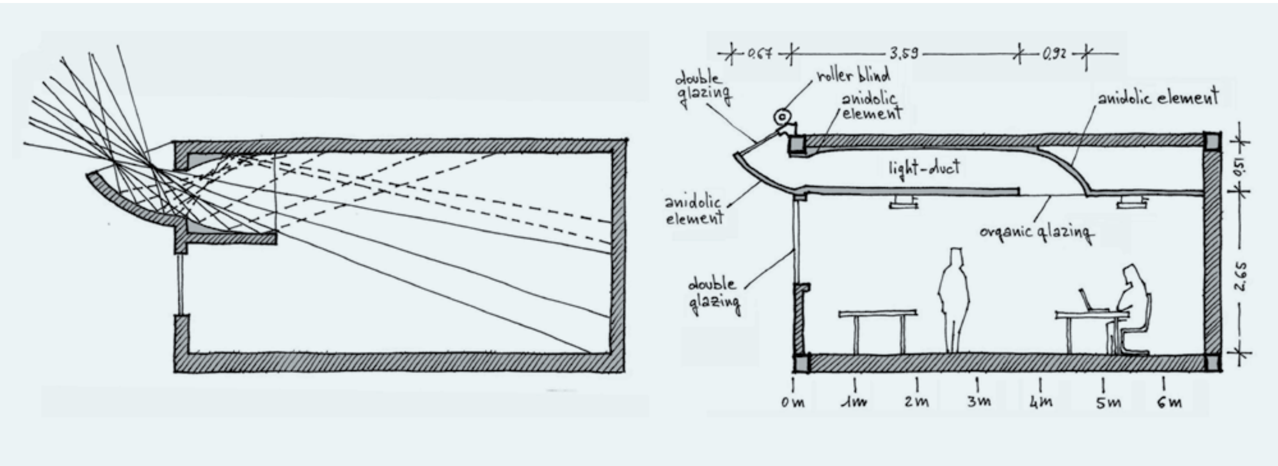


FIGURE 3.6-16 **ANIDOLIC SYSTEM**



3.7 SHADING

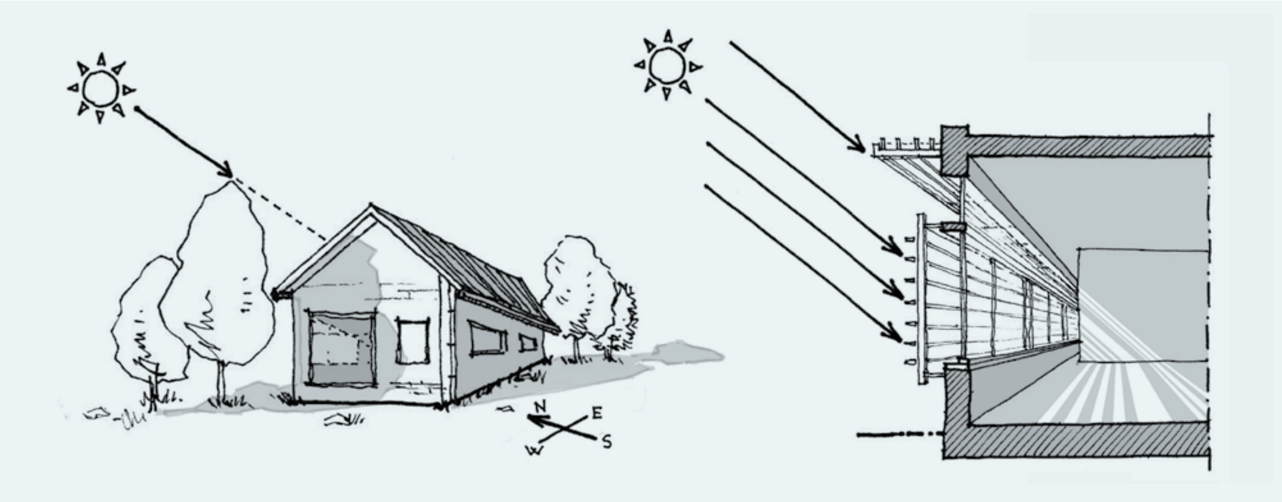
In a space, whether it is air-conditioned or not, the goal is to control direct solar radiation to ensure thermal comfort, light and minimization of energy consumption.

The ideal sun-shading device will block solar radiation while allowing daylight and breeze to enter the window, and an external view.

Shading is related primarily to the direct component of radiation, while the diffuse and reflected components (unless the latter is mirrored), which propagate in an almost isotropic way, are much less involved.

Shading may be unintentional or independent from the design choices, or it can be especially designed to control the flow of solar energy into a building. In the first case, the main cause of shading is the profile of the orographic context and the presence of shading elements such as trees, buildings, etc. In the second case, specific elements and components are used, such as overhangs, shading, etc. (Fig. 3.7-1).

FIGURE 3.7-1 **SHADOWS CAST BY THE CONTEXT AND BY ELEMENTS OF THE BUILDING**



There are many methods for evaluating the shadows cast on a surface by projecting elements or by surrounding obstructions, based on the use of diagrams or on analytical tools.

3.7.1 SUNDIAL

The horizontal sundial is a chart showing, in analogy with charts of the solar path, the paths of the shadow of a peg (also called a gnomon) at different times of selected days of the year (Fig. 3.7-2). A specific sundial corresponds to each latitude.

The sundial method is very quick and easy to use. In order to apply it a scale model of the building and of the surroundings is needed (Fig. 3.7-3).

The procedure is as follows:

- mount the model of the building on a movable support plan with 2 axes;
- place the sundial next to the model, with north on the sundial corresponding to north on the model;
- mount a peg of the size indicated (the gnomon) at the cross marker;
- put the model in the sun, so that is hit by direct radiation;
- adjust the inclination and orientation of the plane and the model so that the end of the peg's shadow marks the time and the month you want to look at;
- the shadow and sun penetration in the model simulate the actual conditions in the building for that time and day.

Note that, if there is no sun available, a lamp with a projector can be used. It should be placed at the maximum possible distance from the table, to reduce the error due to the fact that the light rays are not parallel.

FIGURE 3.7-2 **PEG'S SHADOW CAST ON A SUNDIAL**

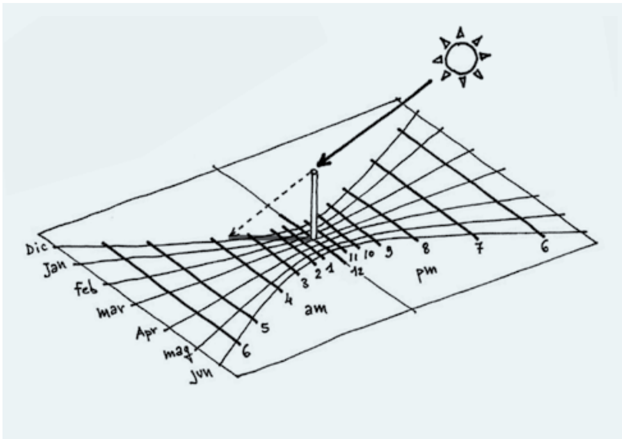
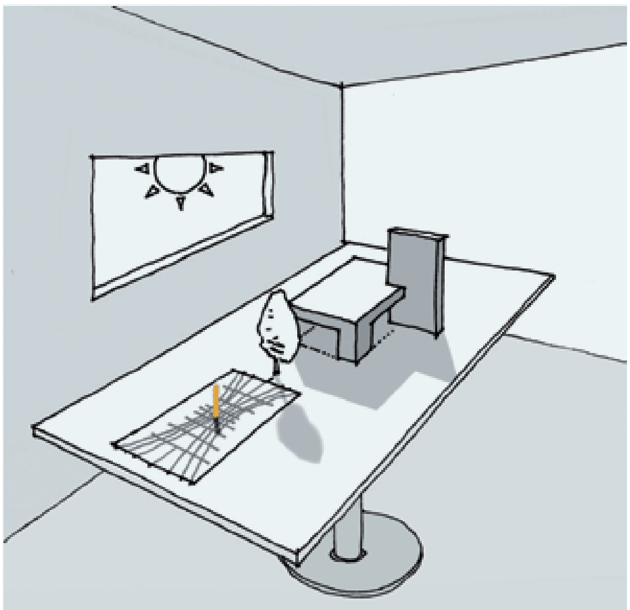


FIGURE 3.7-3 **EXAMPLE OF APPLICATION OF SUNDIAL METHOD**



Furthermore, if you have a camera with a telephoto lens you can frame the model with the table so oriented that you can see the tip of the gnomon touch the desired hour and month. The resulting picture corresponds to a "view from sun," in which the hidden surfaces are those shaded.

Finally, the sundial can also be used to estimate shadows by analogy. As explained, the chart shows the length and angular position of the gnomon's shadow in different hours and days of the year. Calculating the ratio of the height of the gnomon to that of the shading element being analysed, it is possible to estimate the shade projected by any point of the context at any time (Fig. 3.7-4).

3.7.2 SHADING MASKS

Solar path diagrams can be used for studying the shading related to a particular site during the year, and for drawing the profile of the sun obstructions due to the surroundings (mountains, houses, trees), using the same angular coordinates that are used to describe the position of the sun. For example, when the ideal line is drawn from a treetop to the observer, the two angles α' and β' can be identified (Fig. 3.7-5), and thus the whole profile of the obstruction can be determined.

FIGURE 3.7-4 **EVALUATION OF SHADOWS CAST BY OBJECTS USING THE SUNDIAL**

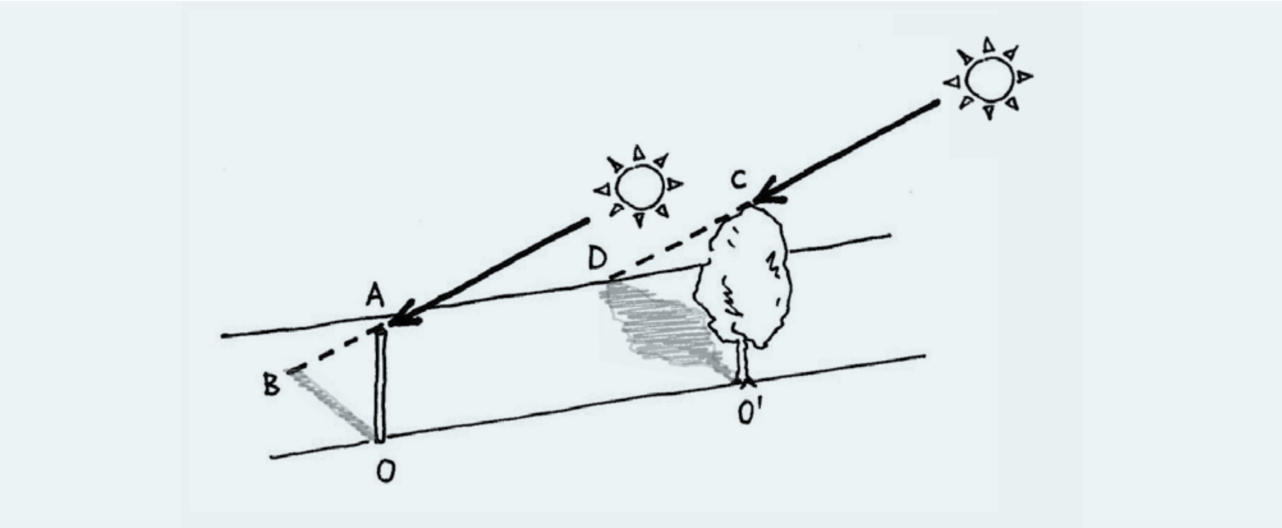


FIGURE 3.7-5 **ANGULAR COORDINATES OF A SHADING OBSTRUCTION**

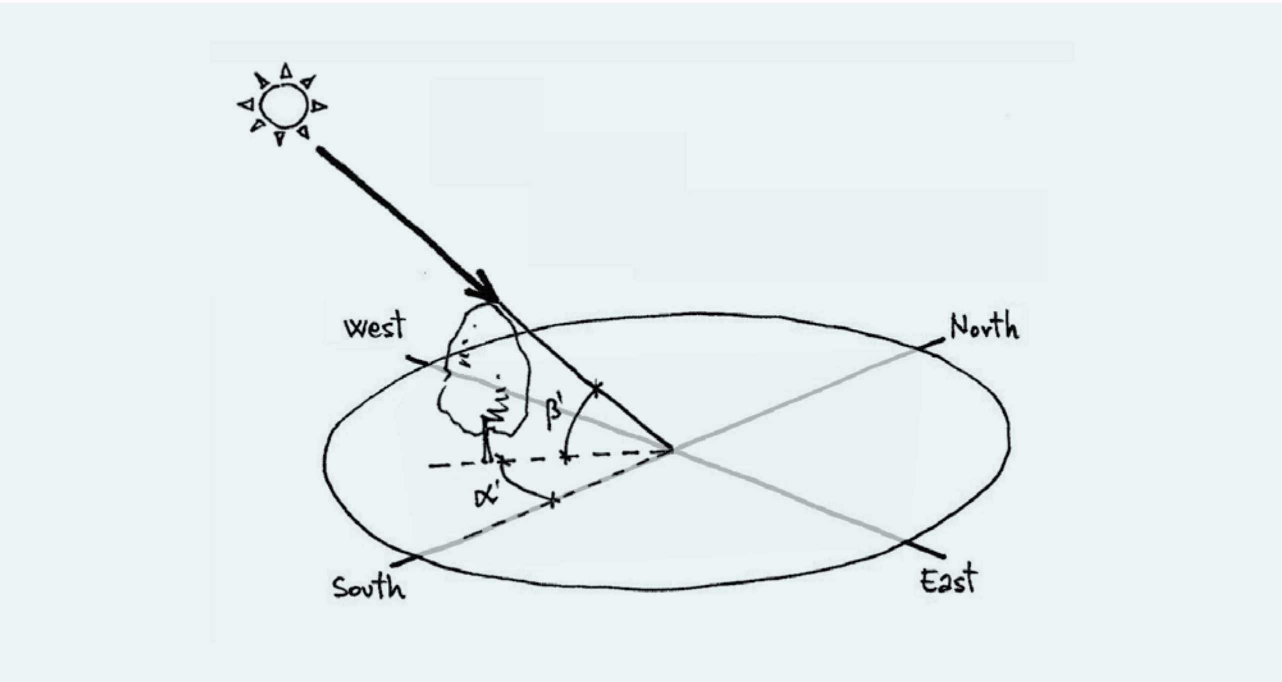
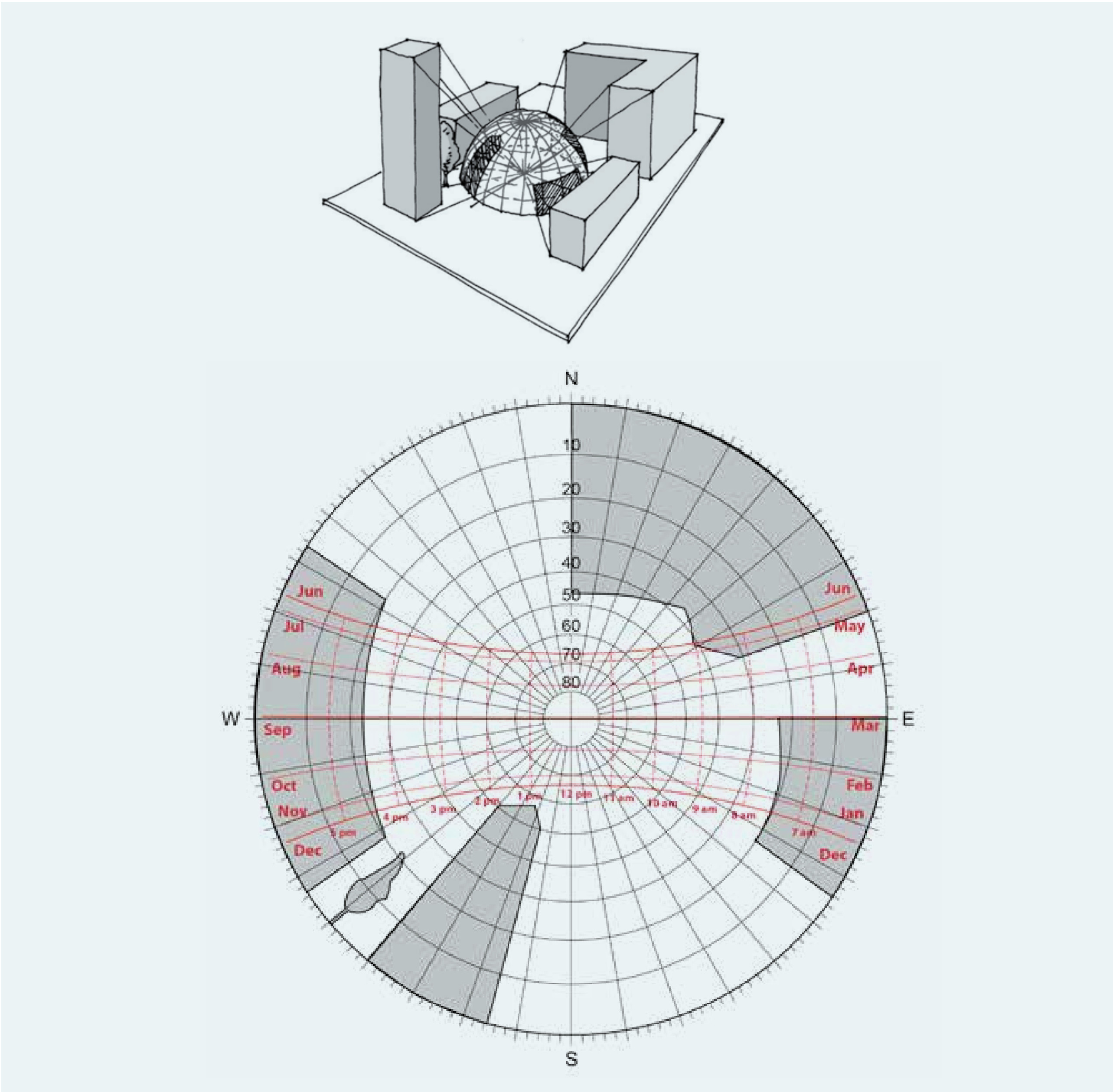


FIGURE 3.7-6 **SHADING OBSTRUCTIONS PROFILES ON THE POLAR DIAGRAM**



In this way it is possible to obtain the so-called shading masks by tracing the profile of the obstructions on the polar diagram. When the solar path falls within the area of the solar obstructions , that is, inside the mask, the observer is shaded (Fig. 3.7-6).

The solar shading protractor was developed (Fig. 3.7-7) to enable us to study the effects of sunshades, overhangs and fins on the façades of buildings.

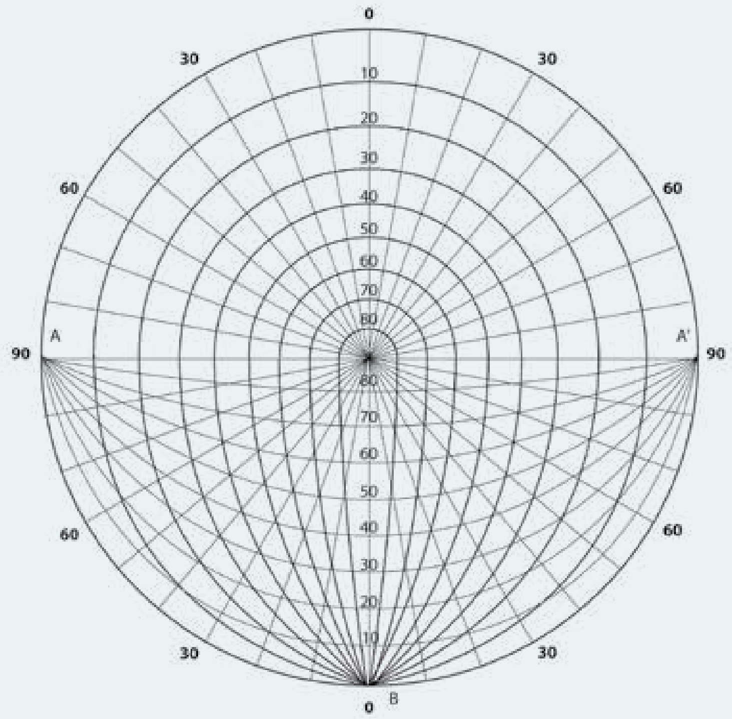
The shading protractor has the same dimensions as the polar diagram which will overlay it. It shows the shading effects caused by vertical and horizontal overhangs, viewed from a specific point, which must coincide with the centre of the chart.

In order to use the diagram, the vertical lower semi-axis (from the centre to point B) must be overlaid onto the line perpendicular to the façade drawn in plan at the point being considered. Furthermore, the diameter A-A′ must be aligned with the profile of the façade.

The semicircle in the upper part of the diagram is divided into concentric circles and radial lines, just like the polar diagram.

The part of the diagram of practical interest is, however, the lower semicircle, which represents half of the sky dome - the other half being perfectly symmetrical - and on which one can trace the profiles of the overhangs, as described below.

FIGURE 3.7-7 **SOLAR SHADING PROTRACTOR**



- The pseudo-horizontal curved lines represent the influence of shadows created by overhangs which have horizontal edges parallel to the façade, and are drawn by calculating the angle ε. This is the angle lying in a vertical plane orthogonal to the façade, formed by the horizontal line passing through the analysis point P and the line joining this point with the outer edge of the horizontal overhang (Fig. 3.7-8a). The corresponding values can be read on the vertical lower semi-axis of the diagram (from the centre to the point B in Fig. 3.7-7). For example, if ε = 60°, the corresponding pseudo-horizontal curved line scaled 60° will be used, as in Fig. 3.7-8.

- The pseudo-vertical curved lines, which are the extensions of the concentric semicircles contained in the upper half of the diagram and converge at point B, take into account both the influence of shadows created by horizontal overhangs with edges perpendicular to the façade, and the influence of the upper limits of vertical overhangs. These lines are identified through the calculation of the angle σ, lying in the plane of the façade and formed by the horizontal line passing through point P and the line joining P with the terminal point of a horizontal overhang (Fig. 3.7-8b) or with the upper limit of a vertical overhang (Fig. 3.7-9b). The values of σ are readable on the upper vertical semiaxis in correspondence of its intersection with the semicircles (Fig. 3.7-7). For example, if σ = 40°, the corresponding pseudo-vertical line connected to the 40° semicircle in the upper part of the diagram will be used, as in figures 3.7-8 and 3.7-9.

- The radial lines that branch out from the centre in the bottom half of the diagram represent the influence of shadows generated by vertical overhangs. These lines indicate the value of the angle ω, which lies in the horizontal plane orthogonal to the façade and is formed by the horizontal line passing through the point P and the line joining this point with the outer edge of a horizontal overhang (Fig. 3.7-9a). The values of ω are readable on the external circumference of the diagram and are symmetric with respect to B (Fig. 3.7-7). For example, if ω = 50°, the corresponding radial line marked 50° in the lower left part of the diagram will be used, as in figure 3.7-9.

Figure 3.7-8 shows an example of the calculation of the angles ε and σ for a horizontal overhang, and the display of the overhang on the diagram (considering its lateral extension to be symmetric to point P).

Similarly, figure 3.7-9 shows an example of the calculation of the angles ω and σ for a vertical overhang, and the related display of the obstruction on the diagram.

Finally, for a better understanding of the shading mask, figure Fig. 3.7-10 illustrates the construction lines related to the angles ε, σ and ω.

FIGURE 3.7-8 **CONSTRUCTION OF THE SHADING MASK FOR A HORIZONTAL OVERHANG**

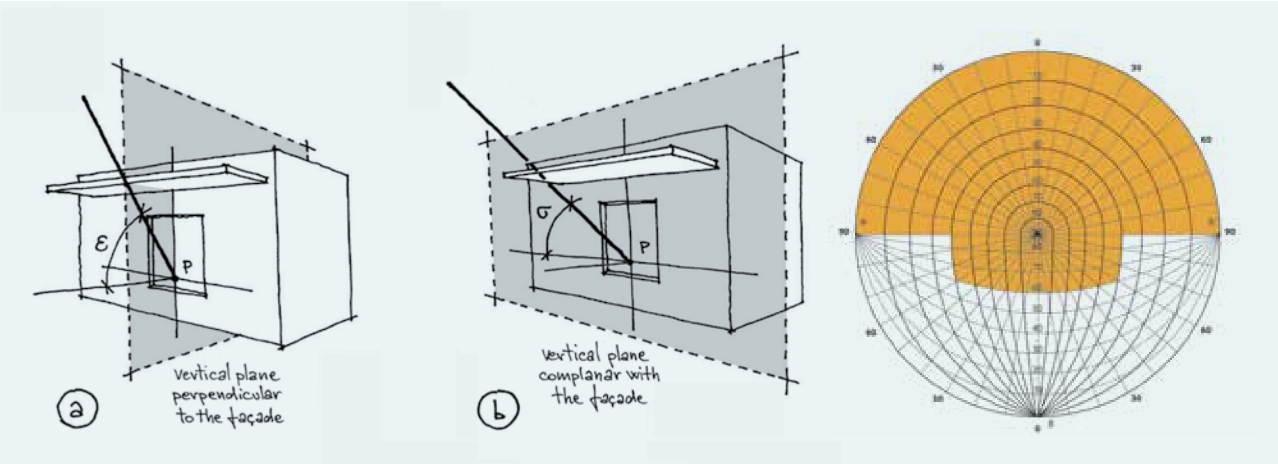
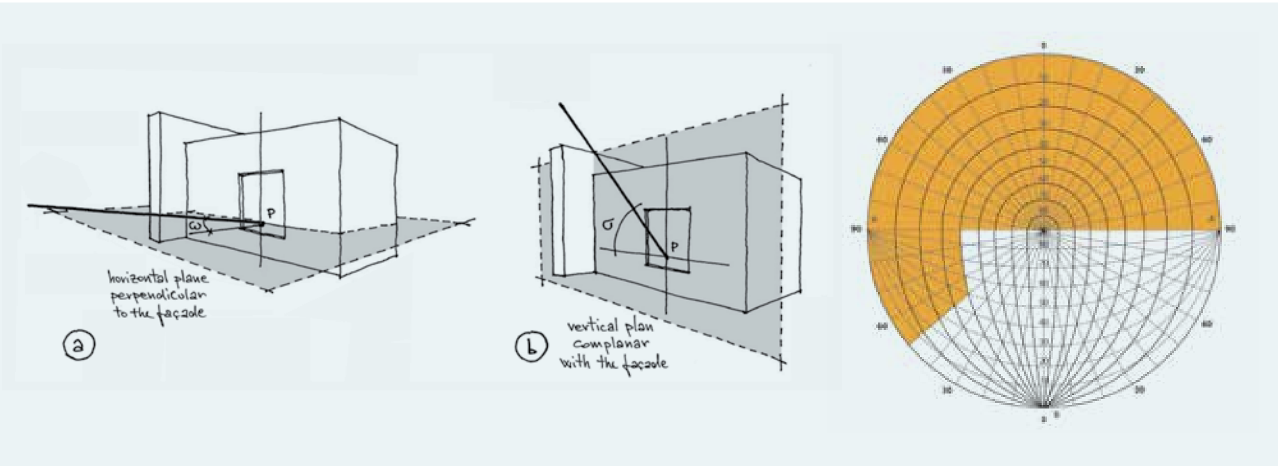


FIGURE 3.7-9 **CONSTRUCTION OF THE SHADING MASK FOR A VERTICAL OVERHANG**



The hatched areas of the diagram represent the portions of the sky dome obstructed by the shading elements (the upper semicircle represents the obstruction of the building to which the façade belongs). When the masks obtained on the solar chart of the site are overlaid, the times of day when the observation point is shaded can be found (Fig. 3.7-11).

For example, in correspondence to southern solar paths, the horizontal overhang in the left-hand chart in figure 3.7-11, always casts a shadow on the underlying window between 8:45 a.m and 3:15 p.m, while the vertical overhang drawn in the right-hand chart casts shadows from 2 p.m. onwards during the months of January, February, March, September, October, November and December.

In the previous examples, situations corresponding to façades oriented exactly south were shown. It is, of course, always possible to consider any other orientation by rotating the protractor and aligning the lower vertical semi-axis with the façade. For example, in the next picture (Fig. 3.7-12) a horizontal obstruction on a south-west façade is displayed.

Note that in this case, the underlying window is always shaded during the morning hours, up to 2-3:30 p.m., depending on the month.

FIGURE 3.7-10 **CONSTRUCTION LINES OF ε, σ AND ω**

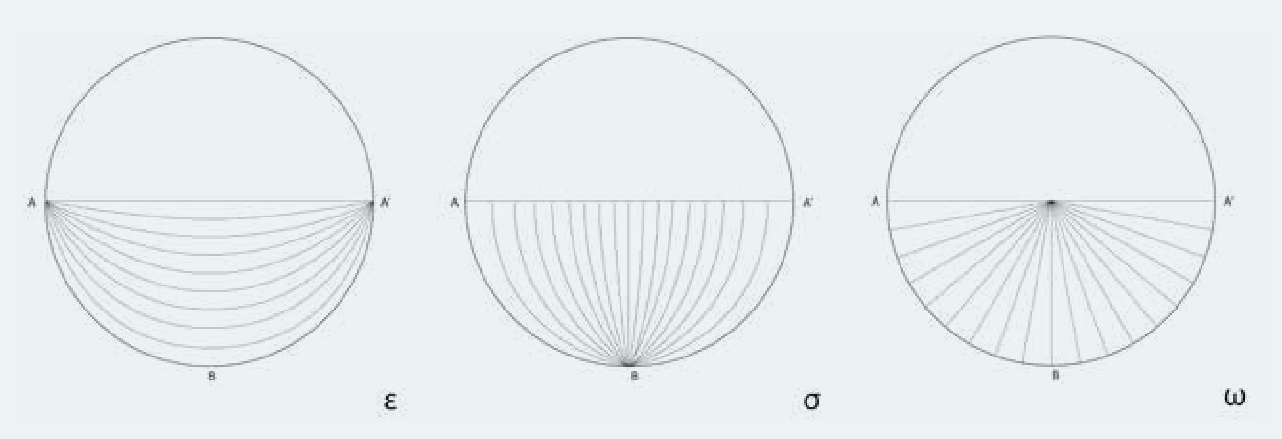


FIGURE 3.7-11 **OVERLAYING THE SHADING MASKS ON THE POLAR DIAGRAM**

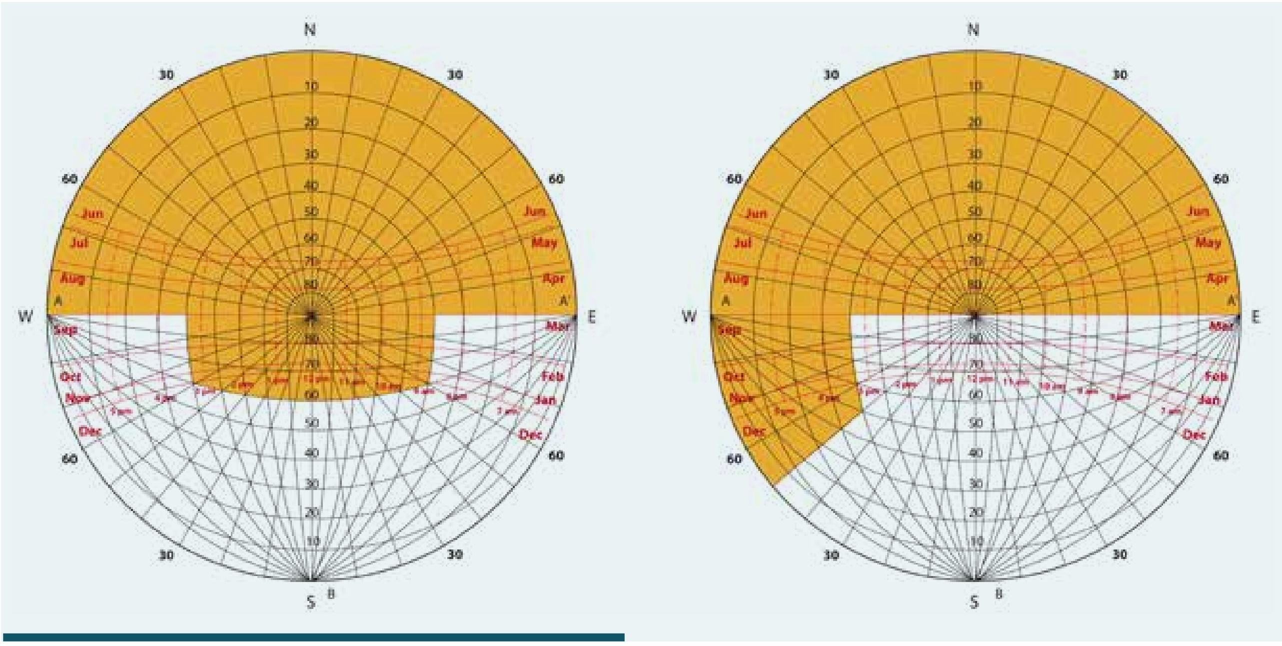
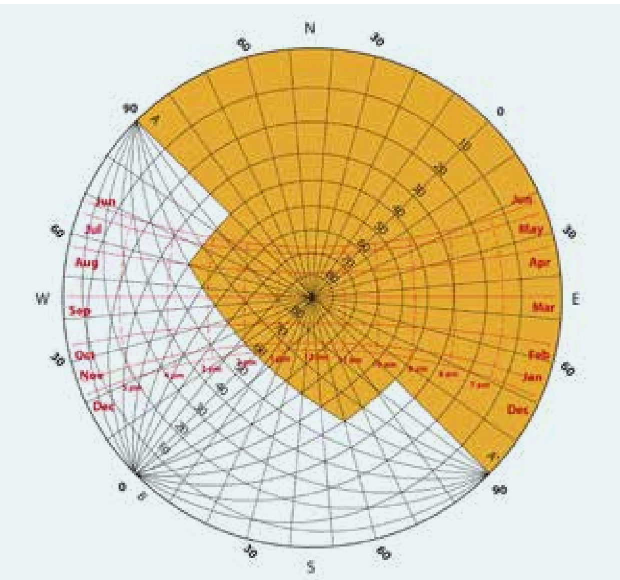


FIGURE 3.7-12 **ORIENTATION OF THE SHADING MASK**



Note that it is possible to combine the coincident effects of vertical and horizontal obstructions, by reading on the same diagram the relative values of ε, σ and ω, as shown in figure 3.7-13.

Finally, it should be noted that it is the angular geometry, and not the actual physical size, which determine the mask generated by the obstruction. For example, a single large horizontal overhang or a series of horizontal blades, with the same overall angle of obstruction, generate the same mask (Fig. 3.7-14).

FIGURE 3.7-13 **SAMPLE OF SHADING MASK FOR A VERTICAL AND HORIZONTAL OVERHANG**

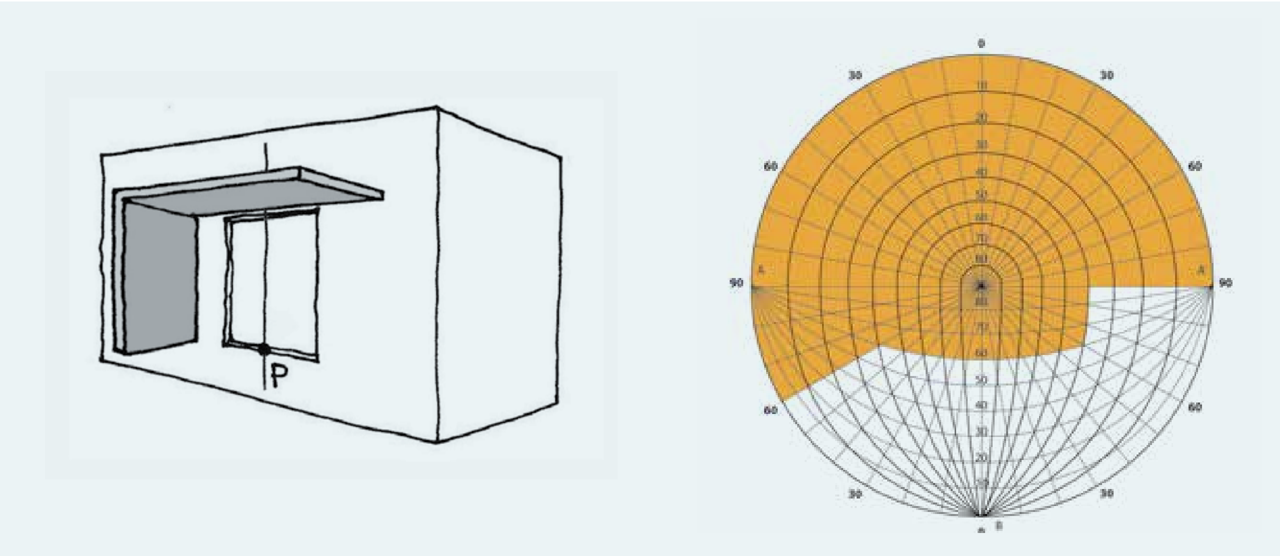
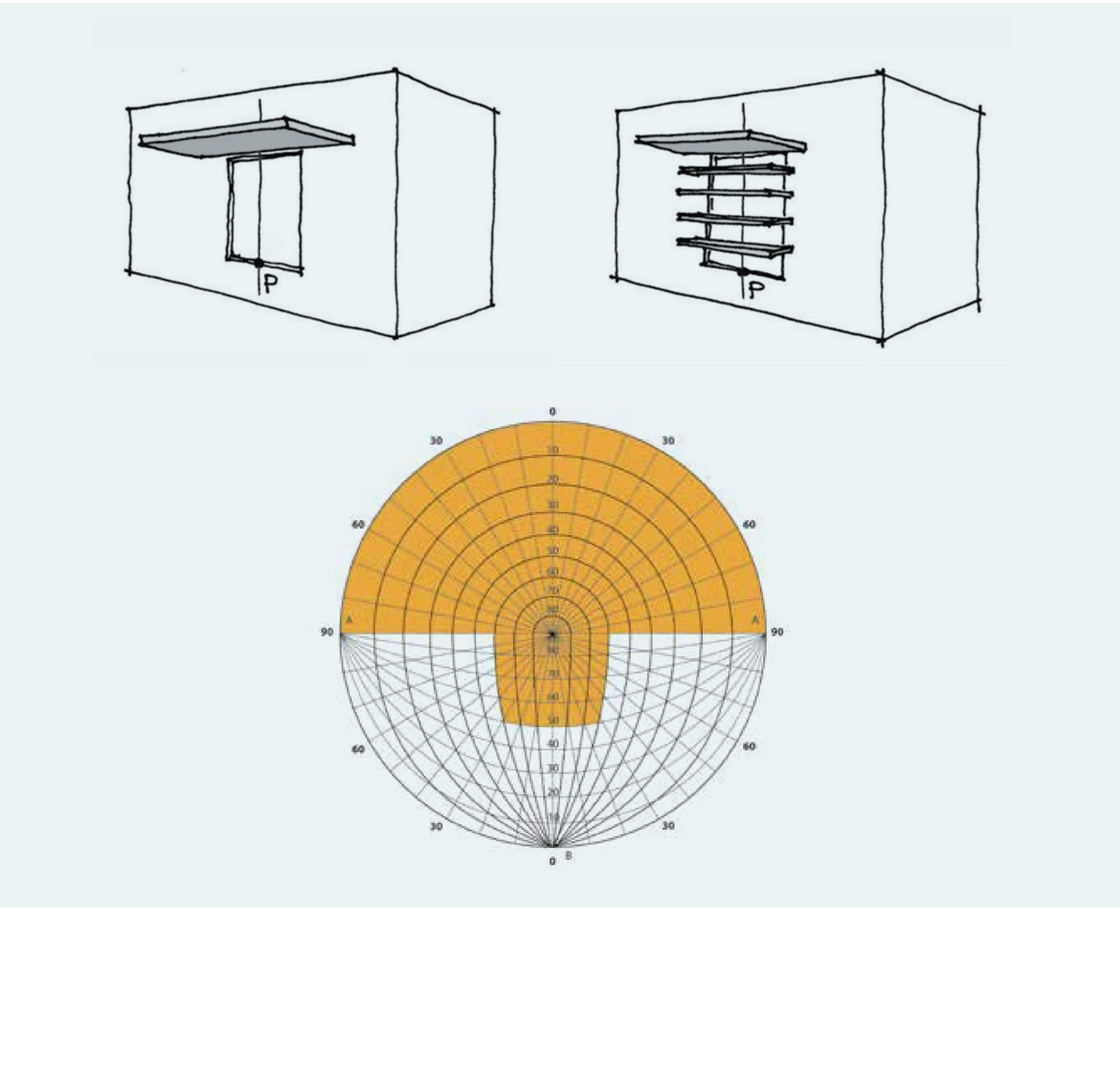


FIGURE 3.7-14 **THE SAME SHADING MASK COULD BE USED BOTH FOR A SINGLE OVERHANG AND FOR A SERIES OF BLADES**



3.7.3 OVERHANG SHADING CALCULATION

At the design stage it is often necessary to correctly define the dimensions of the shading overhangs in order to achieve the required effect where and when it is considered useful. The problem, in a simplified way, can be reduced to the calculation of the depth D of the vertical or horizontal overhang, as illustrated in figure 3.7-15.

In the case of horizontal overhangs, once the height h of the shadow to be obtained corresponding to a given position of the sun has been defined, the following formula can be used:

$$D = h\frac{\cos(\alpha - \gamma)}{\tan\beta} \qquad (3.7\text{-}1)$$

where the numerator of the fraction must always be considered positive and γ represents the surface azimuth of the shaded plane, previously introduced .

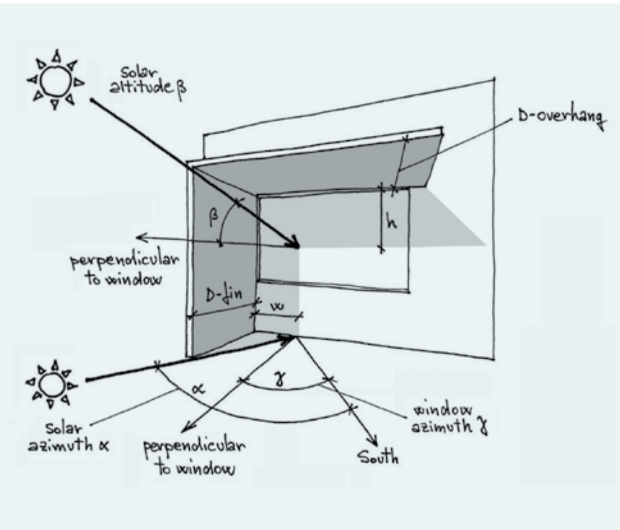
Similarly, for vertical overhangs (or fins), once the width w of the desired shadow has been determined, one can use the expression:

$$D = \frac{w}{|\tan(\alpha - \gamma)|} \qquad (3.7\text{-}2)$$

where the denominator of the fraction must always be considered positive.

If, instead, the purpose is to analyse the shading effects of overhangs of predetermined dimensions, the same equations can be used for testing purposes, by inserting the known values of D, α and γ, and resolving them in respect to the parameters h and w.

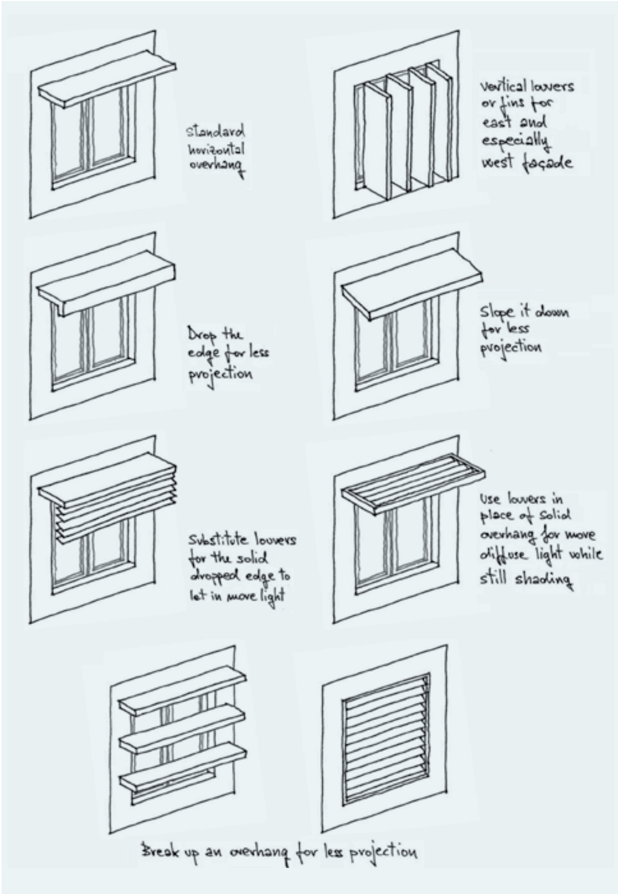
FIGURE 3.7-15 **CALCULATION SCHEME FOR VERTICAL AND HORIZONTAL OVERHANGS**



3.7.4 SHADING DEVICES

Solar gains are controlled most effectively with sunshades outside the windows (Fig. 3.7-16 and Table 3.7-1). As the sun is always high in the sky at the equator, horizontal shading devices are the optimal choice for north and south-facing façades. Horizontal overhangs located above the windows on the north and south-facing façades are very effective and should extend beyond the width of the window to shade it properly. Horizontal overhangs on the east and west-facing windows need to be very deep for protection in the early morning and in the late afternoon, and are not recommended.

FIGURE 3.7-16 **SOLAR PROTECTION TYPES**



East and west-facing façades are harder to protect than those facing north and south, because of the low position of the sun in the morning and afternoon. Vertical fins, which are usually recommended for east and west orientations at latitudes above 40°, are less suitable in the tropics, because they need to be tilted in order to give effective protection ,and so preclude the exterior view.

An appropriate shading device for east and west orientations is the egg-crate type.

TABLE 3.7-1 **CHARACTERISTICS OF DIFFERENT TYPES OF SHADING DEVICES**

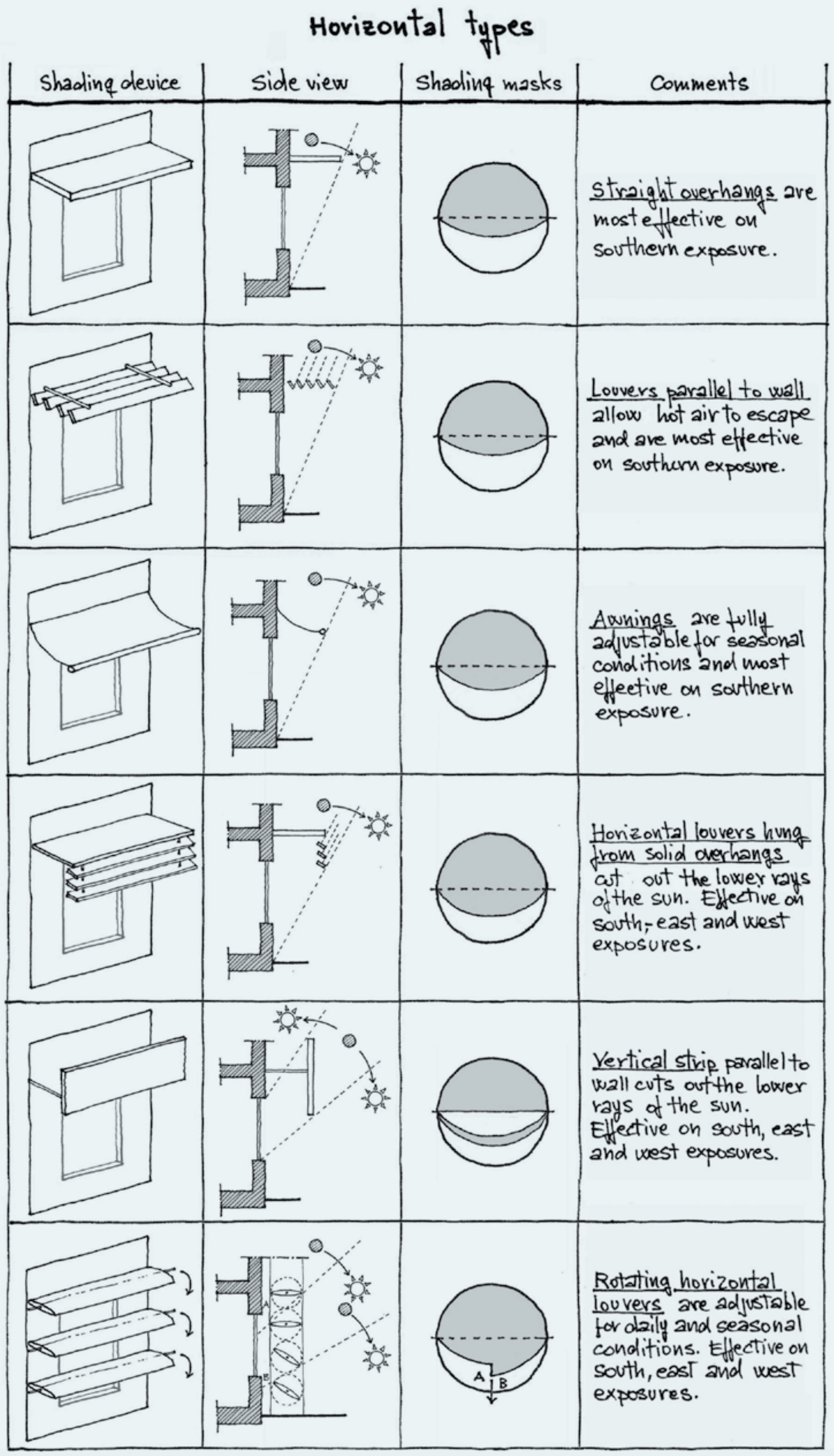
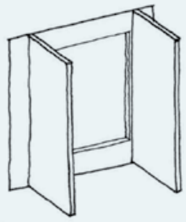
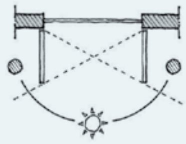
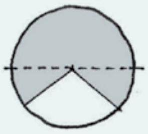
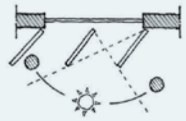
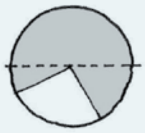
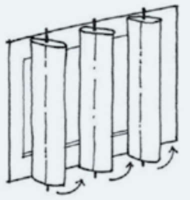
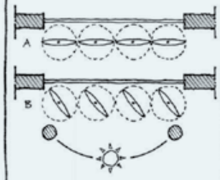
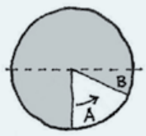
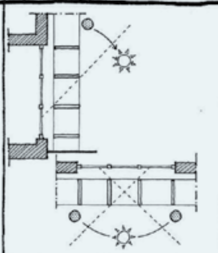
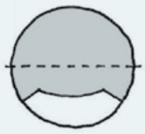
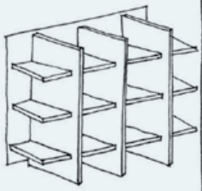
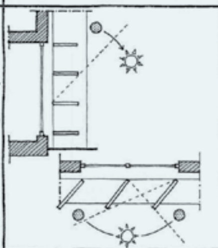
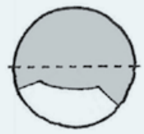
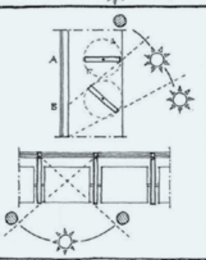
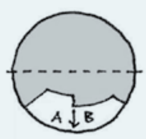


TABLE 3.7-1 **(CONTINUED) – CHARACTERISTICS OF DIFFERENT TYPES OF SHADING DEVICES**

Vertical types

Shading device	Plan view	Shading masks	Comments
			Vertical fins are most effective on the near-east, near-west exposures.
			Slanted vertical fins are most effective on east and west exposures.
			Rotating vertical fins are the most flexible and adjustable for daily and seasonal conditions. Most effective on east and west exposures.

Eggcrate Types

Shading device	Plan & Side view	Shading masks	Comments
			Eggcrate types are combinations of horizontal and vertical types. Most effective in hot climates on east and west exposures.
			Eggcrate with slanted vertical fins (slant toward north). Most effective in hot climates on east and west exposures.
			Eggcrate with rotating horizontal louvers. Most effective in hot climates on east and west exposures.

Shading systems can be fixed or movable:

- **Fixed systems:** fixed systems are generally placed externally, in order to intercept the incident solar radiation before it strikes the glazed surfaces or other openings, dissipating the absorbed energy into the outside air;
- they include structural elements such as balconies and overhangs, but also non-structural elements such as awnings, louvres and blinds;
- each façade requires specific treatment: each orientation has to be evaluated separately;
- the tilt angle has to take into account the direction of the solar rays hitting each façade at different times of day.
- **Movable systems:** movable shading systems "react" in a more suitable way to sun movement, as compared to fixed systems;
- they include systems such as deciduous vegetation, roller blinds, perforated slats, Venetian blinds, curtains;
- each façade requires specific treatment: each orientation has to be evaluated separately;
- the tilt angle can be regulated according to the solar rays hitting each façade at different times of day.

Shading devices can vary in size without changing their shading characteristics, as long as the ratio of the depth to the spacing of elements remains constant, as shown in figure 3.7-17. The same applies to vertical fins and egg-crate types (Fig. 3.7-18).

FIGURE 3.7-17 **SINGLE OR MULTIPLE HORIZONTAL SOLAR PROTECTION OF A WINDOW (SECTION). THE SHADING EFFECT IS A FUNCTION OF THE ANGLE α. IT IS NOT A FUNCTION OF THE ACTUAL SIZE**

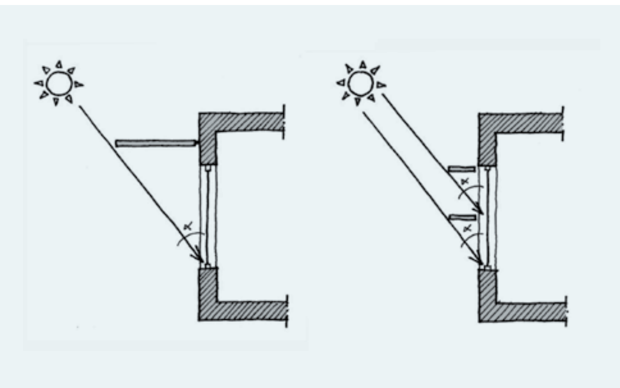
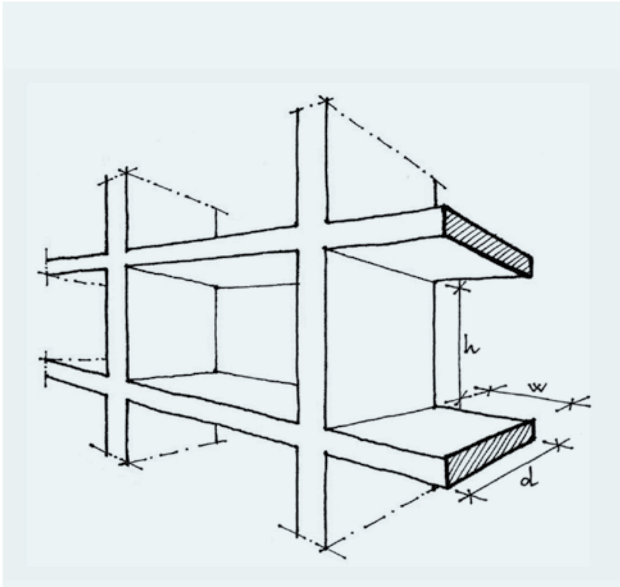


FIGURE 3.7-18 **THE SHADING EFFECT IS A FUNCTION OF THE RATIOS *h/d* AND *w/d*. IT IS NOT A FUNCTION OF THE ACTUAL SIZE**



3.7.5 RECOMMENDATIONS

- Use external shading systems whenever possible; they are much more effective than interior shading systems at controlling solar gains, especially if the space is artificially cooled.
- Use horizontal elements for openings facing south and north.
- Use egg-crate elements on windows facing east and west.
- Prioritize shading of windows facing east and – especially – west.
- The colour of the sunshades affects light and heat. External solar protection systems should be light if you want the diffuse solar radiation to be transmitted and dark if you want to block the light.
- Choose the materials the shading devices are made of and their surface properties carefully; they should have high thermal resistance because, being heated by solar radiation, they became hot and re-radiate towards the interior space.
- Use fixed systems if the budget is limited. Using mobile systems in order to allow a more efficient use of natural light and natural ventilation. Take into consideration the fact that the ideal exterior shading device should not hinder natural ventilation, should provide security against intrusions, and should allow natural ventilation at night, when required.

3.8 NATURAL COOLING

To cool the air without making use of a refrigerating machine some "natural" technical solutions are available, which were sometimes adopted in the past.

Natural air cooling systems are usually subdivided into two categories: those based on the adiabatic humidification process and those exploiting the low temperature of the subsoil (which is lower than air temperature in cold and temperate climates in summer). The latter is not suitable for hot-humid climates because the temperature of the subsoil, up to a depth of 3-4 m is very close to air temperature. In hot-arid climates, where the outdoor air temperature during daytime is higher than that of the subsoil, the system would only be effective for one-two weeks, which is the time taken for the soil around the buried pipes to warm up. To avoid this effect it would be necessary for the system to work during nighttime, when cooler outdoor air would cool down the subsoil around the pipes, but the effect would be to warm up the air entering the indoor spaces[27]. Alternatively, the evaporative cooling principle can be exploited, as shown in figure 3.8-1, where the underground soil is cooled by keeping it wet. The evaporation cools down the soil and the gravel or pebble layer protects it from solar radiation.

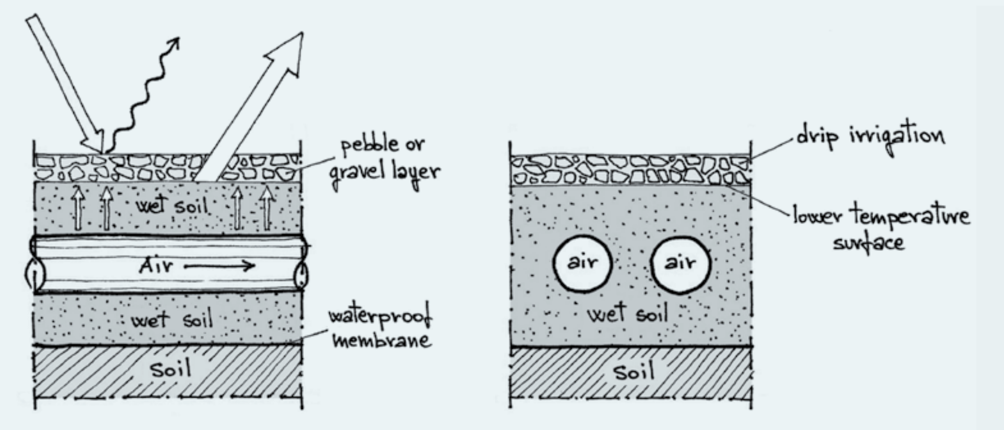
3.8.1 EVAPORATIVE COOLING

In hot-arid climates, the adiabatic humidification process (or evaporative cooling) is always effective. Spraying water into a stream of air cools and humidifies it (see Appendix 1 – Principles of Building Physics). In very hot, dry climates (or times of year) , this physical phenomenon can be used to improve environmental comfort. One way to take advantage of this physical principle and at the same time to facilitate good ventilation is shown in figure 3.8-2. Here the air cooled by adiabatic humidification "sinks" in the tower, and spreads into the space.

For a first approximation of the sizing of a downdraft evaporative cooling tower as in Fig. 3.8-2, the following procedure can be followed:

- Step 1 – From climatic data, find the design dry bulb temperature and coincident relative humidity for the site[28].
- Step 2 – On the psychrometric chart (see Appendix 1 – Principles of Building Physics) mark the point corresponding to the chosen design values (as in the example of figure 3.8-3, where the marked point corresponds to dry bulb temperature = 35 °C and relative humidity = 20%).

FIGURE 3.8-1 **SOIL TREATMENT WITH WETTED PEBBLES**



Source: *S. Alvarez Dominguez et al., Control climatico en espacios abiertos, Ciemat, 1992*

27 This is not in contradiction with the traditional use of underground living spaces in hot dry climates, since in that case comfort is achieved because of lower walls and floor temperature, i.e. mean radiant temperature (see Appendix 2 – Principles of Thermal and Visual Comfort), not because of lower air temperature.

28 Depending on the aim of the designer, the design temperature and humidity chosen can be those currently used for sizing air conditioning systems or according to the maximum mean values of the hottest month. In the latter case comfort conditions will not be provided in the hours in which temperature and humidity are above the mean maximum (not so many, however; for this reason the second approach is recommended).

FIGURE 3.8-2 **EVAPORATIVE COOLING. SUITABLE FOR HOT, DRY CLIMATES**

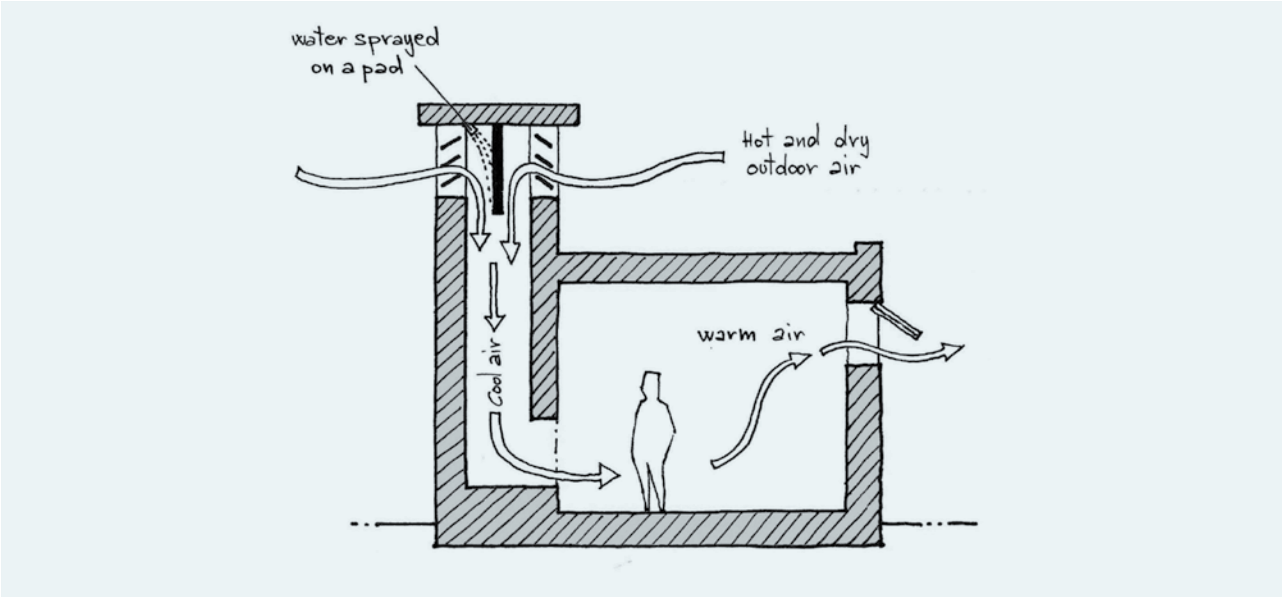
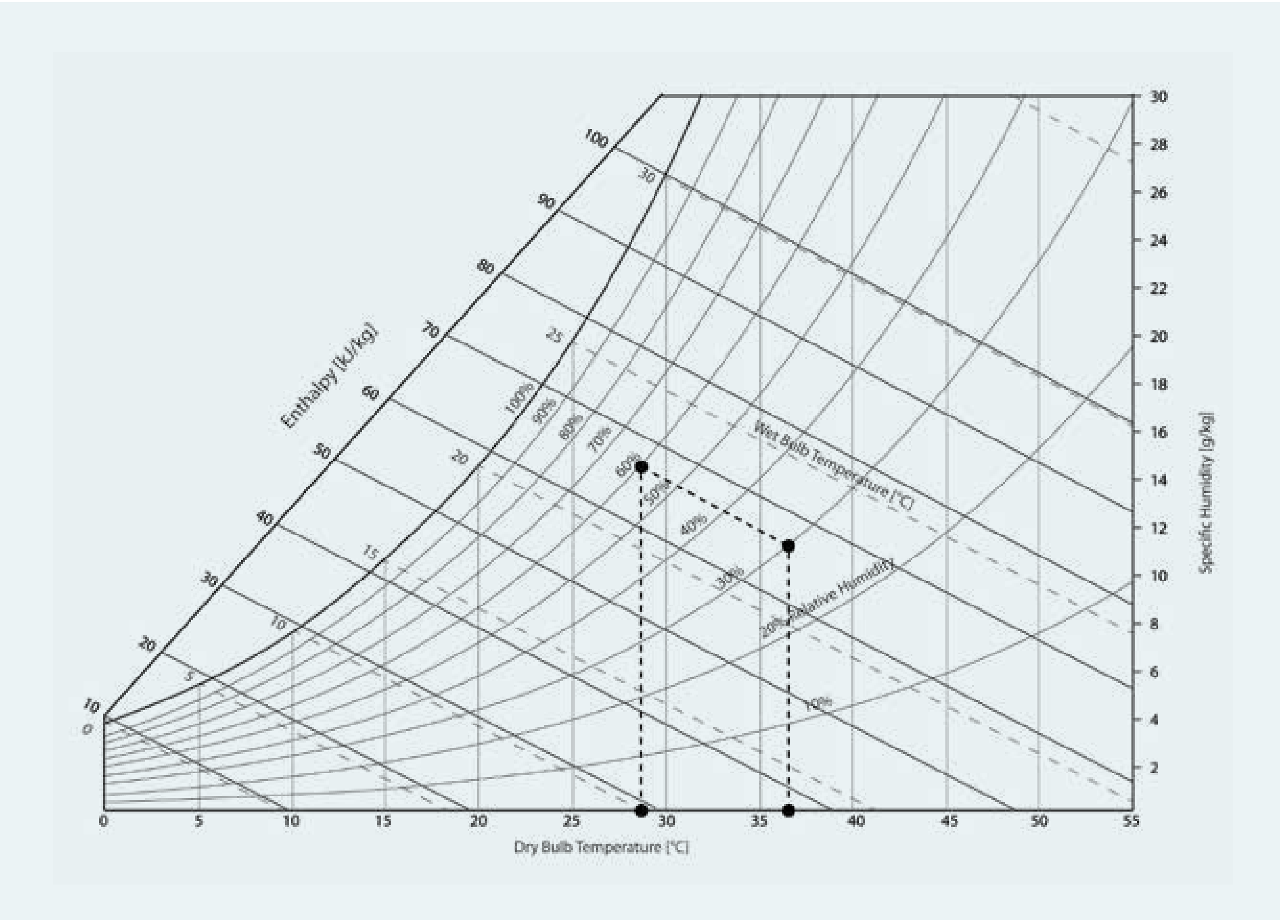


FIGURE 3.8-3 **EVALUATION OF OUTLET TEMPERATURE IN THE TOWER**



- Step 3 – Move along the line at constant enthalpy (see example figure 3.8-3) until the relative humidity curve 60% is reached, to take into account the fact that not all the air flow will be involved in the evaporative cooling process, (i.e. the effectiveness of the sprayed pad system).

- Step 4 – Find the dry bulb temperature after the adiabatic humidification (Fig. 3.8-3); the value found in the example is 22 °C.

- Step 5 – Calculate the airflow rate using the equation (3.5-2) given in paragraph 3.5 Natural Ventilation, Stack effect,using T_o = 22 + 273 = 295 K and T_i = 32 + 273 = 305 K as a first approximation (indoor temperature should be calculated iteratively using the room heat balance as indicated in Appendix 1 – Principles of Building physics) and H = distance between the centre of the pad and the centre of outlet.

The procedure assumes that the walls of the tower are insulated. If this is not the case, the cooling capacity will be less than that calculated. If there is wind, and the inlet is properly designed, the cooling tower also acts as a wind catcher, and the airflow is enhanced.

For optimal operation, the outlet openings should have a total area not less than that of the cross section of the tower, which in turn should be about half of the total area of the inlet openings.

Technological advancement has created more opportunities for control options on cooling towers, with the use of motorised dampers, variable water flow, various types of sensors and actuators managed by a computer.

There are several examples of cooling towers in modern buildings, such as the Zion National Park Visitor Center in Utah (USA) and the Council House 2 (CH2) in Melbourne, Australia.

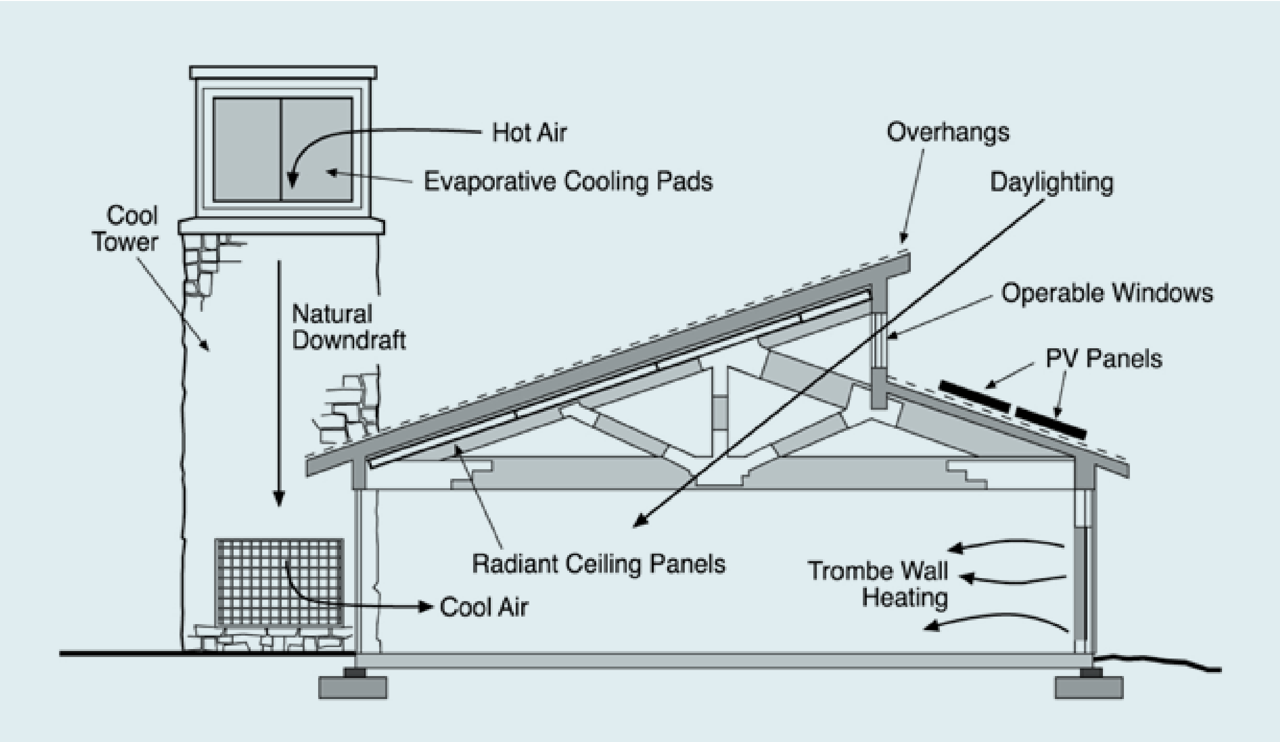
In the Zion National Park Visitor Center (Fig. 3.8-4) all cooling loads are met with natural ventilation using computer controlled clerestory windows, evaporative cooling from the cooling towers, and careful design of shading devices and daylighting apertures to minimize solar gains (Fig. 3.8-5). The only mechanical input to the cooling system is a pump to circulate water through the evaporative media.

In the CH2 building, the towers along the southern façade of the building cool air for intake and use in the ground floor (Fig. 3.8-6). The shower towers are made from tubes of lightweight fabric 1.4 metres in diameter. As the water falls within the tower, it sucks in air from above. This air falls down the tower, and is cooled by evaporation from the shower of water. The cool air is supplied to the retail spaces and the cool water pre-cools the water coming from the chilled ceiling panels.

In climates where the direct evaporation of water in an air stream would lead to too high a relative humidity, which would not be comfortable, indirect evaporative cooling can be used (Fig. 3.8-7). With this technique the air cooled and humidified by the process of adiabatic humidification is sent to a heat exchanger, which the ambient air to be cooled passes through (see paragraph 4.2.1 HVAC types and features).

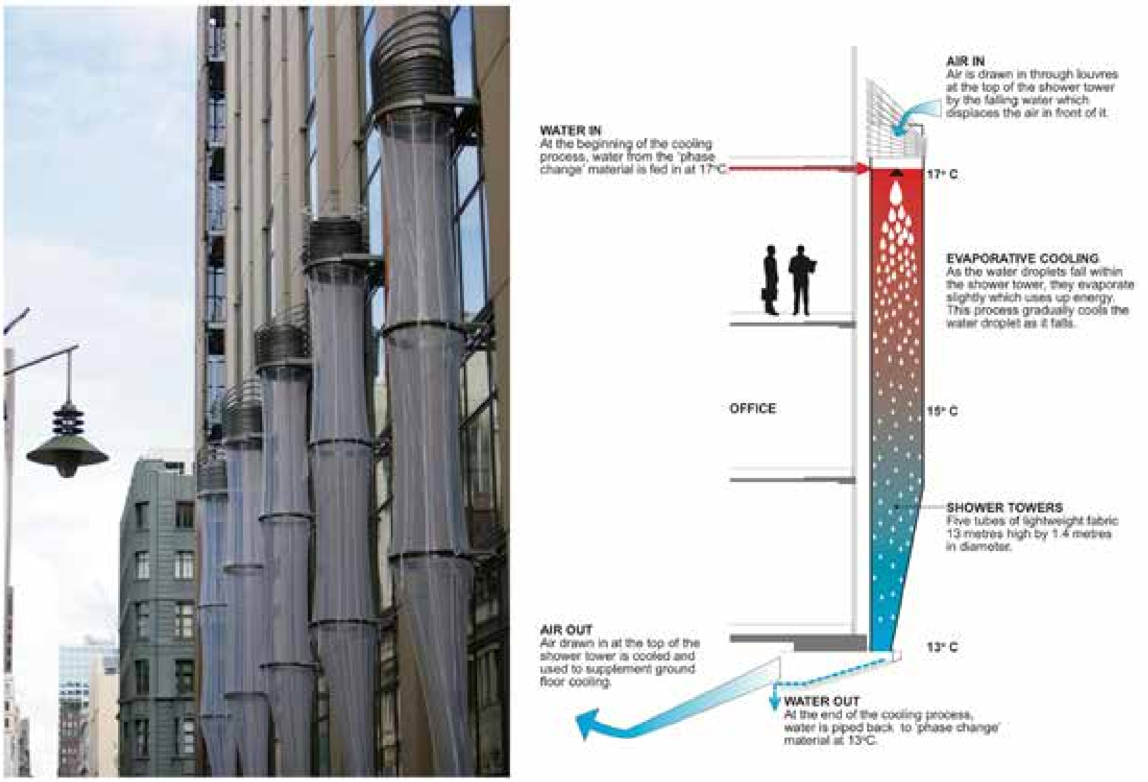
FIGURE 3.8-4 **ZION NATIONAL PARK VISITOR CENTER (LEFT) AND COOLING TOWER OUTLET (RIGHT)**

FIGURE 3.8-5 **CROSS SECTION OF THE BUILDING SHOWING INTEGRATED DESIGN STRATEGIES**



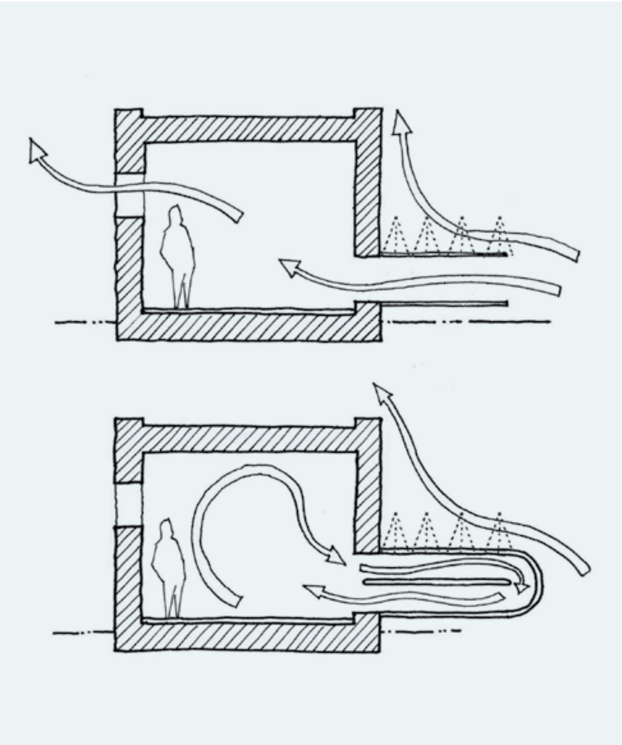
Source: *P. Torcellini, R. Judkoff, and S. Hayter, Zion National Park Visitor Center: Significant Energy Savings Achieved through a Whole-Building Design Process, proc. ACEEE, 2002*

FIGURE 3.8-6 **COUNCIL HOUSE 2 COOLING TOWERS**



Source: *http://www.melbourne.vic.gov.au/Sustainability/CH2/DesignDelivery/Documents/CH2_Snapshot6.pdf*

FIGURE 3.8-7 **PRINCIPLE OF INDIRECT EVAPORATIVE COOLING; A) OPEN CIRCUIT; B) CLOSED CIRCUIT**



3.8.2 CEILING FAN

In an urban environment, due to the noise of the external traffic, it is very often not possible to keep the windows open for natural ventilation. Consequently, even in those periods when the outside air temperature is such that, with adequate ventilation, the air conditioning should not be needed, it becomes necessary to use it. This is the case especially in workplaces where the internal loads due to equipment are significant or where it is not possible to adequately protect the interior space from solar gain.

In these cases, or in spaces with no air conditioning and where air movement is not sufficient, a ceiling fan can be used. Ceiling fans are also useful when used in conjunction with air conditioning, because the increase in air velocity means that the air temperature can be increased, with the same comfort level but lower energy consumption (see Appendix 2 - Principles of thermal and visual comfort). The simultaneous use of fans and air conditioning allows the temperature of the thermostat to be raised to 28° C instead of the usual 26° C, allowing an energy saving in the order of 15-20% with the same comfort level.

The air movement caused by the ceiling fan varies as a function of its position, power and rotation speed, as well as of the size of the blades and the number of fans present in the room. Moreover, air speed varies greatly depending on the distance from the fan and on furnishings.

Ceiling fans are suitable for different situations, including offices and classrooms. They may be less suitable for small spaces.

Ceiling fans are also very effective when natural ventilation is not available because of lack of wind or a weak stack effect. For this reason they should be combined with natural ventilation strategies for best results.

The minimum ceiling height for the use of fans is 2.7 m. The blades should be about 30 cm (minimum 25 cm) from the ceiling and more than 2.4 m above the floor. Tables 3.8-1 and 3.8-2 can be used to size ceiling fans.

TABLE 3.8-1 **FAN DIAMETER IN FUNCTION OF THE LARGEST DIMENSION OF THE ROOM**

Length of the room [m]	Minimum fan diameter [cm]
< 3.5	90
3.5 – 5.0	120
5,0 – 5.5	140
5.5 – 6.0	160
> 6.0	Two fans

TABLE 3.8-2 **FAN DIAMETER IN FUNCTION OF SPACE AREA**

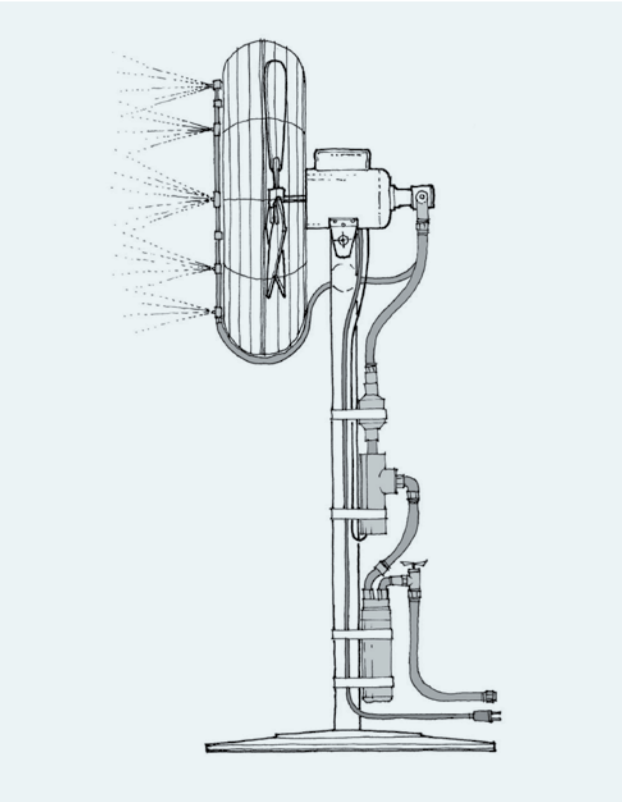
Room area [m^2]	Minimum fan diameter [cm]
10	90
10-20	120
20-30	140
30-40	160
> 40	Two fans

3.8.2.1 **MISTING FANS**

In hot-arid climates, the effect of a fan can be improved by exploiting the evaporative cooling effect with the use of a misting fan. Misting fans are normal fans equipped with fog nozzles, which are designed to produce a very fine mist so that the water evaporates quickly (Fig. 3.8-8). They combine evaporative cooling and convective cooling, at the same time reducing the temperature and increasing the velocity of the air. The improvement in the level of comfort can be significant.

Misting fans are also appropriate outdoors.

FIGURE 3.8-8 **TYPICAL MISTING FAN**



3.9 BUILDING MATERIALS

Building materials play a significant role in sustainable architecture. The heat flow rate through the various components of a building, its time lag and amplitude decrement (see Appendix 1 – Principles of Building Physics), as well as the energy storage capability of the building are all governed by the materials used, which also determine the embodied energy of the building. The choice of materials is therefore crucial from the perspective of both the thermal performance and the environmental impact of the building.

In all tropical countries, traditional construction materials and methods are still used in buildings. Some of the advantages of traditional materials are their plentiful supply, low environmental impact, low cost, and good reaction to climate; moreover they can be handled by local skilled labour, who are familiar with both the production and repair of traditional constructions.

The use of modern building materials, which are generally imported, is now developing in towns. These are the materials used in developed countries and are characterised by a high environmental impact, especially as far as the embodied energy is concerned (see Introduction and Appendix 1 – Principles of Building Physics). It is thus desirable to focus on alternative materials that combine tradition and innovation, in order to reduce costs and energy consumption.

Eco-friendly materials are characterised by low-embodied energy and low related emissions; they are durable and convenient for recycling and reuse. Traditional building materials are mostly made from naturally available materials such as clay, stone, sand and biomass. The selection of appropriate materials should be driven by local/regional and environmental considerations. Unfortunately however, building design is heavily influenced by prevailing fashions, especially the fashions in the developed world.

The recommendations for material and product selection, taking into account climate and sustainability, are:

- minimize the quantity of the resource used (more breathing spaces, smaller quantity of materials) and use materials efficiently in the construction process. Make choices that ensure reduction of scrap materials; this is very significant particularly for materials with high embodied energy;
- select materials with low embodied energy and low energy construction systems. For example, use domestic, certified timber in place of concrete for beams, lime-pozzolana mortars in place of cement mortars, soil or stabilized soil blocks or sand-lime blocks instead of burnt clay bricks, gypsum and plasters instead of cement plasters. Use low-energy structural systems like load-bearing masonry in place of steel frames;
- use naturally available materials, especially renewable organic materials like timber, trees, straw, grass, bamboo etc. Even non-renewable inorganic materials like stone and clay are useful, since they can be reused or recycled;
- use durable materials and components. The utilisation of durable structural and functional components and materials allows long-term use as well as a reduction in maintenance and renovation and refurbishment costs during the lifetime of buildings;
- use locally available materials and technologies, and employ a local work force;
- use materials with greater potential for reuse and recycling; pure material like bricks, wood, concrete, stone, metal sheets are most suitable for this purpose. Composite materials like prefabricated solid foam-metal or foam-plaster elements are difficult to separate and to recycle;
- use industrial waste-based bricks/blocks for non-structural or infill wall systems;
- reuse/recycle construction debris;
- use water-based acrylics for paints;
- use adhesives with no/low Volatile Organic Compound (VOC) emissions for indoor use;
- do not use products containing asbestos (it is carcinogenic) and CFCs;

- minimise the use of metallic surfaces and metallic pipes, fittings, and fixtures;
- use products and materials with reduced packaging.

3.9.1 SUSTAINABLY MANAGED MATERIALS

The use of sustainably managed materials is an environmental responsibility, contributing to a sustainable habitat. The degree of sustainability of a material/ component can be evaluated by means of the Life Cycle Assessment (LCA), a technique for assessing environmental impacts associated with all the stages of a product's life, from-cradle-to-grave (i.e., from raw material extraction through processing, manufacture, distribution, use, repair and maintenance, to disposal or recycling of the materials). The LCA is a tool for measuring the environmental performance of a building material, which gives the designer a comprehensive understanding of the environmental impact and the improvement that can be offered at each stage in the life cycle of a material; it thus forms a system for comparing and selecting materials.

The guiding principle remains that all the stages in the life cycle of a material - right from raw material extraction, manufacture, and production to operation, installation and maintenance, and ultimate demolition - have potential environmental impacts.

3.9.1.1 WALLS

Brick and block products made up of recycled content.
Use brick and block products that have waste and recycled contents such as fly ash[29] from coal burning plants, blast furnace slag, sewage sludge, waste wood fibre, rice husk ash, etc. Concrete blocks using lime, gypsum or fly ash, or furnace slag, or waste wood fibre reduce waste and save energy. Fly ash can be used to replace about 15% to 35% of the total cementitious material. The slag content should usually be between 20% and 25%. Concrete masonry units with finished faces can provide the structure and either the interior or exterior surface of a wall, thereby reducing whole layers of additional material. Concrete blocks are also made from sintered clays, PFA (pulverized fuel ash), lime, which sinter the waste product using the residual fuel in the waste, and thus have very a low embodied energy content. Use glass blocks with recycled content.

Perforated burnt clay and cement bricks also reduce the energy requirements.

Earth blocks
The production of simple earth blocks only requires around one thousandth of the energy needed to fire bricks, and even in cases where the earth is stabilized with cement it is no more than a sixth per kg of material.

29 Fly ash is a by-product of coal in thermal power plants. It consists of organic and inorganic matter that is not fully burnt, and can be recycled for use in a variety of building materials.

Earth blocks stabilized with 5%-15% of cement are also a good choice for low cost, low-rise construction in all climates, provided that their thickness is appropriate (thick in hot- arid, thin in hot-humid, intermediate in other climates).

Stones.
Native or quarried stones available within a delivery radius of less than 100 km have a much smaller embodied energy content, negligible transport energy costs, and only need shaping.

Organic, vegetal materials.
Matting of bamboo, grass, or leaves is a good material in hot-humid zones, which has no thermal storage capacity and no airtightness, thus allows proper ventilation.

3.9.1.2 ROOFS

In the tropics the outer roof covering must satisfy opposing requirements. Its waterproof capability must remain unaltered in high humidity and heavy rainfall, as well as in extremely high surface temperatures combined with minimum humidity.

All roofing materials such as tiles, metal, etc., are suitable for the tropics, when appropriately used.

Earth.
Good thermal insulation and emissivity, suitable in arid climates.

Burnt clay tiles.
A traditional material still very suitable today, with quite good thermal properties. Although heavier than sheet roofs, their thermal mass is not great enough to store heat during the day and release it at night if a ventilated void is provided. They are relatively heavy, and require a strong support structure. They are permeable to air through the gaps between the tiles.

Concrete tiles.
Similar properties as clay tiles but somewhat reduced heat resistance.

Fibre concrete (FCR) and micro concrete (MCR) tiles.
Similar properties but lighter than concrete tiles, hence less heat storage capacity.

Monolithic concrete slab.
Poor thermal resistance and high storage capacity. Due to their large mass they are relatively cool during the morning, but re-radiate the daytime heat to the interior in the evening and at night.

Natural stone (flag stone, slate).

Thermal performance similar to concrete tiles depending on the thickness and the surface (brightness).

Organic, vegetal roofing materials bamboo, leaves, thatch, wooden shingles.

Climatically and environmentally suitable, but of relatively low durability. Thatch roofing is widely used in rural situations throughout East Africa. It is cost efficient and effective for sound and thermal insulation. The lifespan of an average thatch roof is 7-10 years if maintained properly.

Bituminous roofing.

Problematic in the tropics, because of quick deterioration due to the intense solar radiation combined with the dark colour.

Single skin corrugated galvanized iron sheeting (CGI).

Even though it is one of the most widely used roofing materials, it has many drawbacks: it has no significant thermal resistance; aged sheeting has no significant reflectivity, it re-radiates the received solar radiation into the building creating intolerably high indoor temperatures during the daytime. In order to preserve the reflective quality of corrugated iron sheets, and increase their life span, such roofs should be painted in a light colour. Lime wash can be used, but frequent maintenance is required. Rapid cooling at night may cause condensation in humid climates. It has a short life-span and it is noisy when it rains.

Corrugated aluminium sheets

With their high degree of reflection, they have been a success, but a good quality article is also fairly expensive. The high initial price is largely compensated for by low maintenance costs, which are definitely preferable to those for galvanised corrugated iron roofs, or worse non-galvanised and just painted. However, an insulating layer below the sheet is required or a ventilated cavity, for good thermal and acoustic performance.

Bituminous roofing felt

Guaranteed as suitable for tropical use, roofing felt and plastic foil are used for flat roofs, as in the temperate zones. Excessive heating of the material can be prevented simply by whitewashing it. A layer of gravel is even better because the durability of the roofing is improved and it is protected from mechanical damage.

3.9.1.3 INSULATION MATERIALS

Various natural and artificial materials are available and have to be selected carefully.

Glass fibre insulation

Available as batts (blankets) that can be attached to the underside of a roof or laid on top of a ceiling. Glass fibre insulation is produced from sand and limestone or recycled glass and typically has a formaldehyde-based binder added to it. Some manufacturers make glass fibre insulation that is free of binders or that use acrylic binders.

Cellulose insulation

Typically made from recycled newsprint, and can usually be produced locally. Since it takes relatively little energy to produce, it is usually the insulation product with the lowest embodied energy and lowest environmental impact. Cellulose is produced by either chopping newsprint into small pieces (hammer mill), shredding (disk refining) or disaggregating into fibres (fibrerization).

Moulded Expanded Polystyrene (MEPS)

Commonly known as "beadboard". Beadboard is made from loose, unexpanded polystyrene beads containing liquid pentane and a blowing agent, which are heated to expand the beads and increase thermal resistance.

Extruded Expanded Polystyrene (XEPS)

This is a closed-cell foam insulation similar to MEPS. Polystyrene pellets are mixed with chemicals to form a liquid, and a blowing agent is injected into the mixture, to form gas bubbles. The liquid mixture is solidified through a cooling process and the gas bubbles are trapped to give it an insulating property. It has a higher compressive strength than MEPS, making it better suited for use on roofs or for wall panels.

Polyisocyanurate

This is a closed-cell foam typically produced as a foam and used as rigid thermal insulation similar to polyurethane. All polystirene and polyisocyanurate based insulations have a more or less significant environmental impact.

3.9.1.4 SUSTAINABLE LOCAL/INNOVATIVE BUILDING MATERIALS

Stabilized compressed earth blocks (CEB)[30].

These blocks are made of mud stabilized with approximately four to six per cent of cement lime and compacted with either motorized hydraulic or hand-operated machines, a process which requires no burning.

Earth building has a long history in Africa and CEB have been used in East Africa for the past 25 years.

The advantages of CEB are that they use locally found materials, shipping costs are eliminated, the blocks have a low moisture content, and the blocks are uniform thereby minimizing, if not eliminating, the use of mortar and decreasing both labour and materials costs. Construction is fast, minimal cement is used and the blocks produced are

30 Source: Architectural Design Guide EMI EAST AFRICA - http://emiea.org/documents/eMiEA_Architectural_Design_Guide.pdf of comparable strength to locally fired bricks but without their environmental impact. CEB machines can be used by supervised unskilled labour and can be transported by wheelbarrow or cart to remote locations.

The quality of the blocks is dependent on consistent quality control during the making of the blocks and throughout the construction process.

Durability may be a problem if the blocks are exposed to wind and/or rain.

Reinforced concrete columns are required for all CEB buildings in order to provide lateral stability. Quality control must be maintained throughout the entire manufacturing and construction process. Ring beams must be made from reinforced concrete and tied into the reinforced concrete columns. Soils must be tested to determine their suitability. Large overhangs are recommended to protect the blocks from wind and rain.

Stabilized adobe.

Stabilized adobe is an improvement over the traditional adobe or hand-moulded, and sun-dried mud block in which mud is mixed with a small proportion of cement or lime or broken or cut dry grass to impart added strength and lower the permeability. It is appropriate in dry climates.

Fly ash/sand lime bricks.

These are bricks produced from fly ash or sand with lime as the binder. They are strong, have superior water absorption properties, and crushing strength. However, they need autoclaving.

Fly ash-lime-gypsum products.

These are products manufactured by binding fly ash, lime and calcined gypsum (a by-product of phosphogypsum or natural gypsum) to make 'Fal-G', and can be used as a cement-like material for mortar/plasters, and for masonry blocks of any desired strength.

Fal-G stabilized mud blocks.

These blocks are stronger, have less water absorption and are cheaper than cement stabilized blocks. With five to ten per cent Fal-G (fly ash, lime, gypsum), 30% saving in cement could be achieved in addition to the utilization of a waste product like fly ash.

Clay fly ash burnt bricks.

Clay fly ash burnt bricks are produced from fly ash and clay. They are stronger than conventional burnt clay bricks, consume less energy, provide better thermal insulation, and are environmentally efficient as they utilize fly ash and industrial waste.

Pre-cast stone blocks.

Pre-cast stone blocks are of a larger size than normal bricks, and are manufactured by using waste stone pieces of various sizes with lean cement concrete and enable a rationalized use of locally available materials. This saves cement, reduces the thickness of stone walls, and eliminates the use of plaster on the internal or external surface.

Pre-cast concrete blocks.

Pre-cast concrete blocks are made to dimensions similar to stone blocks without large sized stone pieces, but using coarse and finely graded aggregate with cement. They have excellent properties comparable to other masonry blocks.

Lato blocks

These are bricks made from lateritic soil and cement or lime. The blocks are moulded under pressure to produce strong, good quality blocks that consume less energy than conventional bricks, and hence are cheaper. They are available in various colours ranging from cream to light crimson.

Pre-cast hollow concrete blocks.

Pre-cast hollow blocks are manufactured by using lean cement concrete mixes, extruded through block-making machines of egg laying or static type. They need less cement mortar, and enable speedy construction compared to brick masonry. The cavity in the blocks provides better thermal insulation and also does not need external/ internal plastering. These can be used as walling blocks or as roofing blocks along with inverted pre-cast T-beams.

Fly ash-based lightweight aerated concrete blocks.

These blocks are made for walling and roofing and are manufactured by a process involving the mixing of fly ash, quick lime, or cement and gypsum with foaming agents such as aluminium powder. These are considered excellent products for walling blocks and prefabricated floor slabs.

Precast/aerated cellular concrete units.

Walling blocks and roofing slabs are manufactured through an aerated cellular concrete process. When used in multi-storeyed structures, they reduce weight, resulting in a more economic design of structure. They have a high fire resistance rating and provide better insulation.

Composite ferro-cement system.

The system is simple to construct and is made of ferro-cement (rich mortar reinforced with chicken mesh and welded wire mesh). This reduces the thickness of the wall.

Bamboo/timber mat based walls

These are made up of bamboo mats placed between horizontal and vertical timber/bamboo frames. The plastering is done using mud or cement mortar on either side. These are easy to construct, cost less and are popular in hilly areas as they can be self-assembled. However, they are not load-bearing and need a supporting structure.

3.9.2 INTERLOCKING STABILISED-SOIL BRICK (ISSB) TECHNOLOGY[31]

The Interlocking Stabilised-Soil Brick (ISSB) is a technology that pioneers the idea of dry- stacking bricks during construction; hence they are called mortarless bricks.

Production and laying of ISSB are labour intensive, making use of unskilled labour. Moreover building with ISSB reduces the use of industrial products like cement and depends on local resources. It is considered to be an environmentally friendly technology, because it consumes less production energy, reduces deforestation, reduces the use of non-renewable resources and produces less waste from the construction process than the main walling alternatives (fired bricks, cement-sand blocks)

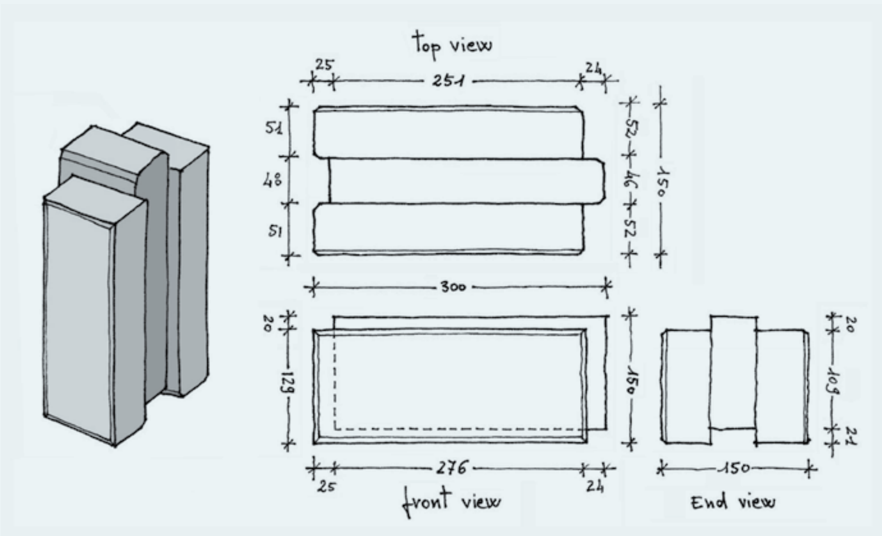
Interlocking bricks can be produced as solid, perforated or hollow bricks. The demarcation between hollow and perforated bricks depends on the surface area of holes. If they occupy less than 25% of the surface area, they are called *`perforated bricks`*, if more they are called *`hollow blocks`*. Bricks can be characterised in terms of their solidity as follows:

- the more solid the brick the more material required and the more powerful the press needed to attain enough brick density, but less binder will be needed for satisfactory brick strength. They are more massive;
- the more perforations, increasing to 50%, the more binder will be required in the mix to achieve the higher strength needed for thin membranes formed onto a hollow block. They are lighter and better insulating.

There are many interlocking systems, with a more or less complex brick shape. Among the simplest is the Hydraform system from South Africa, which has a grooved joint at the sides and top and bottom (Fig. 3.9-1).

The Bamba brick has a more complex shape. It is perforated and has protrusions and depressions (Fig. 3.9-2). The top and bottom faces of Bamba brick have negative symmetry: configurations opposite to each other that allow them to fit together. Bamba bricks interlock better than other types, but require high accuracy in production and in construction.

FIGURE 3.9-1 **HYDRAFORM SYSTEM**



Recently a Tanzanian brick has been introduced, whose shape lies – in complexity – between the Hydroform and the Bamba bricks (Fig. 3.9-3).

31 *Source: S. H. Kintingu, DESIGN OF INTERLOCKING BRICKS FOR ENHANCED WALL CONSTRUCTION FLEXIBILITY, ALIGNMENT ACCURACY AND LOAD BEARING, PhD Thesis, The University of Warwick, School of Engineering, 2009 - http://wrap.warwick.ac.uk/2768/*

FIGURE 3.9-2 **BAMBA BRICK**

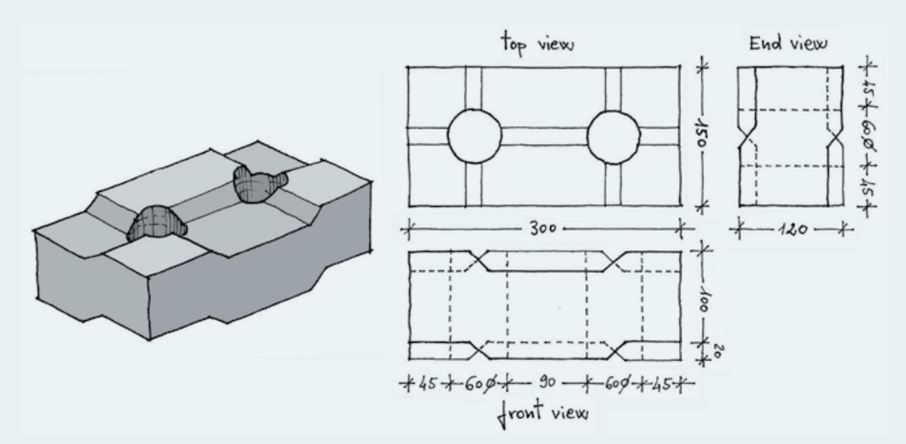
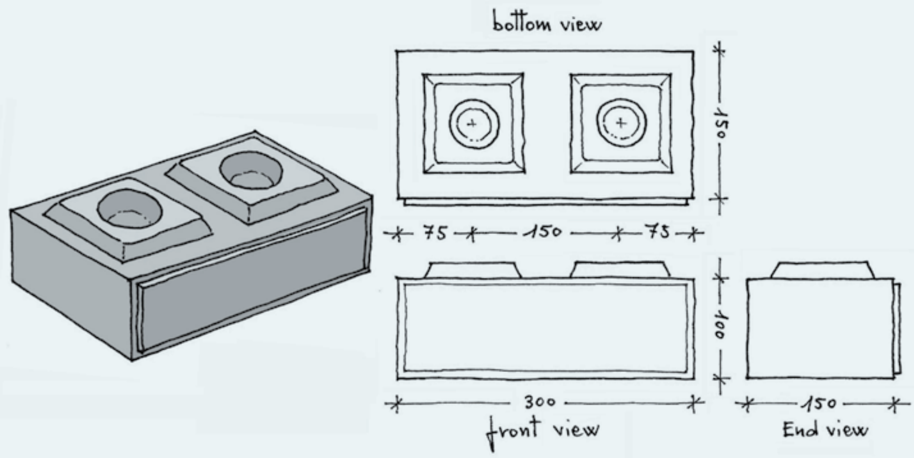


FIGURE 3.9-3 **TANZANIAN BRICK**



3.10 DESIGN GUIDELINES ACCORDING TO EAC CLIMATES

Design guidelines for roofs, walls and openings in hot-arid, hot-humid and uplands climates are at the vertexes of a triangle encompassing the complex variety of climates in EAC countries. These climates (hot semi-humid, hot semi-arid/low savannah, savannah, and great lakes) are more or less close to each of the basic three, and the rules that apply in them, regarding envelope design, are intermediate (with the exception of a high upland climate), as described in detail below.

3.10.1 ZONE I: HOT-HUMID

Because of the temperature and humidity, the most that can be done is to keep indoor comfort conditions similar to those outside in the shade and to achieve this, two main provisions should be made:

(1) Protection from direct and/or indirect solar radiation;

(2) Maximum ventilation.

3.10.1.1 **SITE PLAN**

Sun protection

The building should be surrounded by trees, shrubs and grass, which will absorb solar radiation and not reflect it into the building. Trees should have high trunks, and be appropriately positioned to avoid screening the wind.

Ventilation

Sites exposed to prevailing breezes are highly desirable. The closer to the sea and the higher the ground, the more breeze there is. Local orography may change the direction of the north-east/south-west monsoons.

When the monsoons are not blowing, it is important to exploit the local breezes; these winds are useful from one to eight km inland depending on the terrain. Their direction is perpendicular to the coast line.

Sites surrounded by hills or screened from the prevailing wind by hills or thick forest should be avoided.

The primary objectives of climatically suitable layouts are to allow maximum ventilation and to keep obstructions to a minimum. This usually implies a well-spaced layout. Buildings in a row should not be so placed that they screen the other buildings from the prevailing winds, but should be spaced at a distance of 7 times their height if facing each other; closer if they are staggered. A street layout that is appropriate for the prevailing wind direction and the use of wing-walls may significantly reduce the distance needed between buildings, to allow a more compact urban structure.

Ventilation in well-spaced high-rise or multi-storey dwellings is likely to be better than in single-storey houses. Therefore, at high urban densities, an increase in height is generally preferable.

Outdoor spaces

As the outside shade temperature is the coolest that can be obtained, it is important to design outdoor spaces near the house in such a way that they can be fully utilised for various household activities.

From a comfort point of view, outdoor spaces should be shaded and well ventilated.

The minimum shade area for cooking[32] is approximately 1.5 x 1.5 m, while the minimum area for taking meals is approx. 2.0 x 3.0 m.

Whatever the type of outdoor space, it is important that it is correctly placed in relation to the prevailing winds and that it is slightly higher than the surrounding ground to prevent flooding.

3.10.1.2 BUILDING PLAN

Sun protection

Buildings should be orientated with the long axis running east-west to provide effective shading and east and west-facing openings should be minimised to reduce early morning and late afternoon heat gain.

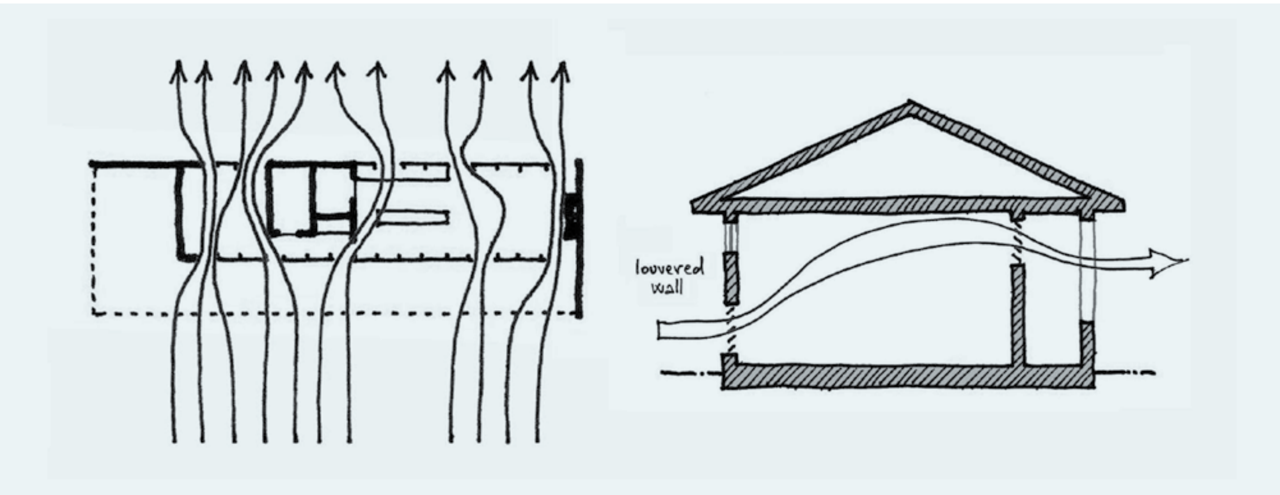
For better use of the monsoon during the hottest period, the axis can rotate a little clockwise. It is recommended that the building be raised above the ground in order to better exploit winds for ventilation. Single banked houses are the most appropriate. If carefully sited, single-banked houses may be given L, U or H shaped plans provided that bedrooms and living rooms are shaded and located where air movement is most pronounced.

Ventilation

After sun shading, this is the most important element affecting comfort.

Buildings should allow maximum ventilation, with rooms distributed only on one side of an access corridor (Fig. 3.10-1). If they are positioned according to the direction of prevailing winds, wing walls can improve ventilation (see paragraph 3.5).

FIGURE 3.10-1 **USE OPEN PLAN INTERIORS TO PROMOTE NATURAL CROSS VENTILATION**



32 *Bodoegaard, T. (1999). Climate and Design in Tanzania-Guidelines for Rural Housing, Building Research Unit, Ministry of Lands and Human Settlements Development, Dar Es Salaam, Tanzania*

Buildings should be more than one storey high, preferably with the ground floor left open or used for non-living purposes because there is more wind in higher storeys.

Ventilation openings at the top of the exterior walls should be provided, so that heated air close to the underside of the ceiling can be regularly evacuated.

Structures

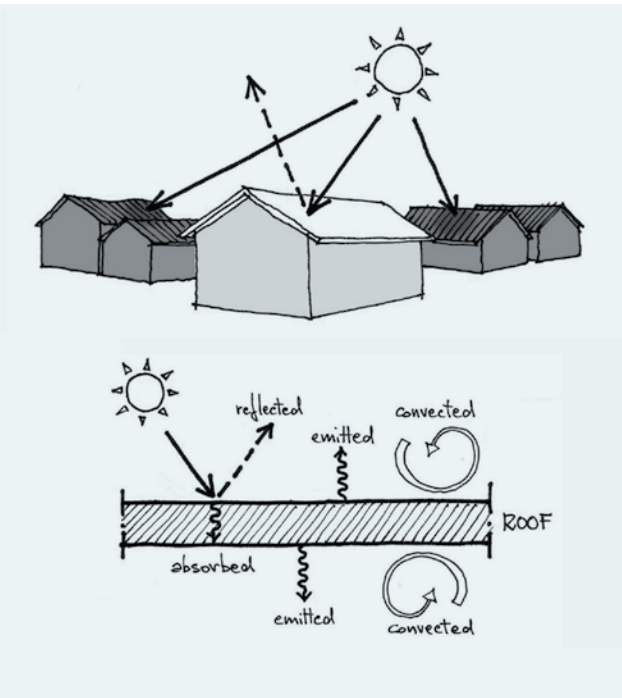
All the building elements should be as light-weight as possible.

Roof

An important function of the roof is to protect the walls, openings and interior from direct sunlight, particularly on east and west walls. Whatever type of roof is used; it should have generous overhangs of not less than 0.6 m but preferably of 1.0 m.

The roof should be made of lightweight materials with low thermal capacity and high reflectivity (Fig. 3.10-2). It should be ventilated or well insulated to reduce heat gain due to solar radiation.

FIGURE 3.10-2 **DARK, HEAT-ABSORBING ROOF SURFACE INCREASES HEAT TRANSMISSION INSIDE**



Ceiling

If the roof is not insulated, a ceiling is needed and the space between the roof and the ceiling should be ventilated, to reduce thermal discomfort; it is better if the ceiling is also insulated.

A roof with high thermal conductivity, such as a roof made of corrugated iron or burnt clay tiles, and a ceiling with poor thermal insulation, such as hard-board, will cause over-heating regardless of ceiling height and ventilation in the attic space. It should be noted that it is not the ceiling height that influences indoor air temperature and comfort – as is sometimes stated - but the temperature of the ceiling's surface, which is why good insulation is so important.

Walls

Walls should have a low thermal capacity. Sun protection is very important and can be achieved by:

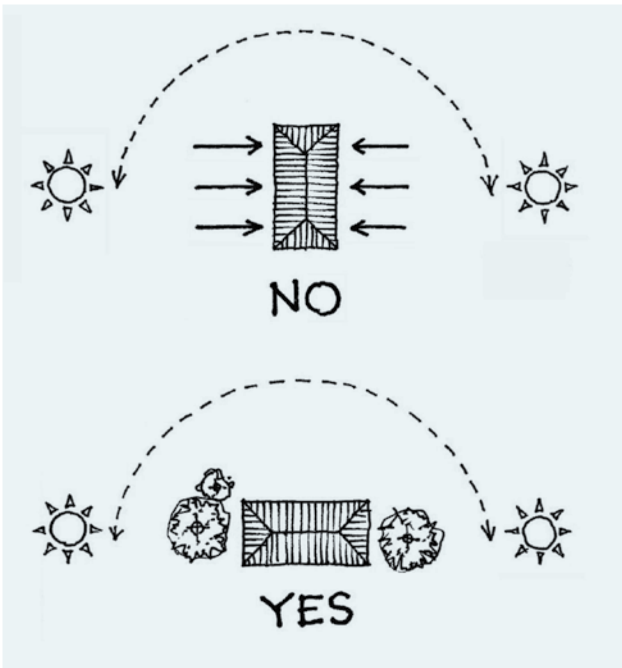
- long axis of the building orientated east-west (Fig. 3.10-3);
- shading with overhangs, verandas or other devices;
- shading with trees.

Cavity or hollow brick walls should be used for non-shaded elevations. Screen walls help to increase air movement. Operable walls give the best results, but they are expensive.

Windows and ventilation openings

In order to allow maximum air movement, large openings are required. These should be located in north and south-facing walls. The sill height should not be higher than 0.9 m. above the floor, and preferably 0.6 m., to provide a cooling effect for the body when a person is sitting or sleeping. Glazing, when used, should not exceed 20% of the area of the wall.

FIGURE 3.10-3 **THE BEST ORIENTATION FOR SOLAR PROTECTION OF WALLS IS WITH THE LONG AXIS EAST-WEST**



Windows on opposite walls should not be on the same axes, except for very large windows. If ventilation openings are on one wall only, or are not opposite one another, ventilation will be less effective. In order to have stack effect ventilation and to ventilate the ceiling, one fifth of the total openings should be at ceiling level. When possible some openings should also be placed at floor level.

All openings should be protected from both direct and indirect solar radiation.

Sun shading devices

Many sun shading devices have been developed, especially in recent years, but care should be taken to install them properly to avoid unsatisfactory results. Several methods of sun control can be considered:

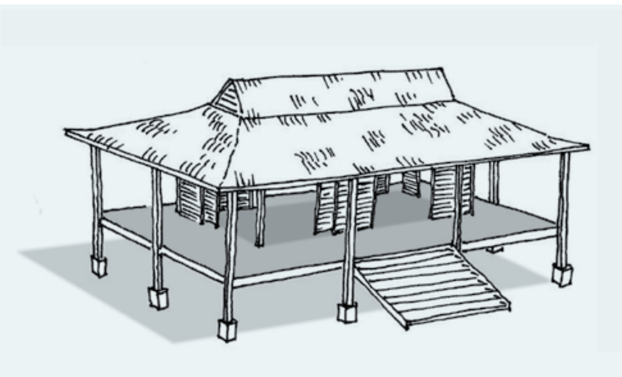
(a) Sun breakers and verandas.

These become a source of reflected heat if they are not properly designed.

Sun breakers of heavy materials such as concrete should be avoided. They store heat and are likely to release it to the inside through radiation or convection. Heat absorbing materials start to radiate as soon as the sun hits them. Lightweight blades with reflecting surfaces or made of insulating materials, such as aluminium or wood, are recommended.

Verandas and porches are a very effective means of providing shade and also may enhance natural ventilation (Fig. 3.10-4).

FIGURE. 3.10-4 **LIGHTWEIGHT CONSTRUCTION WITH VENTILATED ROOF, OPERABLE WALLS AND SHADED OUTDOOR PORCHES, RAISED ABOVE GROUND**



(b) Louvred shutters

These are very good and recommended for dwellings. They are rainproof, allow good ventilation and are secure against thieves. They are not satisfactory in rooms where a high level of daylighting is required, such as classrooms.

(c) Moveable glass louvres (jalousie)

They provide very good ventilation and are rainproof but they need to be shaded from the sun and are not secure against thieves.

(d) Moveable solid louvres (metal or wood, horizontal or vertical)

They regulate, sun, ventilation and daylighting and are thief proof. If rain and ventilation control is required, the blades must be almost closed and daylighting may be insufficient.

(e) Perforated walls

These can be made of ordinary masonry or built of specially cast elements in clay or concrete. Care should be taken to avoid secondary radiation inside the rooms from reflection or from heat stored in the material.

(f) Venetian blinds

These are useful because they allow excellent sun and light control and good ventilation, but they are expensive. They should be placed on the outside of windows when air conditioning is used.

Fly-proofing

Insects are a permanent source of discomfort and are a health hazard, particularly the malaria mosquito. The insects breed during the wettest periods of the year.

The serious risk to health of malaria and other insect-borne diseases justifies the promotion of mosquito screens. The main drawback with permanently fitted screens is that they greatly restrict ventilation. Increasing the area of the opening may offset this drawback.

3.10.2 ZONE II: HOT-ARID

Because of the high daily temperature variation, it is best to keep the heat out during the day and ventilate during the night. To achieve this, three main provisions should be made:

(1) Protection from direct and/or indirect solar radiation;

(2) Use of high-medium thermal mass for walls and roof;

(3) Use of operable windows.

3.10.2.1 **SITE PLAN**

Housing layouts should be in a compact urban form. Compact planning minimizes the solar exposure of individual houses and reduces solar heat gains by providing mutual shading and by reducing external surface areas. Compact layouts keep down wind speeds and thereby considerably reduce the sand and dust content of the air within settlements during sandstorms.

Buildings should preferably be located on elevated ground, where the breezes offer more relief at night and keep mosquitoes away.

Outdoor space

The heat during daytime makes shaded spaces most welcome. Shade giving trees, simple roofed spaces and verandas are most welcome assets. As people usually sleep and rest indoors at midday, outdoor spaces tend to be used more in the mornings and afternoons. Food preparation and other household activities are usually carried out in a shaded space. The main evening meal is often taken outside.

3.10.2.2 **BUILDING PLAN**

In this zone, buildings should be compact, but allow good natural night ventilation. Buildings should be orientated with the long axis running east-west to provide effective shading; it is not necessary to modify this orientation for wind direction. House layouts should be planned so as to provide protected and enclosed outdoor spaces between as well as within the houses. Public open spaces should be limited in size unless planting is possible.

A heavyweight building envelope is recommended because of the high daily temperature swing.

In order to keep building interiors as cool as possible during daytime, it is important that the solar exposure of façades is reduced to a minimum. Although single-banked houses are excellent for cross ventilation, double-banked houses are the most appropriate provided that the internal walls allow for some night ventilation. Traditional courtyard houses are well established; they are compact and give sufficient ventilation.

Bedrooms should be located on the eastern side. The living room should be located on the northern side. In order to protect the main rooms from the hot afternoon sun, store and other secondary rooms should be west-facing.

In order to allow cross ventilation during the night, ventilation openings should face the central corridor or should be located between rooms.

It is desirable to locate yards and verandas on the northern or the eastern side of the house. As mornings might be chilly, a sunny yard facing east is a pleasant place for taking early meals and for various household activities. Since cooking is done outside as well as inside the house, the kitchen must have direct access to a sheltered veranda. Simple roof structures that provide shelter are most useful, whatever the activity that is taking place outside the main house.

Structures

A heavy structure with a large thermal storage capacity is desirable for those parts of the house that are used primarily during the daytime, provided that the interiors are sufficiently ventilated at night. Rooms intended for evening and night use should be enclosed by a light structure so that they cool down more quickly when the temperature drops.

Roofs

Roof should be made of heavyweight materials with high reflectivity. They should be ventilated.

Alternatively, if the roof is lightweight, the ceiling should be heavyweight, and the attic ventilated.

Walls

Heavyweight walls are well suited to this climate zone. Walls with a time lag of 11-12 hours are excellent for day rooms, provided that the rooms are adequately ventilated at night. Mud block, brick or soil cement walls should preferably be not less than 30-40 cm thick. Walls should be light coloured.

To improve comfort during the night, bedroom walls should be lightweight.

The same guidelines for sun protection as given for Zone I should be adopted.

Windows and ventilation openings

Wooden louvre shutters are recommended for houses because they have good sun-shading properties and are burglar-proof. Tight-fitting wooden shutters are the most practical option for housing as they will prevent sun light from entering the house and thus prevent overheating. Casement windows are preferred to glazed louvre windows, as the wind often carries dust. If louvred windows are used, care should be taken to ensure that they are as tight-fitting as possible in order to prevent dust on windy days.

Some 10-20% of the area of north and south-facing walls should be operable.

Ventilation should be limited during daytime, when the air is hot; it should be increased at night to cool the building down.

The provision of adequate night ventilation is critical to prevent overheating. Ventilation openings should be provided at high as well as at low level. Ventilation openings in internal walls are required in order to obtain cross-ventilation.

Early morning sun in a living room might be desirable, and windows in east-facing walls are acceptable.

Fly-proofing
Ventilation openings should be permanently fitted with fly-screens in order to prevent insects and reptiles from entering the house.

Evaporative cooling
Evaporative cooling is effective because of the low values of relative humidity during daytime. Simple direct evaporative cooling devices can be used during the hottest times of day if water is available.

3.10.3 ZONE III: HOT SEMI-ARID/SAVANNAH

The design strategies for this zone are similar to those for the hot-arid zone except for the use of a mid-weight building envelope in the hot semi-arid areas because of the lower daily temperature swings. Heavyweight walls should be used for savannah plains due to the lower night temperature.

Evaporative cooling is not as effective because of higher values of relative humidity, but it is still recommendable during the hottest hours of the day.

3.10.4 ZONE IV: GREAT LAKES

Because of the high daily temperature variation and the high humidity values that can be reached, it is best to keep the heat out and ventilate during the day, and to take advantage of the stored heat in the structure during the night. To achieve this, three main provisions should be made:

(1) Protection from direct and/or indirect solar radiation;

(2) Use of medium thermal mass for walls and roof;

(3) Maximum ventilation during the day.

3.10.4.1 SITE PLAN

Site selection criteria are similar to those of the hot-humid coastal zone. Early afternoon breezes from the lake and evening breezes from the land are due to the difference in temperature between water and land. This means that the prevailing winds are perpendicular to the lake shore. Sites should face the main body of the lake and not be inside deep bays or creeks. They should be on high ground to avoid the high humidity at lake level and to catch stronger breezes. Sites surrounded by hills or with hills between the site and the lake shore should be avoided.

Microclimatic conditions may vary considerably from place to place.

A compromise in the orientation of the building may be necessary, between the long axis running east-west to provide effective shading and the direction of the winds blowing perpendicular to the lake shore.

Houses should be widely spaced in order to secure sufficient air movement in and around buildings (see Zone I). If many buildings are erected, care should be taken to ensure that they do not block off the cooling breezes from the lake.

Outdoor spaces
As the zone has a hot humid spell during the day, people tend to seek shade during the hottest hours. Very often they prefer to rest or sleep inside the house during hot afternoons. Shaded outdoor spaces should be provided near the houses, which provide shade during the hottest part of the day, are sufficiently exposed to the lake breeze and protect from rainfall.

3.10.4.2 BUILDING PLAN

Building plans should favour good natural ventilation.

In this zone, single-banked houses are appropriate. Ventilation openings in external walls should be shaded, particularly in east and west-facing walls.

A more compact type of house requires careful orientation and design of openings, in order to reduce heat gain and secure sufficient cross ventilation.

Solar radiation on east and west-facing walls makes it desirable to locate bedrooms and living rooms facing north or south. Secondary rooms, such as store, bathroom etc. should face west to avoid too much solar gain from the low afternoon sun.

Roof
For the construction of roofs, sun protection, openings and flyscreens, the same guidelines as given for Hot-humid Zone apply here.

Walls
Mid-weight walls are recommended to even out indoor temperatures: night temperatures are often below the comfort range. External walls should be light-coloured.

Openings
The area of the openings should be in the order of 25-40% of the area of north and south facing walls to ensure sufficient ventilation for comfort and for cooling the structure at night. The glazed part of these openings should not exceed 15-20% of the whole to provide adequate daylighting. Ventilation openings should be evenly distributed on two sides of the rooms for adequate cross ventilation.

The proximity to the lakes makes the presence of mosquitoes a permanent nuisance, particularly at night after heavy rains. Windows should be equipped with fly-screens.

3.10.5 ZONE V: UPLAND

Because of the lower temperatures compared to the other zones, some passive heating is welcome during the cool period. To achieve this, two main provisions should be made:

(1) Protection from direct and/or indirect solar radiation in the hot period and some openness to sun during the cool period;

(2) Use of medium thermal mass for walls and roof.

3.10.5.1 **SITE PLAN**

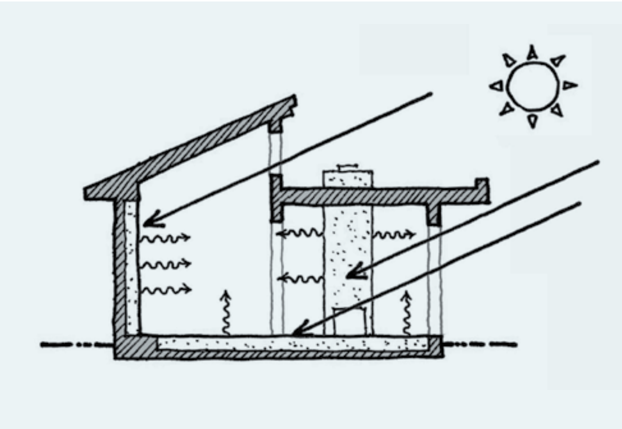
Sites should be selected so as to provide shelter against prevailing winds and cold air pockets in ground depressions. The varied topography and vegetation should be utilised when locating and planning housing areas, whether in town or villages.

There is no need for buildings to be widely spaced for ventilation.

3.10.5.2 **BUILDING PLAN**

Buildings should have their main glazed elevations orientated north-south; a NE-SW orientation with most of the rooms facing north-east is appropriate: with carefully designed sun shading this orientation will allow a certain amount of solar heat to penetrate in the early morning during the cold season, and cut off the low westerly sun early in the afternoon (Fig. 3.10-5).

FIGURE 3.10-5 **PROVIDE SOLAR ACCESS DURING THE COLD SEASON AND MID-WEIGHT ENVELOPE**



It is an advantage to locate living room and bedrooms to the northern or eastern side of the house. Controlled ventilation is a pre-requisite, either through doors, windows or separate ventilation openings.

The construction of double-banked buildings is acceptable, if central corridors are of limited length and offer adequate ventilation. Walls of some insulating value are recommended.

Structures

A medium weight structure is recommended. Due to intense sunshine during the day, considerable heat will be stored in heavy structures and emitted at night to reduce the drop in temperature.

Roof

Roofs can be light or heavy but they must have a good insulation value. Ventilation of roof cavities or the underside of ceilings may not be necessary.

Walls

Medium-weight walls, floors and ceilings are recommended for the best exploitation of passive solar gains.

Windows and ventilation openings

Devices for sun control are necessary in order to keep out the sun during certain hours of the day. They should be adjustable to let sun in when it is required.

Windows should be mainly on north and south-facing elevations for easier sun control. Adjustable louvres outside and curtains or preferably Venetian blinds inside the room will be the best method of sun control.

Large windows facing east or west should be avoided. The temperature in rooms with large glazed areas to the east or west will rise steeply when the sun is low, due to the greenhouse effect; consequently it would be necessary to open windows and on cold days uncomfortable cool draughts would result. The only effective solution is to put adjustable louvres or Venetian blinds outside or inside the windows. The north-facing windows should be large enough to allow passive heating. If all openings are on north and south-facing walls, about 15-25% of wall area should be operable to provide adequate ventilation.

All windows should be glazed and window frames should be reasonably airtight (jalousies would not be appropriate).

Heating system

In this zone, a flexible heating system should be provided.

Fireplaces are needed in most areas, at least at altitudes above 1600 m or even in lower areas where there is considerable rainfall at nights. Fireplaces should be located in living rooms.

Fly-proofing

Mosquitoes and other insects are not a major health hazard or cause of discomfort, but vegetation should be kept tidy and sufficient drainage should aim at preventing insect-breeding pools.

3.10.6 ZONE VI: HIGH UPLAND

In this zone the same provisions as for Zone V should be made, with more attention paid to the need for heating, due to the lower temperatures all through the year.

3.10.6.1 SITE PLAN

There is a wide range of site conditions in this zone. The topography of the zone is varied, with hills, valleys and plateaus, thus making careful site selection an important part of the building design process.

Exposed sites should be avoided, particularly along deforested ridges where strong winds and driving rain may be experienced.

The exposed nature of many sites in this zone makes it necessary to group houses in order to give protection and shelter against cold winds. Compact layouts are an advantage and should also be applied on sloping sites whenever possible.

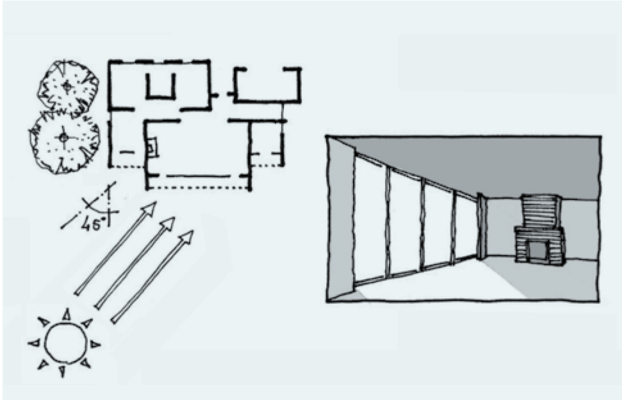
Spacing of houses should be kept to be the minimum compatible with the need to exploit solar radiation.

3.10.6.2 BUILDING PLAN

The major climatic performance criterion for houses is to provide protection from the cold.

The design strategies for this zone are similar to those of Zone V, with increased emphasis on passive solar design (Fig. 3.10-6).

FIGURE 3.10-6 **LET THE SUN IN DURING THE COLD SEASON FOR PASSIVE HEATING**



3.10.7 PROVISIONS FOR SCHOOLS AND OFFICES BUILDINGS

In classrooms and other school rooms in which a number of students are concentrated and in offices where internal gains are high due to equipment, the above guidelines should also be followed, with additional care taken regarding the openings. As the internal gains are high, ventilation must be enhanced as much as possible if mechanical cooling is not provided. Thus, windows must be larger than in a residential building. In order to keep the indoor temperature increase to within 1 °C above outdoors when there is no wind (i.e. relying only on stack ventilation), the area of the windows should not be less than 50% of the floor area in a classroom with 35-40 persons in Zone I[33]. The same value should be used in Zones II, III and IV.

The other issue differentiating residential buildings from schools and office buildings is daylighting.

Because lighting is a significant component of the energy consumption in schools and offices, efforts to use daylighting should be given high priority. To this end, the first design rule is to minimize the depth of the rooms to maximize the contribution of daylighting. Properly designed daylighting reduces the need for electric lighting and helps to create a more pleasant environment.

Clerestories are recommended and lightshelves (see paragraph 3.6) can significantly enhance the uniformity of the natural lighting within a space and can also provide good lighting in narrow rooms (less than 5 to 6 m). Light-coloured walls and ceilings are recommended.

33 *C. Fera, F. Scriven, J. Soulat, Tanzania secondary school facilities inventory, UNESCO 1967*

Finally, in air-conditioned non-residential buildings it is better to have light-medium weight envelopes in all climates.

3.10.8 DESIGN GUIDELINES SUMMARY

ZONE I: **HOT-HUMID CLIMATE**

Site plan

- Houses should be located on sites exposed to sea breezes; avoid sheltered sites. Trees should be used for shading.
- Layouts should be open, so houses should be widely spaced to allow maximum ventilation in and around buildings, which should be spaced at a distance of 7 times their height if facing each other; closer if staggered.
- At high urban densities, building height should be increased in preference to an increase in ground coverage.

Building plan

- Single banked houses provide maximum ventilation.
- Buildings raised above ground favour ventilation; as wind velocity increases with height, high-rise buildings are appropriate.
- Apartments in multi-storey buildings experience better ventilation.
- Main elevations should face north and south and buildings should be orientated with the long axis running east-west to provide effective shading - unless the direction of the prevailing breezes suggests an offset from this orientation - and raised above the ground.
- Shaded verandas for houses or balconies for flats are essential.
- Bedrooms should be located upstairs to provide maximum access to cooling breezes and to provide a sleeping area separate from other zones that may have gained heat during the day.

Structures

- Lightweight and light-coloured or reflective roof and walls (possibly operable); shaded outdoor porches.
- Ceilings highly desirable for heat and sound insulation.
- Air cavity between ceiling and roof, which is permanently ventilated and provided with reflective foil to block radiant heat; roof pitch to vent roof heat gains.
- Roof overhangs not less than 0.6 m, preferably as wide as 1.0 m.
- Shallow floor plan of one-room width to allow maximum cross ventilation.

Openings

- Openings should be large and shaded, with sill height not above 0.9 m.
- The size should be preferably at least 50% of north and south walls.
- Glazed area should not exceed 20% of the area of wall.
- There should be vertical space for upward movement of heat from ground floor (internal stairs).
- Wing walls should be constructed to channel predominant breezes through the building.
- All fixed shading should be insulated or reflective to avoid radiant heat gain at openings.
- Fly-proofing should be installed.

ZONE II: **HOT-ARID CLIMATE**

Site plan

- Housing layouts should be compact.
- Trees, hedges and other vegetation should be planted to reduce dust, glare and reflected heat.

Building Plan

- Courtyard houses protect against hot, dry winds and can be combined with plants and water features.
- House plans should be inward looking with rooms opening off, and roofs sloping towards the courtyard.
- Courtyards should be limited in size .Outdoor living space should be enclosed.
- Buildings should be orientated with the long axis running east-west to provide effective shading; it is not necessary to modify this orientation for wind direction.
- No bedroom should face west.

Structures

- A heavyweight building envelope is recommended because of the high daily temperature swing.
- Heavy structures are good for day rooms if they are well ventilated in night.
- Light structures are essential for rooms used at night.
- External surfaces should be reflective.
- Roofs should be made of heavyweight materials, have high reflectivity and be ventilated. Alternatively, if the roof is lightweight, the ceiling should be heavyweight, and the attic ventilated.

Openings

- Large openings may be inappropriate, unless well shaded.
- Ventilation should be controlled to ensure that the building is not heated when the inside temperature is lower than the outside temperature on a hot day, and that it is cooled during the night.

- Heat gain is reduced as much as possible with no or small windows on the eastern or western sides and small, well-shaded windows elsewhere.
- Some 10-20% of the area of north and south-facing walls should be operable.
- High and low level openings should be created in walls bordering courtyards to facilitate air movement.
- Small openings in perimeter walls are required for cross ventilation.
- Shuttered and permanent openings are preferable to glazed windows except where exclusion of dust is required.
- Fly-proofing is required where mosquitoes are troublesome.

Cooling

- Evaporative cooling should be used to improve comfort when the relative humidity is low. Consideration should also be given to the sustainability of available water resources.

ZONE III: **HOT SEMI-ARID/SAVANNAH CLIMATE**

As for to the hot-arid zone except:

- Medium-weight building envelope in hot-semi arid parts and heavyweight walls for savannah plains.
- Evaporative cooling not as effective because of higher relative humidity.

ZONE IV: **GREAT LAKES CLIMATE**

Site plan

Site selection criteria are similar to those of the Hot-humid Coastal Zone. Care should be taken to ensure free air movement yet ensure minimum solar exposure:

- Exposed sites are desirable. Sites in depressions, or on the leeward side of hills should be avoided.
- Houses should be widely spaced in order to secure sufficient air movement in and around buildings.

Building plan

- As wind velocity increases with height, high-rise buildings are appropriate.
- The type of house is largely determined by the need for cross ventilation.
- Main elevations should face north and south.
- Single-banked houses raised above ground are appropriate.
- Well placed openings in internal walls and shaded permanent openings in east and west-facing walls are effective for cross ventilation in double banked houses.
- Bedrooms and living rooms should face north or south.
- Secondary rooms, such as storerooms, bathroom etc., should face west.

Structures

For roof construction, sun protection, openings and flyscreens, the same guidelines as for hot-humid zones apply, except:

- Mid-weight walls are recommended to even out indoor temperatures: night temperatures are often below the comfort range.
- External walls should be light-coloured.

Openings

- Openings should occupy 25-40% of the area of north and south -facing walls, and the glazed part should not exceed 15-20% of the whole.
- Ventilation openings should be evenly distributed on two sides of the rooms for adequate cross ventilation.
- Fly-proofing is essential.

ZONES V-VI: **UPLAND AND HIGH UPLAND CLIMATE**

Site plan

- Sheltered sites desirable.
- Compact layouts that protect rather than expose houses to wind required.
- Terraced houses appropriate.
- Outdoor spaces adjacent to house, exposed to the sun, but protected from wind, advantageous.

Building plan

- Compact double-banked forms are desirable.
- Buildings should have their main glazed elevations oriented north-south; NE-SW orientation with most of the rooms facing north-east is also appropriate.
- Floor plan should be organised so that the sun penetrates into daytime spaces on cool days. Living room and bedrooms should be located on the north or east sides of the house.
- Controlled ventilation is a pre-requisite.

Structures

- Medium weight walls and roofs are highly desirable.
- Massive interior material to store passive heat in the cool season and night “coolness” in the warm season.

Openings

- 15-25% of North and South wall area should be operable to provide adequate ventilation.
- Windows should roughly be 50% of the floor area of the house.
- Windows should be mainly on north and south-facing elevations.

- Adjustable louvres should be used outside and curtains or preferably Venetian blinds inside the room for sun control.
- Windows should be glazed and window frames should be reasonably airtight.

Heating

- Passive solar building design should be emphasised.
- A flexible heating system should be provided.

3.11. LESSONS FROM THE PAST

The Oxford Institute for Sustainable Development estimated that the people who use them rather than architects designed over 90% of all structures in existence today. The number of dwellings associated with this estimate includes approximately 800 million units.

The term vernacular architecture is used to describe structures built by people whose design decisions are influenced by their traditions and their culture.

Vernacular architecture varies widely with the world's vast spectrum of climate, terrain and culture and it is important to recognise that it contains inherent, unwritten information about how to optimise the energy performance of buildings using low cost local materials. Over the course of time, indeed, vernacular dwellings have evolved to respond to the challenges of climate and to cultural expectations in a given place.

In most cases expectations of comfort levels in new constructions are no longer compatible with the solutions of vernacular architecture; however the cultural heritage underlying vernacular constructions (i. e. morphology, functional distribution of rooms, use of local and natural materials, shading and protection devices, and strategies for filtering or channelling natural resources into the building) can be crucial for preserving the connection between nature and architecture.

The knowledge of traditional energy-saving technologies can be integrated into a new construction at the initial phase of the building design process and vernacular cultural traditions can be usefully preserved. Moreover, it is important to distinguish between vernacular building traditions driven by climate and those carried on through cultural traditions.

In East African Countries, the cultural aspect can be assumed to be the most influential factor in the choice of materials and in the method of constructing dwellings. Outdoor life and nomadic habits were dominant factors in the success of the morphologies and structures of the houses, while climatic considerations and comfort needs in the indoor spaces were of secondary importance: in most cases a house was conceived simply to protect users and their goods from extreme climatic events, while everyday life was carried on outdoors. The path of colonial architecture was very different. The features of the first colonial architecture in East Africa were borrowed from European buildings. The tropical climate was not considered as the basis for designing the distribution of the indoor spaces, although some elements such as porticoes, roof overhangs and courtyards were used to partially shade the façades and the openings.

Pre-colonial architecture, on the other hand, reflects the influence of Arabic, Indian and Persian cultures, combined with Swahili traditions.

In the following sections, examples of vernacular and colonial architecture in EAC countries are described in relation to the climate in which they are located and their climate responsiveness is assessed.

3.11.1 EXAMPLES OF VERNACULAR ARCHITECTURE IN EAC COUNTRIES

These case studies of vernacular architecture are grouped on the basis of the climate in which they are located. The houses described in the following section are adapted to the local population's functional needs, their specific social requirements, and to the local climatic conditions. Some people have strict requirements for their houses related to social habits and lifestyle, for example, nomadic populations in EAC countries live with their livestock and move as the seasonal needs change. Activities are carried on outdoors and the most pressing need is for protection from solar radiation, wind and rainfall. The house is often just a place in which people shelter their material goods and where they sleep at night. Some houses are simply a shelter and do not comply with any comfort and health requirements. The availability of construction materials is another important issue in these areas and houses are mostly built using local materials in the simplest way. The lack of transportation means that the people building the house need to reduce the distance between the site of construction and the places in which the construction materials are found. Moreover, the tools used for constructing the houses are basic and do not permit complex building techniques.

3.11.1.1 UPLAND AND HIGH UPLAND CLIMATE ZONES

Tembe type house, Tanzania

In Tanzania there are eight cultural groups, which have developed different types of traditional house due to geographical location, available materials, climate different activities and cultural factors.

The Southern Highlands Bantu is the third largest cultural group in Tanzania and is concentrated in the south and south-west of the country, in the regions of Mbeya, Sumbawanga and Iringa.

The traditional houses of this cultural group are *Tembe* type houses, which are mainly constructed of bamboo, grass and mud.

The *Tembe House* is basically a long rectangular house that can have a different shape of roof. For example, a flat earth roof is used in the hot, dry and temperate central part of the country and a vaulted roof built with mud and grass can be found in Iringa Region. One type of *Tembe* house is the traditional house used in Iringa region by the Hehe tribe (Fig. 3.11-1). The walls of the house are built of clay and the roof is a compressed layer of clay and grass that lies over curved wooden supports. The structure is made of bamboo. No windows are provided but there are small ventilation holes (diameter about 15 cm). Ventilation is provided by opening the doors. The house is about 90 m^2 and is subdivided internally by partitions. A sitting room is located in the centre with sleeping room and kitchen at the sides. The house may grow as a family grows, with an L added at each end to form a U shape. If a family is very large, the house may form a square with a central courtyard. The height of the rooms is about 2.5 m.

FIGURE. 3.11-1 **HEHE TRADITIONAL HOUSE**

Source: *http://www.flickr.com/search/?q=hehe%20house*

The roof construction is an interesting compromise between the steeply-pitched, thatched, ridge-pole roofs found in the wet areas of Malawi and the domed, mud covered huts of the dry Masai country. Instead of ridge-poles, these huts have a pair of purlins set on either side of the centre point to allow the rafters to be bent over in a continuous curve, eliminating the ridge. The rafters project to form overhanging eaves, which protect the mud covered vertical walls.

The house seems to be designed to provide some comfort during the cold and windy season, when outdoor conditions are very uncomfortable: medium-weight walls attenuate the daily temperature fluctuations, and small openings prevent the penetration of cold wind. It is not as comfortable during the warm season, but then life is carried on outdoors.

Chagga House, Tanzania

The *Chagga House* (Fig. 3.11-2) normally has a diameter of 5.6 m of and a maximum height of about 4.9 m with two levels. The house is completely covered with grass from the ground to the apex, with leaves on the inside that are woven closely together to provide thermal insulation. Only one door is provided, rarely is there a second door and no windows are provided.

FIGURE. 3.11-2 **CHAGGA HOUSE**

Source: *http://en.wikipedia.org/wiki/Chaga_people*

Houses in Kakamega province, Kenya

In Kakamega District square plan traditional houses can be found (Fig. 3.11-3). People are farmers and the houses are given stability by massive walls made of earth to reduce temperature variations inside the house and exploit the thermal inertia of the materials, which is useful in the high upland climate zone.

FIGURE. 3.11-3 **KAKAMEGA HOUSE**

Photo credit: *courtesy H. Fiebig – 50 treasures of Kenya - http://thetreasureblog.wordpress.com/2013/05/31/kakamega/*

The roof of the Kakamega House has a pyramidal shape and is made of a thick layer of straw, which provides good insulation. The main structure of the roof is made of wood with a double warping on which the thatched roof is placed. The walls have small windows at different orientations to allow ventilation when needed. In the high upland climate it is not necessary to provide constant ventilation but it must be sufficient to exchange air in the hottest period of the day when solar radiation strikes the huts. The overhanging roof provides shade and protection from rain.

Houses in Kikuyu Province, Kenya

North of Nairobi, in the central Province of the Kikuyus, the climate is cool. The typical huts are circular, often as much as 7.5 m in diameter (Fig. 3.11-4). Poles approximately 15 cm thick are driven into the ground close together, with split poles and small branches filling the spaces between them. Wooden boards are used to enclose the building and additional structural posts to support the roof are erected. Rafters 7.5 cm thick are laid radially at an angle of approximately 30° to form the roof structure, which does not have central pole, but is finished with a short wooden finial. The deep overhanging eaves are, in some cases, supported by veranda posts protecting the entrance. Horizontal battens 5 cm wide provide fixings for the layers of bunched grass, over which green grass is placed as a finishing layer. Inside, the house is sometimes plastered with a mixture of cattle dung and ash, a treatment that became more widely used both inside and outside when the scarcity of cedar made the use of other types of wood necessary.

FIGURE 3.11-4 **WOODEN KIKUYU HOUSE**

Source: *http://www.fr.enhols.com/safari-photo-album/view-african-photos.aspx?L=En&aid=25*

Generally the houses have a single door and no windows. The envelope is compact to reduce thermal exchanges and the overhanging roof protects the walls from solar radiation and rainfall. The walls are of lightweight construction, and insulation is rather poor. Only a fire burning inside the hut can provide reasonable comfort on cool nights.

3.11.1.2 **HOT ARID CLIMATE ZONE**

The Min of the Rendille, Kenya

Rendille nomads are camel herders and also keep goats and sheep and some cattle. They live in the semi-arid lowland of northern Kenya and use light, transportable shelters called *Min* (Fig. 3.11-5). Six times a year the Rendille move the *Min* to search for pasture, fresh water or to escape conflicts. The *Min* can be disassembled and loaded onto the camels. The main structure consists of two arched frames of curved sticks embedded into the ground and kept in position by a few stones around the base. The back arch is kept in position by thin curved sticks and the front arch is straight with slanting sticks. A door opening is left in the centre. The back half, equipped with a sloped covering, is high enough to allow the user to stand up. It is used for sleeping . The rear is covered with skins to protect the user from the night winds. The front of the *Min* is used as storage.

FIGURE 3.11-5 **WOODEN STRUCTURE AND REAR SIDE OF THE MIN COVERED WITH THATCH**

Source: *May J., Buildings without architects a global guide to everyday architecture, Rizzoli International Publications, New York, 2010*

The Rendille people live in a hot-arid climate zone. The average temperatures are high as are the daily temperature variations. The materials used to make the outer covering of the *Min* stop the dust and give protection from the wind, while the shape has functional and thermal purposes. The shape has the minimum surface to volume ratio and minimizes the effects of the critical environmental factors (i.e. sun, wind, heat, cold, rain).

The materials used for the main structure of the *Min* are wooden poles and sticks. Agave mats are laid on top and are connected to the structure as a cover; cow hides are used to block the dusty wind. The *Min* is primarily a shelter which is inhabited on cold nights and when protection from dusty winds or rain is needed, as all activities are carried on outdoors.

3.11.1.3 GREAT LAKES CLIMATE ZONE

Houses around Lake Victoria

Circular huts with conical roofs can be found along the shores of Lake Victoria(Fig. 3.11-6). The walls are made of earth while roofs are thatched. The people in this area are mainly fishermen due to the proximity of Lake Victoria. The round shape of the huts minimises thermal exchanges and the earth used in the vertical envelope provides thermal inertia, which mitigates the daily temperature variations of the Great Lakes climate. The thatched roofs provide good thermal insulation, reducing thermal loads, while overhangs protect the walls from rain and sun and create shaded areas for comfort. Ventilation is poor (the only opening is a door), but the hut is inhabited mainly during the night, when the temperature drops.

FIGURE 3.11-6 **ROUND HUTS AT LAKE VICTORIA**

3.11.1.4 HOT SEMI-ARID/SAVANNAH CLIMATE ZONE

Turkana Huts, Kenya

These huts can be found in the Turkana region of Kenya (Fig. 3.11-7). The people in this region are pastoralists, although they are starting to adopt agriculture. Nomadic communities build simple homes that are used for temporary occupation. The structure of Turkana huts depends on the availability of materials and the type of livestock owned by the family. The huts, which are mostly used during the night, are often dome shaped with the entrance opening facing away from the sun. In contrast to other semi-nomadic tribes, the Turkana do not carry building materials with them when they move and everything is collected on site at each new camp.

FIGURE 3.11-7 **TURKANA TEMPORARY HUT**

Huts are built of whatever thorn bushes, brushwood and trees are available in the area. In the plains, huts are usually built using thorn bushes interlaced with leafy vegetation. In the mountains, boughs of trees and thicker foliage are used, while in the relatively arid parts of central Turkana land, it is mainly palm leaves that are collected for construction; these provide shade and at the same time allow ventilation. In the rainy season huts are covered with animal skins, which are fixed with stones or pieces of wood, or fastened with leather thongs; where there is plenty of grass, straw is sometimes used.

The transition to permanent agricultural settlements has led to the development of a different kind of huts, which are circular, with walls made of tree branches and brushwood and,a thatched roof (Fig. 3.11-8)

FIGURE 3.11-8 **TURKANA PERMANENT HUTS**

Photo credits: *the apostrophe, http://www.flickr.com/photos/dirty_dan/4312427571/*

Masai Manyatta, Kenya

The Masai people live in the highlands around the border between Kenya and Tanzania. Often considered nomadic or semi-nomadic they are traditionally transient cattle breeders. Today, especially in Kenya, the Masai are often sedentary and agriculture is their primary source of income.

The Masai build settlements in which livestock enclosures and individual houses are fenced. The compact houses are oval, up to 5 m long, 3 m wide and 2.5 m high and are built around a frame of hardwood posts (Fig. 3.11-9). The walls are made with cow dung mixed with mud and ash placed on a structure of flexible branches. The walls are medium-weight as required in the savannah climate zone. The house has to protect the users from high temperatures, solar radiation, strong wind and heavy rainfall. The huts are constructed to resist even the heaviest rainfall despite the fact that the building materials are not waterproof.

FIGURE 3.11-9 **MASAI, KENYA: THE ENVELOPE IS MADE WITH COW DUNG AND ASH OVER A STRUCTURE IN WOOD AND THATCH**

Nyakyusa house, Tanzania

The Nyakyusa house of Southern Tanzania, found in Mbeya Region, uses bamboo in all its elements (walls, roof and ceiling), is rectangular in shape and has a pitched and gable roof (Fig. 3.11-10).

FIGURE 3.11-10 **NYAKYUSA TRADITIONAL HOUSE: MAIN RECTANGULAR HOUSE AND ROUND HOUSE (WIFE'S HOUSE)**

Source: *Mwakyusa A.T.H., Traditional and contemporary building styles used in Tanzania and to develop models for current needs, A dissertation submitted in partial fulfillment of the requirements for the award of the degree doctor of philosophy, St. Clements University British West Indies, 2006*

Construction materials, besides bamboo, are elephant grass thatch, reeds, ropes treated with black cotton soil, and clay soil. The split or dissected bamboo is tied to the internal face of the bamboo walls and cow dung is used as plaster.

The house is compact and the walls provide a limited level of insulation, as does the thatched roof, while the plaster provides some thermal mass. No finishes are provided externally apart from the decoration of the bisected bamboo pieces tied up with rope.

The house usually has two doors and each room has small windows for ventilation. The roof construction also allows some cross ventilation along the top of the perimeter walls. Door shutters are made of reeds and split pieces of bamboo woven together. They also allow ventilation.

The Nyakuysa house is a good example of climate responsive vernacular architecture, as it can provide better comfort than outdoors, not only at night but also during the day.

Sukuma house, Tanzania

The Sukuma ethnic group lives in the Mwanza and Shinyanga Regions. The traditional houses of these cultural groups are of the *Msonge* type. Usually, they are cone-cylindrical houses with a round hipped roof, constructed of poles, sticks, bamboo, mud and grass (Fig. 3.11-11). The roofs are neatly trimmed into steps using grass and protect the walls from solar radiation.

FIGURE 3.11-11 **SUKUMA TRADITIONAL HOUSE**

Source: *Mwakyusa A.T.H., Traditional and contemporary building styles used in Tanzania and to develop models for current needs, A dissertation submitted in partial fulfillment of the requirements for the award of the degree doctor of philosophy, St. Clements University British West Indies, 2006*

The *Sukuma* House has one door. The walls are made of wetted clay pasted on hard-wooden poles fastened by small sticks and fibres and a small gap is left between the wall and the thatched roof. This air gap (Fig. 3.11-12) improves ventilation and the roof and walls provide insulation and thermal mass.

FIGURE 3.11-12 **AIR GAP BETWEEN WALL AND ROOF**

Traditional hut type common in different EAC areas

Beehive shaped or domed huts can be found in many parts of the EAC (Fig. 3.11-13).

FIGURE 3.11-13 **DOMED STRAW HUTS IN BURUNDI (LEFT) AND IN UGANDA (RIGHT)**

Source of Burundi hut: *http://www.skyscrapercity.com/showthread.php?t=978522*

The thick layer of straw making up the whole external layer of the envelope provides good thermal insulation, but very little thermal inertia. The shelter seems to be designed to provide warmth during the night, as there is poor ventilation: the only opening is a door. This type of house is used by people whose activities are mostly carried on outdoors. Local materials are used in the simplest way to provide protection from sun, wind and rainfall.

This type of traditional house, the Haya house, is found towards the border in the north-west part of Tanzania, in the regions of Kagera, Biharamulo and Kigoma. They are *Msonge* type and are constructed of poles, bamboo, sticks and grass.

The Haya house (Fig. 3.11-14) is conical and is thatched from ground to apex. It generally has a diameter of about 6.5 m and a height of about 4.3 m. The commonly used materials are bamboo pieces, sticks and reeds, which are tied together with ropes of banana bark. Construction is carried out from top to bottom, using closely-packed bamboo held in place by circles of sticks thatched with grass. Strong supporting poles are used and the interior is plastered to provide some thermal mass. Only one door is usually provided and it is protrusive and arched.

FIGURE 3.11-14 **HAYA TRADITIONAL HOUSE**

Photo credit: *Graham'n'Judy, http://www.flickr.com/photos/grahamcole1/5401688845/lightbox/*

The compact envelope minimizes solar gains on the exposed surface and the grass envelope provides insulation.

Another common type of house has a rectangular plan and is built with mud bonded with sticks and reeds applied to a frame made of wood or bamboo (Fig. 3.11-15). The frames are bound together and the thatched roof is tied to the frame with strong materials such as hemp fibres or braided coconut husks. An air gap is often left between the top of the walls and the roof to allow natural ventilation. The thatched roof has been, in most cases, replaced by a corrugated iron roof (Fig. 3.11-16), which requires less maintenance but has an adverse effect on thermal comfort.

FIGURE 3.11-15 **MUD BONDED WITH STICKS AND REEDS APPLIED TO A FRAME MADE OF WOOD**

FIGURE 3.11-16 **RECTANGULAR SHAPED HOUSES: THATCHED AND IRON ROOFS**

Mud bricks, made from a mixture mix of clay, water and straw and dried in the sun, are also used. Mud bricks are cheap and keep warm in winter and cool in summer as they provide thermal mass. Houses built of mud or with mud bricks are vulnerable to heavy rains and flooding. The overhang of the thatch roof is used to shade and protect the walls from rainfall and the house is constructed on stilts, which prevents it from being flooded during the wet season. Houses are not equipped with windows. The thatched roof is about 25-30 cm thick and is made of palm leaves and grass. It helps to mitigate thermal conditions, providing good insulation and maintaining warmth during the cool nights. The houses show adequate strategies to face the climatic conditions, such as sun protection due to the roof and thermal mass due to the walls being made of clay and straw. More recently, ventilation has been improved by the addition of some openings; however, iron sheets are less suitable for roofing because they make the house uninhabitable when the sun shines and are noisy when it rains.

3.11.1.5 **HOT HUMID CLIMATE ZONE**

Swahili houses, Tanzania

Local materials such as mud and poles, sticks, soil, palm leaves and grass are the major building materials used and grass thatch is a common material for roofing (Fig. 3.11-17). The traditional house found in the rural areas of the coastal strip is the *Zaramo* house, probably the origin of the *Swahili* House. Each room of the house is provided with windows for ventilation. The light-weight envelope is adequate for thermal comfort in the climatic conditions. Openings are shaded by the overhanging roof.

The examples of vernacular architecture described above can provide an idea of the technical traditions and skills of local populations in the EAC. The climate is taken into account in building design, for example improved insulation is provided in upland and high upland climates, thermal capacity in hot-arid climates and ventilation and sun protection in hot-humid climates. Sometimes the local materials used are not suitable for making wide openings but ventilation is promoted by the gap left between the walls and roof. The thermal inertia of the vertical envelope and the plant materials preferred for the roofs is the result of traditional habits and techniques and are generally appropriate to the climate. Thick layers of thatch provide insulation in the roofs, reducing the heat flow and allowing breathability in conditions of high humidity. People in the various regions have a lifestyle in which most activities are carried on outdoors. Furthermore, nomadic people living with livestock prefer lightness and transportability of the shelters to thermal properties, and this is clearly related to specific needs.

FIGURE 3.11-17 **SWAHILI TRADITIONAL HOUSE IN KIGAMBONI (DAR ES SALAAM, TANZANIA)**

Photo credit: *Maria Chiara Pastori*

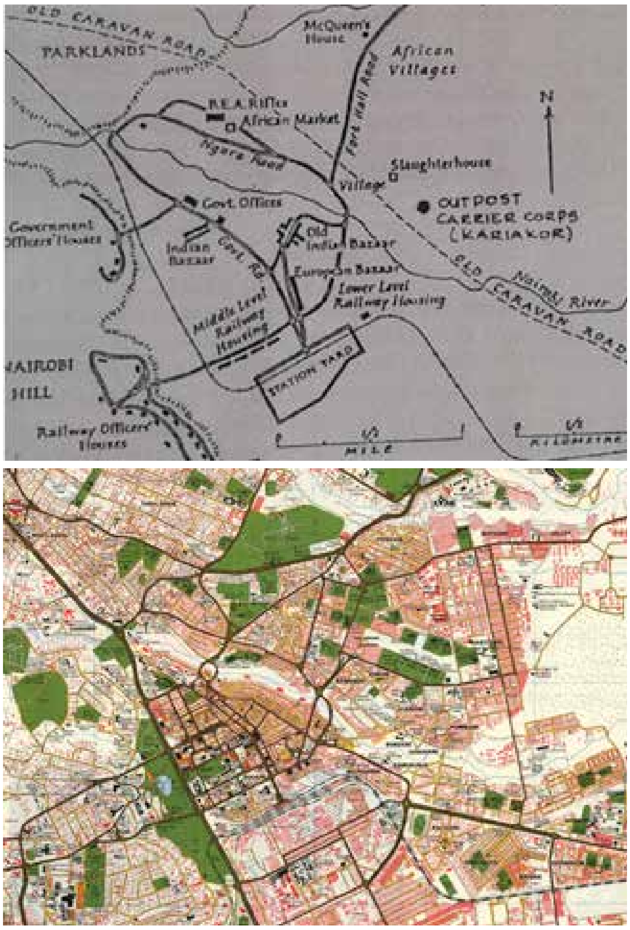
Not all the technical solutions can be considered as optimal for thermal purposes but they are used because of ease of construction, availability of materials, established construction practices, cheapness, and reduced maintenance.

3.11.2 EXAMPLES OF COLONIAL AND PRE-COLONIAL ARCHITECTURE IN EAC COUNTRIES

As opposed to the Romans, who planned new cities in their colonized territories with a layout based on the *Cardo* and *Decumanus* orientation (north-south and east-west, respectively) complying with environmental needs, in East Africa the colonizers planned cities on the basis of criteria not related to climatic requirements.

For example, the urban layout of Nairobi derives from the blueprint for the railway and from the consequent position of the railway station, whose yard faces the south quadrant (Fig. 3.11-18). The orientation of the railway station generated the entire urban layout, which is reasonable as far as solar protection is concerned (the ideal would have been a north-south/east west street grid orientation), but is not optimal for exploitation of natural ventilation. In fact, the street grid would be better if rotated 45° or more clockwise, to exploit the north-east wind which blows during the hot season.

FIGURE 3.11-18 **ORIGINAL TOWN PLAN OF NAIROBI, 1900, SHOWING THE RAILWAY LINE/STATION AND PRESENT MAP OF THE CITY**



Source: *(top) Hake A., African Metropolis, Sussex University Press, 1977; (bottom) http://nairobiarch638.wordpress.com/*

Similarly, in Tanzania the layout of Dar es Salaam does not meet the fundamental needs of ventilation required for the hot-humid coastal climate. The urban layout grew around the bay due to the particular commercial nature of the city, which was based on the port and whose layout was dictated by the layout of the harbour itself (Fig. 3.11-19). Monsoon winds (south-west from April to October and north-west from November to March) cannot be efficiently exploited to ventilate the buildings because of the orientation of the streets.

Lamu Old Town is the oldest and best-preserved Swahili settlement in East Africa, retaining its traditional functions. Lamu Old Town is located on an island off the coast of East Africa to the north of Mombasa. Most of the street grid is oriented north-south/east-west, to ensure maximum solar protection of the façades of the buildings (the town also has narrow streets) and to exploit the prevailing winds to the best advantage for natural ventilation (Fig. 3.11-20). Moreover, the buildings have porticoes, arcades and open verandas that shade openings. The orientation combines two requirements, religious (all *quibla* walls face Mecca, which from East Africa is to the north) and environmental.

FIGURE 3.11-19 **PLAN OF THE COLONIAL AREA OF DAR ES SALAAM IN THE MID 19TH CENTURY (TOP) AND TODAY (BOTTOM)**

FIGURE 3.11-20 **PLAN AND SEA FRONT OF LAMU OLD TOWN**

3.11.2.1 PRE-COLONIAL BUILDINGS IN LAMU

The Swahili architecture in Lamu is representative of a technology based on coral, lime and mangrove poles. Coral is the ideal building material: light, strong and readily available, it improves with time, becoming harder and more homogeneous with exposure to rain and the tropical sun. The walls were made with large chunks of coral stone (50 cm thick).

The high thermal mass of the structure does not allow the occupants to benefit from a temperature reduction during the night, which is, however, rather limited. The temperature inside the buildings is almost constant throughout the 24 hours and thermal comfort is entirely dependent on solar protection and natural ventilation.

3.11.2.2 COLONIAL BUILDINGS IN NAIROBI

Most of the colonial buildings in Nairobi were two to three storeys high, dominating the generally single storey urban configuration.

The main façades had symmetry, rhythm and order and incorporated classical elements such as colonnaded porticoes.

The use of the porticoes and loggias is appropriate for the climate as it:

- serves as a transition space from the hot dusty street to the cool interiors;
- shades windows and adjacent walls;
- provides a visual transition from the bright sky, with illuminance as high as 120,000 lux, to relatively dark interiors;
- acts as a shelter for visitors to the buildings during the rainy season.

The properties of these elements were not always fully exploited. In the Archives building, for example, the portico has visual importance rather than a functional role, as the double volume lacks depth (Fig. 3.11-21). The depth of the cornice, however, helps to shade the upper windows by reducing solar gains.

The design of the Kenya Railways Headquarters Building, takes into consideration the need for solar protection, with large overhanging roofs and horizontal shading devices (Fig. 3.11-22).

In the case of the Macmillan Library (Fig. 3.11-23), the main façade faces south, but the west-facing windows, which are not protected, cause a heavy solar load. On the other hand, the east wing is well ventilated during the hot season, exploiting the north-east winds.

FIGURE 3.11-21 **THE ARCHIVE BUILDING PORTICO**

Source: *Mweu M., Colonial public architecture in Nairobi, Kenya: an environmental analysis, M.Phil.Essay 01, Architecture and History of Art Library (The Martin Centre), 2001*

FIGURE 3.11-22 **RAILWAYS BUILDING WITH DEEP ROOF OVERHANGS AND EARTH COLOURED FINISHES**

FIGURE 3.11-23 **MACMILLAN LIBRARY**

The City Hall building (Fig. 3.11-24), with its elongated plan shape and the south facing main façade, exploits the street layout to the best advantage.

FIGURE 3.11-24 **CITY HALL BUILDING**

Heavy masonry walls (60 cm thick) built with hand hewn blocks of trachyte tuff were invariably used, with several advantages:

- the stones were locally available, unlike iron sheets that had to be imported;
- there was also locally available skilled labour in the Indian masons and craftsmen;
- in the Nairobi climate, the heavy masonry walls kept out the high outdoor temperatures for the better part of the day, ensuring a cool internal working environment during the hot season, and took advantage of passive heating in the cool season.

The external finish was largely determined by the architect's attitude to the control of heat and light. For example in the City Hall building the external façades were painted white. Though good at reflecting incident radiation, light colours become dirty and darkened due to dust and smoke, reducing their reflective properties. Iron sheet roofs were thought to be unsightly and were normally hidden behind elaborate parapets integrated into the design of the building façades. Examples of these are the Macmillan Library and the Archive building.

It was not until the late 1920's that terracotta roof tiles were used for the first time in Nairobi. The roof tiles looked more graceful and attractive, which made it possible for the eaves of the buildings to be designed with large roof overhangs to shade walls and openings.

The window to wall ratio was low and fairly consistent. The wall fenestration order replicated the basic window module whose proportions and size were influenced by:

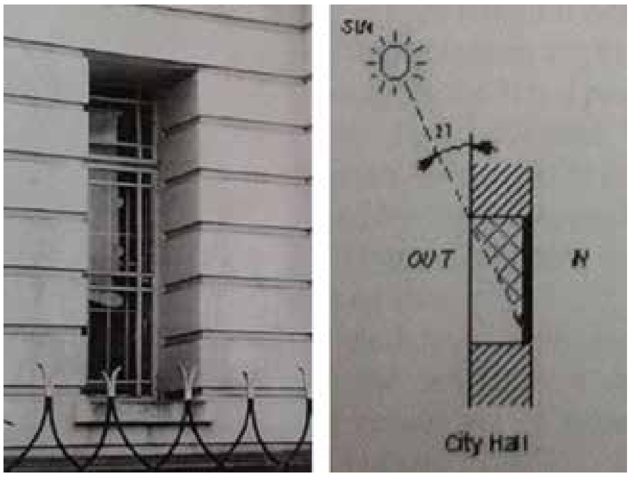
- the high ceilings of the enclosed spaces;
- the load bearing nature of the walls.

This resulted in tall windows with a low frame to glazing ratio, which maximized daylight.

Although the window to wall ratio was low, the combination of the shallow plans and the high sky illuminance made it possible to light the offices adequately.

In the City Hall and Archives buildings, recessed windows provided shade when the sun was high in the sky (but were exposed to the evening and morning sun) and the deep, light coloured intrados reduced glare by minimizing the contrast in illumination levels between the window and the adjacent internal wall surfaces (Fig. 3.11-25).

FIGURE. 3.11-25 **WINDOW DESIGN: CITY HALL WINDOWS EFFECTIVELY CUT OUT HIGH ALTITUDE SUN**



Source: *Mweu M., Colonial public architecture in Nairobi, Kenya: an environmental analysis, M.Phil.Essay 01, Architecture and History of Art Library (The Martin Centre), 2001*

3.11.2.3 **COLONIAL BUILDINGS IN DAR ES SALAAM**

Colonial buildings in Dar Es Salaam can be found in the quarter near the bay of Dar Es Salaam and they have a representative role in the town. The grandeur and the massive character of the colonial buildings in Africa are related to their institutional function. The colonizers wanted to show the impressiveness of the colonial power through big massive buildings although climatic conditions required different strategies, especially in the tropical hot-humid climate of coastal Tanzania.

The main strategy adopted was based on solar protection (porticoes, verandas and overhanging roof to create external shaded spaces) and wide openings to enhance natural ventilation (Fig. 3.11-26).

FIGURE 3.11-26 **LARGE OPENINGS AND VERANDAS FOR NATURAL VENTILATION**

FIGURE 3.11-27 **THE HIGH COURT OF TANZANIA, DAR ES SALAAM: VIEW FROM THE STREET, PORTICO AND GALLERY SHADED TO REDUCE SOLAR GAINS**

In the High Court Building in Dar Es Salaam (Fig. 3.11-27), the ground floor is higher than the other floors for representative purposes. This feature turns into an advantage for the ventilation of the indoor spaces through the elongated windows, which are composed of different operable portions and wooden blinds to allow ventilation as well as preserving privacy and protecting from solar radiation.

The iron sheet roof shades the gallery of the first floor. The Mayai Building is a good example of a colonial building restored to its original form. It has unique historical features. It was German headquarters during colonial times and was later occupied by the British in 1918. It recalls the solidity and strength of the colonisers.

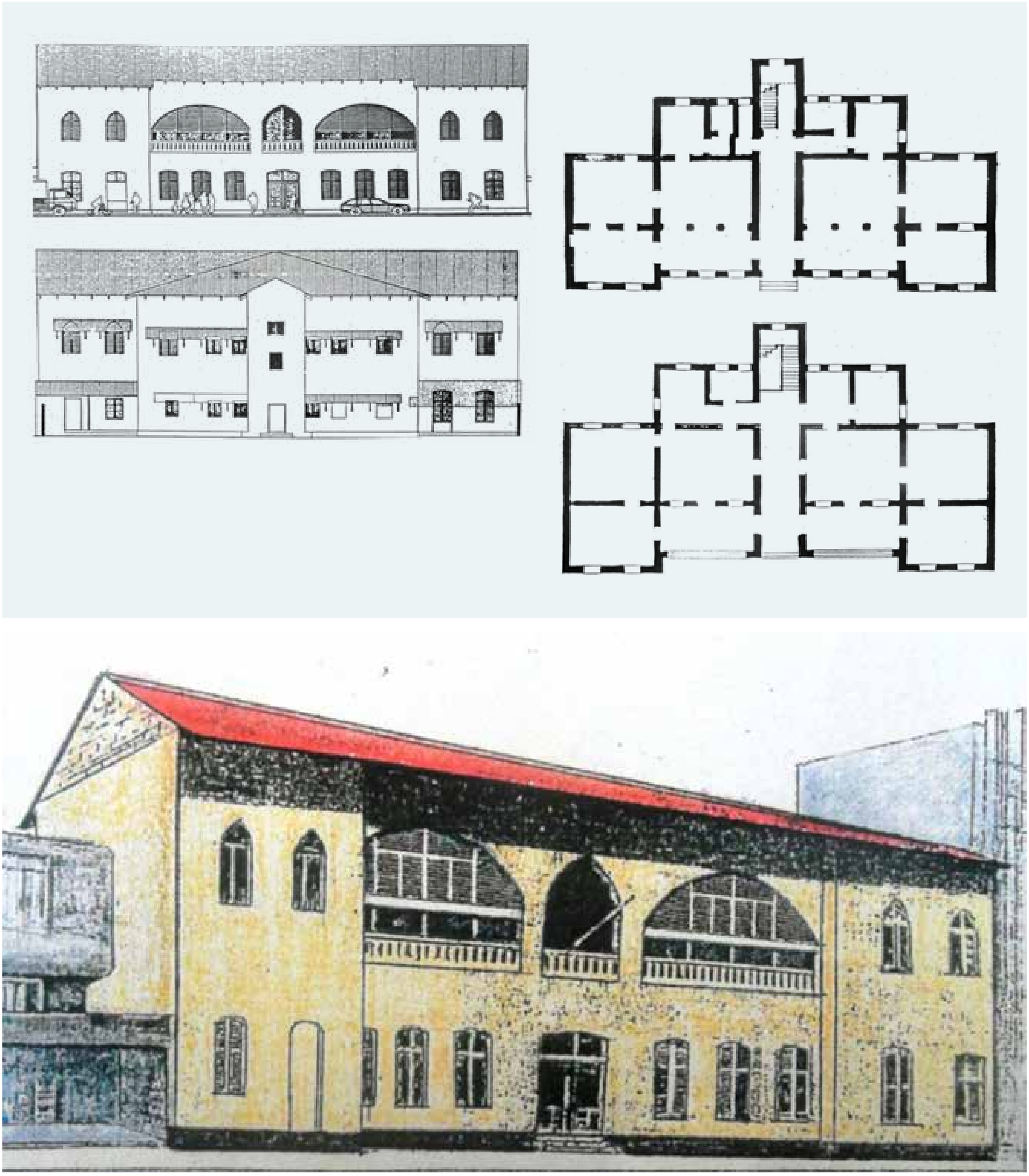
The Mayai building is presently used as the offices of the Tanzania Revenue Authority (TRA) and was renovated in order to restore the building to its original condition, introducing a few changes to improve its thermal performance.

The building has two storeys and the load-bearing walls are made of coral stones set in lime mortar.

The building's long axis is in the direction of the prevailing winds; therefore cross ventilation cannot be exploited to the best advantage. On the other hand, the massive structure, which would be inappropriate in a residential building, can play a positive role as an office building, since it attenuates the temperature variations indoors during the day and the higher night temperature is not a drawback as the building is not inhabited at night.

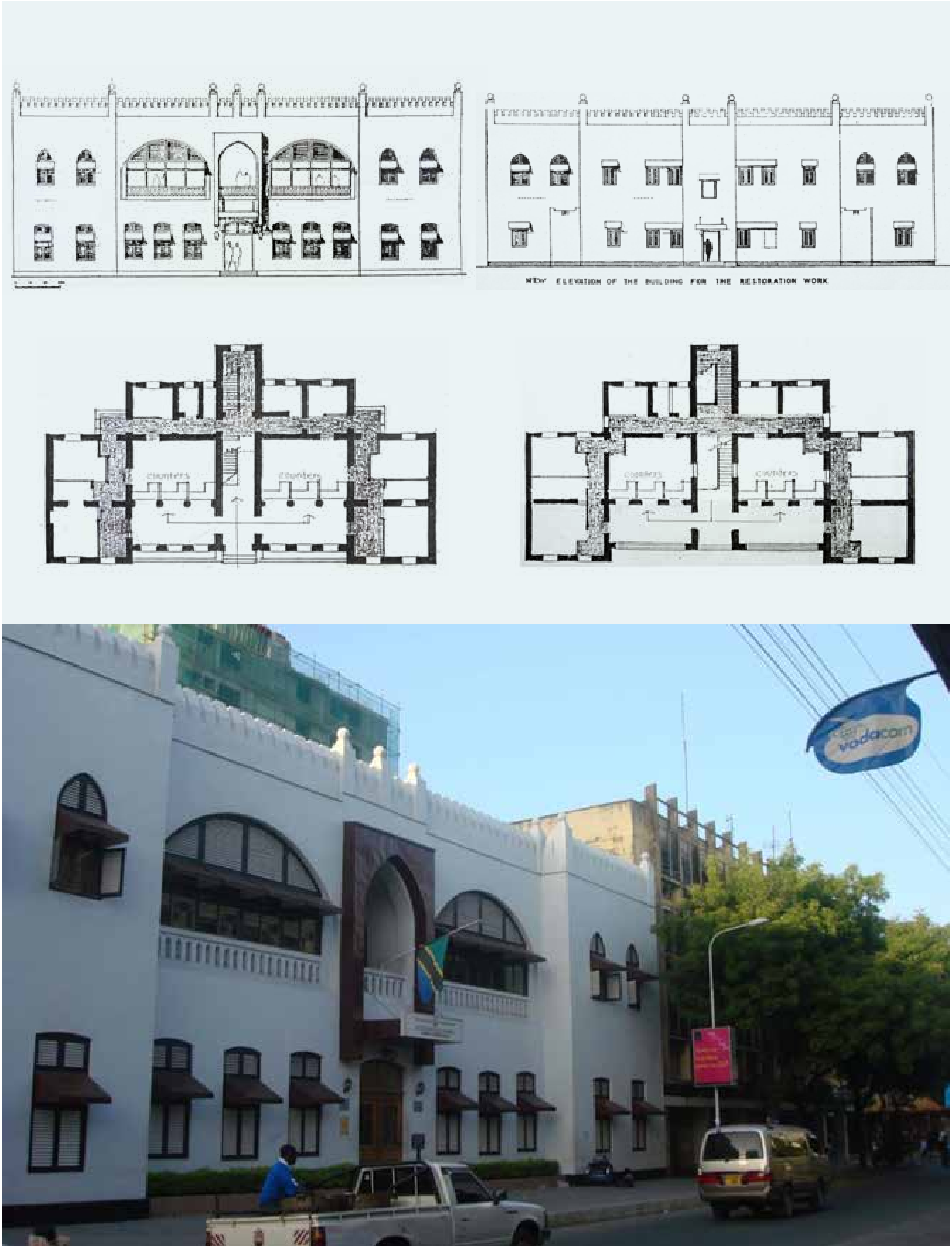
In the British period the appearance of the building was changed as shown in figure 3.11-28. The current renovation (Fig. 3.11-29) aimed to restore the original appearance of the building with adjustments to the floor plans creating secure corridors for fire escape and an additional staircase. At the same time the original structure of the building was retained. The design of the parapet wall demonstrates the Zanzibari and Indian influences of the builders on the architectural style. The choice of coral stone for the walls comes from traditional construction practices, as seen in Lamu Old Town.

FIGURE 3.11-28 **ELEVATIONS, PLANS AND APPEARANCE OF THE MAYAI BUILDING POST 1918 (BRITISH PERIOD)**



Source: *Anthony B. Almeida, Tanzania Revenue Authority building, in Kakuru Linda, Mosha Comfort, Nestory Rose, Theme:Mapping the Stars of Dar, Star Buildings, Star Places, 2011*

FIGURE 3.11-29 **ELEVATIONS, PLANS AND PICTURE OF MAYAI BUILDING RESTORED**



Source: *Anthony B. Almeida, Tanzania Revenue Authority building, in Kakuru Linda, Mosha Comfort, Nestory Rose, Theme: Mapping the Stars of Dar, Star Buildings, Star Places, 2011*

The building had compact plans in which corridors were created and the roof was restored to its original morphology.

The restored building has new shading devices at all the windows to control direct sun radiation. This is also provided by the shutters, which are used to darken the interior spaces without compromising ventilation. The entrance is designed to match the building elevations.

3.11.2.4 **EVOLUTION OF COLONIAL ARCHITECTURE**

Buildings constructed in the first colonial period were a reproduction of occidental architecture. To deal with the obvious inadequacies related to climate, substantial changes were then introduced Particular adaptations can be recognized in:

- widening of the windows to improve natural ventilation;
- double facing rooms (north/south) to adapt to the solar path in near equatorial latitudes and to favour cross ventilation;
- covered porches frequently used around the buildings to provide shading;
- buildings on studs, to avoid rising damp in the humid climate.

All these innovations were introduced in order to adapt the buildings to the tropical climate by protecting them from intense radiation and heavy rains, facilitating natural ventilation and reducing the high rate of humidity and moisture coming into the building from the ground.

04 ENERGY EFFICIENT BUILDINGS DESIGN

4.1 THE ENVELOPE

There are, for some types of building, periods of the year and climate zones in which thermal comfort cannot be achieved without the use of a cooling or heating system even if the building has been designed according to the guidelines given in chapter 3. This is common in commercial buildings, because of the significant internal loads (people, office equipment, artificial lighting), but – to a lesser extent – it also applies to residential buildings. To cope with these situations, in which a mechanical system is needed to provide comfortable conditions, openings must be designed with special care in order to minimise energy consumption. The reason for this is that openings are glazed and windows are shut during the period in which the cooling system is working, with the following consequences:

- solar gains are a more critical issue because of the greenhouse effect;
- natural lighting is a more critical issue, especially in commercial buildings, because of the impact of glare on occupants, who cannot freely choose the position of their workstation and because the visual quality of the environment can be influenced by the type of glazing used;
- thermal comfort is affected by the temperature reached by the glazed surfaces (even if solar protections are provided, diffuse radiation causes an increase in the temperature of the glass).

4.1.1 GLAZING

Glass panes were perhaps the most important technological advance in the history of buildings. They allowed an extraordinary leap forward in the quality of indoor life, making other innovations possible. No longer was there the forced conjunction of light and outside air (cold in winter and hot in summer), which had to pass through the same openings (in fact the word window in English is derived from the Icelandic word meaning "eye of the wind"). And not just light without "wind"; the sun penetrating through the glass also heats the room, thanks to the greenhouse effect. Of course this is a problem in summer, but it is easily solved with external protection and/or by opening the windows.

4.1.1.1 **GLASS, CLIMATE AND ENERGY**

Glazed windows have evolved in such a way as to provide systems which can be adapted to external and internal conditions, according to different climates. In central and northern Europe relatively large glass surfaces are found. They are partially operable (typically the sash window) and have internal sunscreens (curtains), which are often dark. Quite different solutions have evolved in the Mediterranean: glass surfaces are smaller than those in central and northern Europe, windows open fully for greater benefit from natural ventilation in summer, and there is external sun protection (usually in the form of shutters, often with movable slats). This is completely logical: where it is cold in winter, the sky is mostly cloudy and the summers are short and cool, you have to let the sun in as much as possible, sunscreens should serve only to adjust the intensity of the entering light and ventilation should not be excessive because the air is cool. In the Mediterranean, it is a different story: sun protection and ventilation are the prerequisites for a comfortable environment in summer, but in winter ventilation must be limited and some solar gain is welcome.

In hot-humid tropical climates the jalousie window has been the most popular and appropriate technological solution for the fine tuning of natural ventilation.

Up until the nineteenth century these logical solutions were adopted in all types of building, residential or commercial, with few exceptions. Then, at the beginning of the twentieth century a revolutionary tsunami hit architecture, a revolution which made a clean sweep of all the rules of the past by imposing a new slogan: lightness and transparency, which translated into an envelope made of glass .

So, in the midst of brilliant insights, the abuse of glass developed and was consolidated, leading, inevitably, to the abandonment of (often to contempt for) the principle of adaptation to climate, and buildings - glittering jewels - became the same everywhere, from Oslo to Dubai.

Lightness and transparency. At that time it was a little known fact, but it is a lightness that creates thousands, if not millions of tons of CO_2, due to the enormous waste of energy needed for heating in winter in cold climates, for cooling in hot seasons and climates and for the artificial lighting necessary even when the sun is shining, as it does every day.

It is a transparency that exists only in pictures in magazines, because in reality the curtains are always closed by the occupants trying to restore the visual and thermal comfort that such transparency precludes.

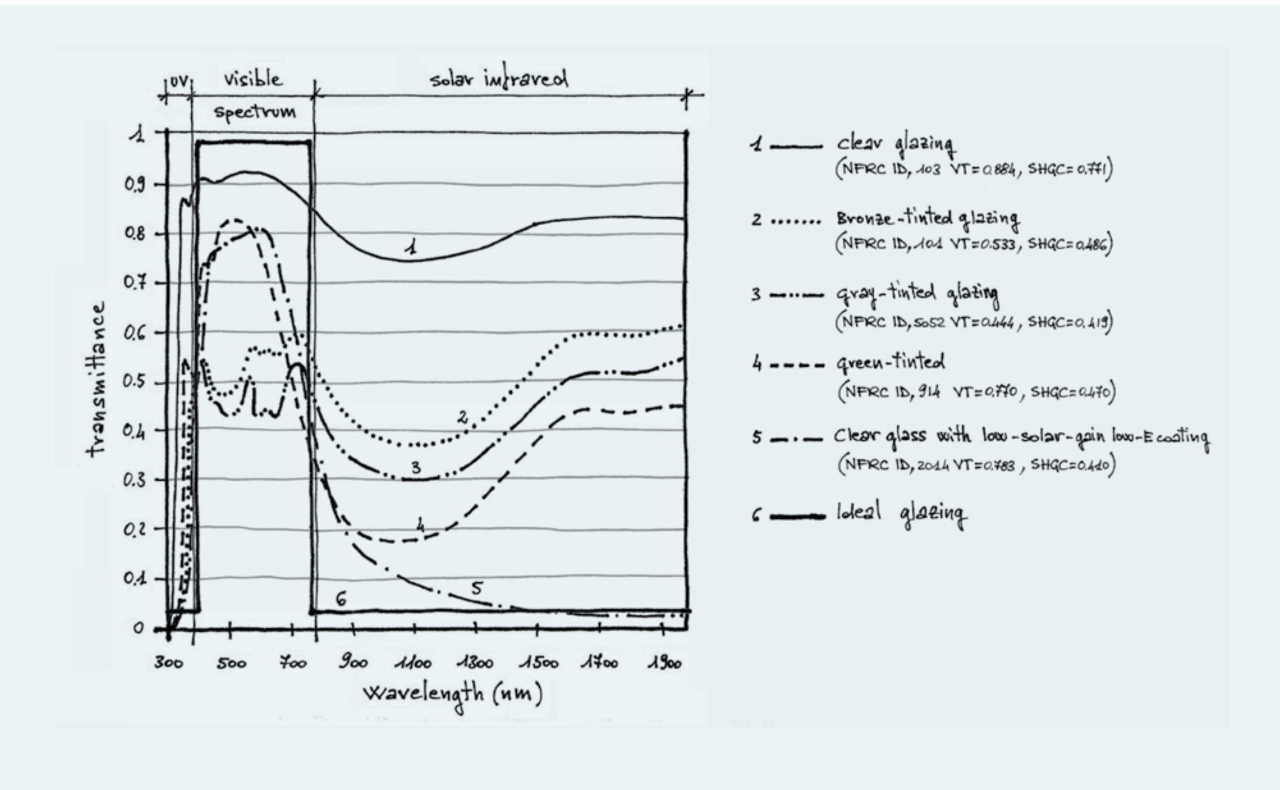
4.1.1.2 GLASS AND SOLAR RADIATION

Glass causes the so-called greenhouse effect, due to the selectivity of glass to radiation: glass transmits short and near infrared waves (radiation of wavelengths less than 2.5 microns), but blocks the long waves[34]. Short and near infrared waves pass through the glass and are absorbed by surfaces and objects inside. These objects warm up and re-radiate long waves, i.e. thermal radiation, which - being of a wavelength greater than 2.5 microns - is retained in the indoor environment, blocked by the glass, thus generating a temperature increase.

The transformation of solar energy into thermal energy is an ambivalent factor; on the one hand, it allows the room to be heated with solar energy in cold climates, on the other hand it causes an energy gain that must be removed to avoid overheating in hot climates and seasons.

Figure 4.1-1 shows that glass has a selective transmittance as a function of wavelength, and that the spectral transmission curve is different in relation to the type of glass: spectrally selective glass, for example, attenuates transmission in the visible range a little but in the near infrared, where a large part of the solar radiation (about 50 %) lies, it attenuates transmission by a great amount. Reflective glass has big disadvantages from both the thermal and visual points of view. If the reduced transparency in the infrared is advantageous, the benefit is heavily outweighed by the poor transparency to visible radiation, resulting in the need for the use of artificial lighting even on the brightest days. This type of glass is not recommended from the energy point of view.

FIGURE 4.1-1 **SOLAR RADIATION TRANSMITTANCE THROUGH DIFFERENT TYPES OF GLASS.**



***Legend:** NFRC = National Fenestration Rating Council; SHGC = Solar Heat Gain Coefficient; VT = Visual Transmittance*

34 Visual and thermal performances of glass panes are treated in detail in Appendix 1 – Principles of building physics.

Long-wave radiant heat has considerable weight in the overall energy balance of glass, thus reducing it dramatically improves the performance of glass in cold climates. For this reason low-emissivity films are used. Standard glass has an emissivity equal to 0.84 in the far infrared, which means that it emits 84% of all the energy that can theoretically be emitted by radiation; since the value of the emissivity coincides with that of absorption it also means that when a flow of radiant energy in the far infrared strikes the glass, it absorbs 84% of radiant energy and reflects 16%. Glass protected by a low-emissivity film, however, has an emissivity of about 0.04, so this glass emits only 4% of the radiant energy that it can theoretically emit, and reflects 94% of the radiation in the far infrared that strikes it; the radiation that comes from the inside is therefore almost totally returned, greatly reducing the losses. This property, which is extremely positive in cold climates and seasons, makes the low-e glass unsuitable or even useless in hot climates and seasons and constitutes an unjustifiable cost, as shown in figure 4.1-2.

Since the solar radiation spectrum extends from ultraviolet to the near infrared, while objects at room temperature emit radiation in the far infrared, the ideal glass should be capable of transmitting the radiation in the visible range leaving the spectral distribution unchanged, so as to ensure the same colour perception that would occur in the absence of glass. It should also be capable of meeting other different (and contradictory) needs in the cold and the hot seasons. In the cold season, the ideal glass should be able to transmit the near infrared fraction of solar radiation indoors, to contribute to space heating, and it should be able to block the far infrared radiation emitted by heated rooms (Fig. 4.1-3, line 1); in the hot season, by contrast, the ideal glass should be able to block the near infrared component of solar radiation, to reduce the heat gain, and transmit the far infrared radiation emitted by the interior space (Fig. 4.1-3, line 2).

FIGURE 4.1-2 **RELATIVE ENERGY CONSUMPTION IN A ROOM WITH DIFFERENT TYPES OF GLAZING AND ORIENTATION IN THREE EAC CLIMATES (SINGLE GLASS = 100)**

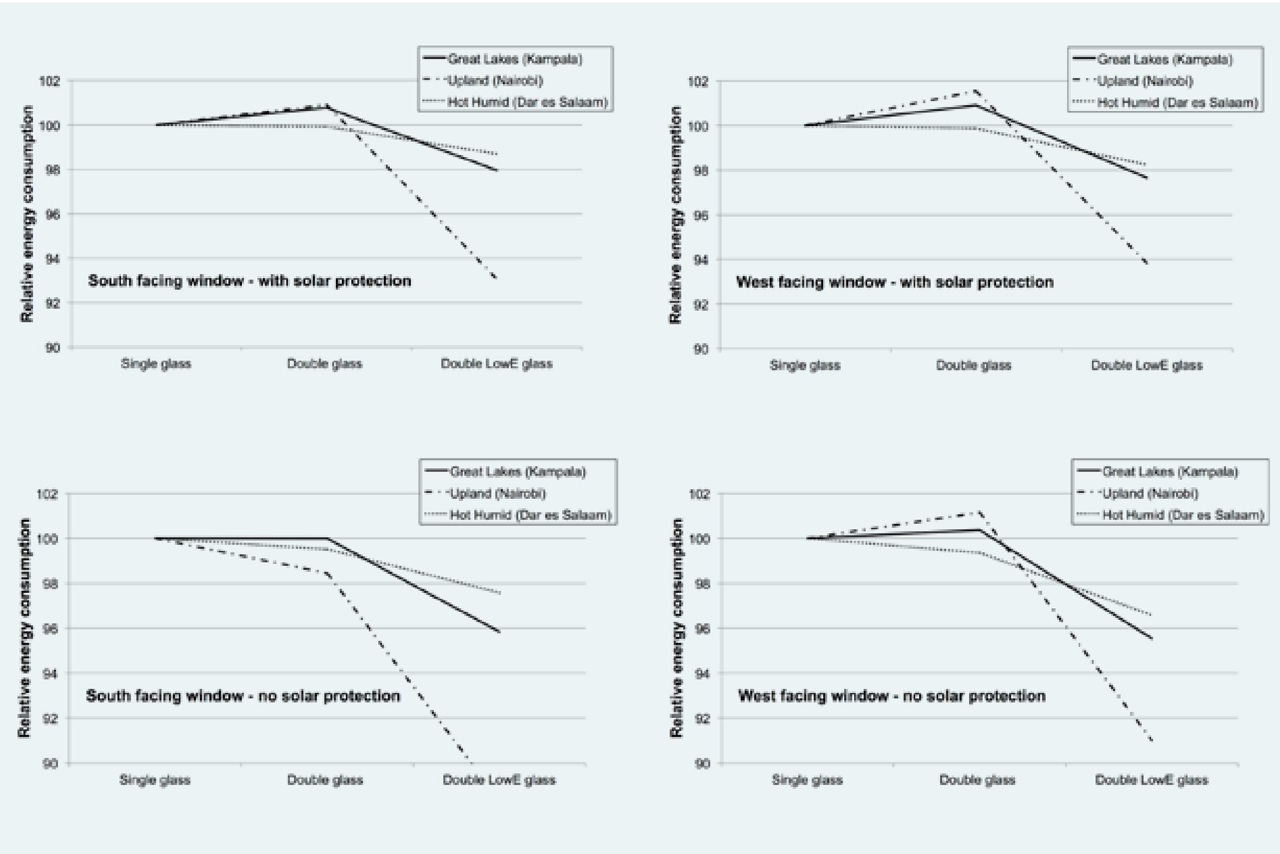
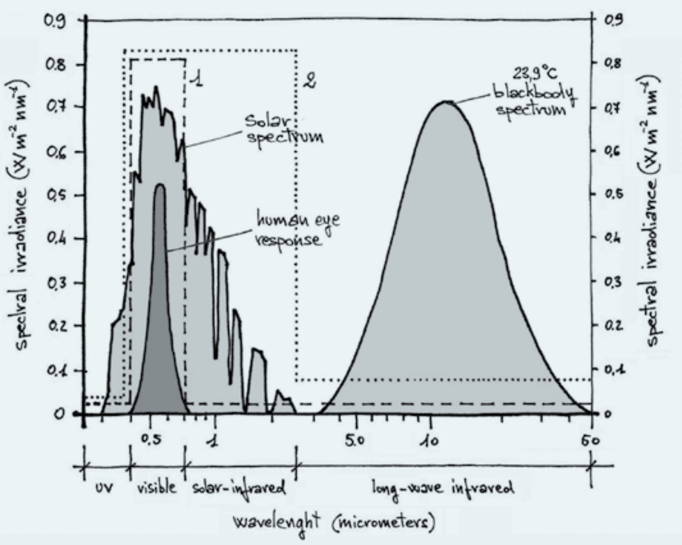


FIGURE 4.1-3 **SPECTRAL TRANSMISSION OF ELECTROMAGNETIC RADIATION OF AN IDEAL GLASS IN DIFFERENT CLIMATES**



In order to meet the ideal requirements, glazing has evolved a great deal in recent years, but still has limitations, which must always be taken into account.

Clear glass is fairly uniformly transparent to all wavelengths of solar radiation (excluding a slight reduction outside the range of the visible, between 700 and 1700 nanometres), figure 4.1-3. This has two consequences:

1. The solar spectrum in the visible range is changed only slightly, so an object inside looks - chromatically – the same as outside;
2. The radiation which falls in the near infrared also passes through the glass: it is invisible to our eyes, but full of energy (about 50% of total).

The first feature is certainly positive, and glass is the perfect material for comfortable natural lighting, and the second presents pros and cons. The pros are in cold seasons, when it is good that all the energy of the sun penetrates through the surface of the glass, as it contributes to a reduction in energy consumption. The cons are in hot climates/seasons, when this energy is unwanted, because it needs to be extracted by cooling to maintain comfort conditions.

Tinted glass changes the solar spectrum. As can be seen in figure 4.1-1, green glass is less transparent than clear glass to wavelengths greater than 520 nanometres, i.e. those that characterise the colour orange-red. It follows that this colour is attenuated, and in the resulting light – which is deprived of much of the red component – the green component is dominant. This glass, however, reduces the amount of solar energy passing through it, since the transmission of the radiation is lower over the whole spectrum, than that of clear glass. Grey and bronze glass, on the other hand, attenuates the radiation (low transmission), but does not alter the spectrum in any appreciable way.

In order to alleviate the problem of high solar gains in buildings with large window areas, a type of "spectrally selective" glass, has been developed, which has the capability of attenuating the infrared component of the solar spectrum, while maintaining good transparency to visible radiation (glass n. 5 in Fig. 4.1-1).The result is that the ratio of light transmission to solar gain is greater than 1. According to the Department of Energy of the United States, glass whose index of selectivity is ≥ 1.25 is defined as spectrally selective (Table 4.1-1).

In principle, in hot climates with high solar radiation, such as in the tropics, the ideal would be to use glass with low SHGC (see Appendix 1 and Glossary for its meaning). This would apply if the properties of the glass were those of the "ideal glass" described above. Unfortunately, real glass with low SHGC also shows poor light transmission (which forces occupants to use artificial lighting), or poor light quality (too "cold", resulting in the need to blend it with artificial light). If the glass is bronze or grey, light quality is little altered, but the low light transmittance leads to a high WWR (Window to Wall Ratio), which outweighs the benefit of a low SHGC. In conclusion, the best choice would be to use clear glass with low WWR, and well-designed sun shading devices.

TABLE 4.1-1 **INDICATIVE VALUES OF THE CHARACTERISTIC PARAMETERS OF SOME TYPES OF GLASS**

Grazing type (double)	Light transmission τ_{vis}	Solar Heat Gain Coefficient SHGC	Selectivity index τ_{vis}/SHGC
Clear	0.82	0.87	0.94
Bronze	0.62	0.64	1.03
Reflective	0.2	0.16	1.25
Selective	0.7	0.46	1.52

Thermal Comfort

The design of glazing and shading systems greatly affects the thermal comfort of a building's occupants, because thermal comfort in a space also depends on the radiant temperature of the interior surfaces. Glass, because of its particular characteristics, often works as a radiating plate (cold or hot) and, regardless of the air temperature, can create uncomfortable conditions in the perimeter zones. Coloured glass, for example, struck by solar radiation, can reach a significant surface temperature – especially in warm-hot climates/seasons – and cause great discomfort, even if the air temperature is comfortable. The occupants react by adjusting the thermostat to a lower temperature, wasting energy, and even then are not able to obtain satisfactory comfort conditions.

Visual comfort

An often underestimated consequence that derives from the use of green and blue tinted glass is that the luminous flux entering the room shifts towards green-blue, corresponding to that of a light source with a very high colour temperature (over 7000 K). It follows that, at the usual illumination level (300-500 lux), the occupants have the perception of a "cold" environment. They respond to this unpleasant sensation by turning the artificial lights on, which not only increases the level of illumination but which, mixed with the natural light transmitted by the glass, results in a reduction in the colour temperature, the artificial one being more "warm". This results in a more comfortable visual environment, which accords with the indications of the Kruithof curve (see Appendix 2). For this reason, lights are always on in buildings with green or blue tinted glass, regardless of the external conditions, resulting in a waste of energy and in poor visual comfort.

Selective glass has similar problems to those of non-neutral coloured glass. In fact, as shown in Fig. 4.1-1, they absorb a large amount of the solar spectrum corresponding to the orange-red wavelength range, giving rise to a light that becomes green-blue, i.e. "cold". The glass does not preserve the quality of light, and the tendency to turn on the lights can also be seen in this case.

Glazing with low values of τ_{vis} (transmittance in the visible spectrum) may be needed to prevent glare, especially in the case of east or west-facing windows and high values of WWR (Window to Wall Ratio); if the colour of the glass is green or blue the price to pay is a "cold" environment combined with high energy consumption.

4.1.1.3 **SMART WINDOWS**

These are systems capable of changing their optical and thermal properties according to varying climatic conditions, and to the preferences and requirements of the occupants of the building. These technologies are able to provide the maximum flexibility in managing the demand for energy consumption in buildings, especially in the most critical periods of the day.

There are two different types of windows with variable properties: passive, which respond to a single environmental variable, such as light or temperature, and active,which respond to multiple variables such as the preferences of the occupants or the demands of the air conditioning system. Photochromic and thermochromic glazing are passive devices; active devices include liquid crystals, suspended particles and electrochromic technologies.

Photochromic materials

Photochromic materials change their transparency in relation to the intensity of the light coming from the outside. For example, these materials are used in eyeglasses that become totally transparent in the presence of internal penumbra and dark in sunny outdoor conditions.

Photochromic glass may be used for the adjustment of the natural light, avoiding the effects of glare, and for the control of overload in the cooling system. Although elements of small dimensions have been produced on a large scale, those of larger size are not yet available on the market, due to their high cost.

Thermochromic materials

In these materials the transparency varies according to the temperature. They consist of two glass panes separated by a thin layer of a substance that changes its transparency as the temperature increases, from perfectly transparent to white reflective. They still have problems, in particular in relation to the uniformity of transparency and opacity on the surface. They are of little use, however, in tropical climates.

Glasses with liquid crystal devices

A very thin layer of liquid crystal, sandwiched between two transparent electrical conductors, is arranged between two layers of glass. When the power is zero, the liquid crystals are placed at random and then misaligned. In this arrangement the crystals scatter light and make the glass appear translucent, obscuring the direct view and providing privacy in indoor environments. The material transmits most of the incident sunlight in a diffuse manner, thus its solar heat gain coefficient remains high.

When the power is turned on, the electric field in the device aligns the liquid crystals and the glass becomes transparent in a fraction of a second, allowing vision in both directions. Most of the devices have only two states, transparent and translucent. The percentage of transmitted light is generally between 50 and 80% and the solar heat gain factor is 0.55-0.69, although colourants can be added to darken the system when it is off. Products offered by some companies are available in various colours, and either flat or curved glass. Stability to ultraviolet (UV) allows use in external applications, but their cost is still a problem.

Electrochromic glazing

Electrochromic glass is at present the most promising technology for windows that change optical properties. The electrochromic element consists of a thin coating of metal, such as nickel or tungsten oxide, between two layers of electrical conductor. When a voltage is applied between the transparent conductors, the light transmission properties of the glass change, from full transparent to blue, without limiting the visibility.

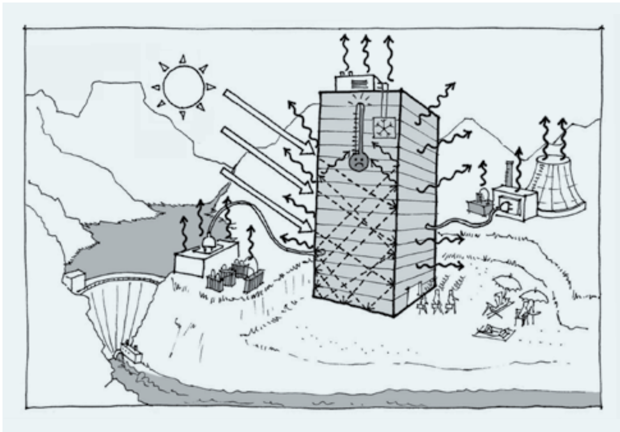
The main advantage of electrochromic windows is that generally they require a low voltage power supply (0-10 volts DC), remain transparent in the full range of property changes and can be modulated from transparent to completely coloured. The high initial price of electrochromic glass is partially offset by the reduction in the energy consumption of the air conditioning system and the elimination of the need for external sunscreens or internal blinds, because electrochromic windows make it possible to modulate solar gains and reduce glare; however, they have a limitation as regards colour: when they lose transparency they shift towards a cold colour.

4.1.1.4 GLASS ARCHITECTURE

The first thing to change must be the architectural fashion for fully glazed buildings, the proliferation of which is a cause of energy waste, especially in hot climates.

What's wrong with glass façades? There is no doubt that glass envelopes are light and transparent in architectural terms (and this is highly appreciated by architects and their clients). The fact is that they are also light and transparent in physical terms, which affects heat gains and thermal inertia in a way that makes them voracious consumers of energy (Fig. 4.1-4). But this is not the only problem. Below is a summary of the ways in which these fully glazed envelopes are used, and their effect on energy consumption and comfort.

FIGURE 4.1-4 **ENERGY AND GLASS BUILDINGS**



Since part of the solar spectrum is absorbed, on sunny hot days the glass warms up to 30-40 °C, and the infrared radiation emitted makes the nearby spaces uncomfortable. In most cases this undesired effect is reduced or eliminated by blowing a jet of cold air parallel to the glazed surface, whose temperature becomes closer to the room air temperature. In this way comfort is improved, but at the expense of higher heat gains.

There is another environmental drawback when tinted glass façades are used, especially if the colour is blue-green, which is the colour that is most appreciated and used by architects. The drawback is evident when we look at such buildings on clear days: in spite of the brilliant sunshine and the large amount of natural light available, the artificial lighting is on. The reason for this is that, even if the illumination level in the rooms reaches or is above the required value, the light coming from the fenestration is too "cold", due to the colour of the glass, and – as has been known for more than 60 years – the occupants feel that the luminous environment is uncomfortable; as a result, they switch on artificial lights, which are warmer and compensate for the cold natural lighting.

DOUBLE SKIN GLASS

The claimed advantages of double skin glass façade systems, compared to a single glass curtain are: greater energy efficiency (the heat loss is less than that of a single skin), better thermal comfort (the interspace is crossed by cold air, bringing the temperature of the inner glass to acceptable values), better sound control (greater attenuation of external noise) and the ability to control natural ventilation, all the while maintaining the architectural value of a light and transparent envelope.

The problem is that many of these claimed benefits are controversial or even contradicted by experimental evidence, sometimes conflicting with each other and in many cases lacking in scientific evidence.

A study carried out under the EU "Intelligent Building" programme, "Best Façades*" showed that:

- the cost of double skin glass is 20-80% higher than that of single skin glass, and 100-150% higher than a normal façade (wall and windows). So, to offset this extra cost, significant energy savings are required;
- maintenance costs for the double skin are obviously higher than those for single skin, because four surfaces instead of two must be cleaned, and more often if this gap is crossed by outside air. These higher costs are partially offset by lower maintenance requirements for sunscreens that are not exposed to rain and wind, being placed in the cavity between the two skins;
- although it is true that a reduction in traffic noise is one of the advantages offered by the double skin, it is also true that in many cases an increase in noise transmission between indoor environments has been reported, due to the reflection of sound in the cavity;
- from the point of view of fire safety the double skin has been strongly criticised, since firemen would be forced to break two glass panes before they could enter the building from the outside, and because of the possible spread of fire through the interspace;
- double skin façades, compared to traditional ones, require more space, more resources and more energy for production and construction (see Appendix 1). Their environmental impact is also higher and reducing it requires compensating with much lower energy consumption and less impact during demolition;
- the performance of a double-skin building is highly dependent on climate and on how the façade is designed. A building with a double glass skin which is well designed for the Swedish climate would not work in Nairobi, and vice versa. Furthermore, the design solutions must be different for each façade. Consequently, to obtain good performances with a double skin it is necessary to carry out complex dynamic simulations, sometimes with models developed "ad hoc": this is an indispensable precondition;
- experience in southern Europe shows that the milder the climate the worse the double skin glass façade performs.

The results of this study indicate that any application of this technology in tropical climates should be excluded.

* *BESTFACADE, Best Practice for Double Skin Façades (EIE/04/135/S07.38652, 2008), Publishable Report, WP5 Best Practice Guidelines, http://www.bestfacade.com*

Another issue related to visual comfort is when clear glass is used. The benefit of a large aperture that lets in a flood of natural light is entirely cancelled out by the effect of glare on the occupants' behaviour: they restore their visual comfort by obscuring the glass surface with curtains, Venetian blinds or whatever is available. The struggle for survival of the unfortunate occupants is clearly evident in all glazed buildings.

The final result on the energy balance of the building is easy to evaluate: there are high and uncontrolled solar gains in hot climates (the curtains inside, even if they are white, absorb solar energy that is transferred to the room) and the lights are always on.

Recently, to temper this undesirable effect, some leading architects have used external shading devices to protect the large glazed walls. It seems a good idea, but unfortunately although they cut off glare, light and outside vision are also cut off, and artificial lighting must be on all the time.

Glass is potentially a very effective material for low energy buildings thanks to the most recent technological developments, but fully glazed buildings exacerbate the problem of air conditioning in hot seasons/climates, increasing energy demands both because of the large solar gains and because of the induced need for artificial lighting in spite of natural light being always available.

The most effective way to stop the proliferation of energy wasting buildings is to develop and enforce appropriate building regulations dealing with energy conservation. In some countries, such as France, Spain and Portugal in Europe, and California in the US, there are limits to the maximum glazed area allowed in each façade, unless it can be demonstrated that the energy required for heating and cooling is less than a pre-set limit (see section 4.6).

4.1.2 SIZING AND DESIGN OF OPENINGS

Designing a window is not just a matter for architects, because the design of the glazed surfaces has a great impact on the design of the HVAC system. Windows have a significant impact on energy consumption in a building's perimeter spaces. The most direct impact is on the amount of energy needed for air conditioning.

If the windows are properly designed and the lighting system is well controlled, windows can eliminate or reduce the need for artificial lighting during the day by providing daylight, but this benefit may be outweighed by solar gains. Solar heat gain accounts for the majority of the cooling load in perimeter spaces with windows. It should also be considered that, although electricity consumption for artificial lighting decreases as the area of glass increases, provided that the area of the glass does not exceed 25% of the entire façade, beyond this value a sort of saturation is reached, and the savings in electricity achieved by continuing to increase the area of glass are very small, while consumption of energy for cooling continues to grow uniformly.

A designer's first choice should be to minimize the amount of direct solar radiation that reaches the windows. If direct sunlight can be kept off the windows, then inexpensive clear glass can be used. By using windows with solar control, it may be possible to reduce the size of the air conditioning equipment; these savings in equipment, in turn, can help offset some of the additional costs of the solar protection.

Window and shading design are closely linked to perimeter zone comfort, regardless of air temperature. Comfort should be considered as seriously as energy in fenestration design.

Using operable fenestration systems to ventilate the building naturally also reduces HVAC energy consumption by reducing the number of hours during which the HVAC system operates. In highland climates a carefully designed natural ventilation system may eliminate the need for a mechanical cooling system

Energy-efficient window design reduces solar heat gain while offering high visible light transmittance to allow more daylight inside. Benefits include:

- smaller and less expensive air conditioning equipment required;
- lower cooling energy costs;
- lower lighting energy costs;
- potentially better dehumidification performance from the air conditioning system because there is less variability in the space's cooling loads, thus the air conditioning system can be smaller and run at a more constant capacity.

4.1.2.1 RECOMMENDATIONS AND TIPS FOR WINDOW DESIGN

Begin daylighting design early in the design process. A building's orientation is critical for maximizing the use of diffused daylight and reducing direct solar penetration. The best orientations for daylight sources are north and south: the high angle of the sun is easy to control with a horizontal overhang.

Avoid east and west-facing windows for daylighting. The low angle of the sun makes it difficult to control direct sun penetration through the use of overhangs or other fixed shading devices. Any window orientation more than 15 degrees off true north or south requires careful assessment to avoid unwanted sun penetration.

The ideal orientation may not be possible in urban situations where plot sizes may be constrained. In such cases increase the surface area exposed to the south and north. This may be done by using light shafts, light wells or light courts such that the west and east-facing walls are shaded and receive diffused light.

Windows should provide three basic services: protect from rain and wind (when required); provide lighting; provide exterior view. Fulfilling these requirements is not free: a large window, which should provide the maximum light and the widest view, also lets in a large amount of solar radiation, with the consequent solar heat gain, and – if it is not properly designed – causes the very unpleasant phenomenon of glare.

Windows are a critical component for the quality of internal spaces, since they play a very important role in determining the level of comfort (both thermal and visual). Bear in mind that large windows require more control. The larger the window, the more critical the selection of the type of glass and the effectiveness of shading in order to control glare and solar gains.

Designing a window is not only a matter of size and shape, it is also a matter of glazing: the choice of the type of glass is of paramount importance for the energy and comfort performances of a window.

The choice of the size and type of glass surface depends on several factors. The climate of the place in which the building will be built must be considered and should always be balanced against both the functional and the aesthetic needs.

Direct glare and reflected glare can make people uncomfortable and can make it difficult for them to perform certain tasks. Glare reflecting off a computer screen, for example, may make it difficult or impossible to view the images on the screen.

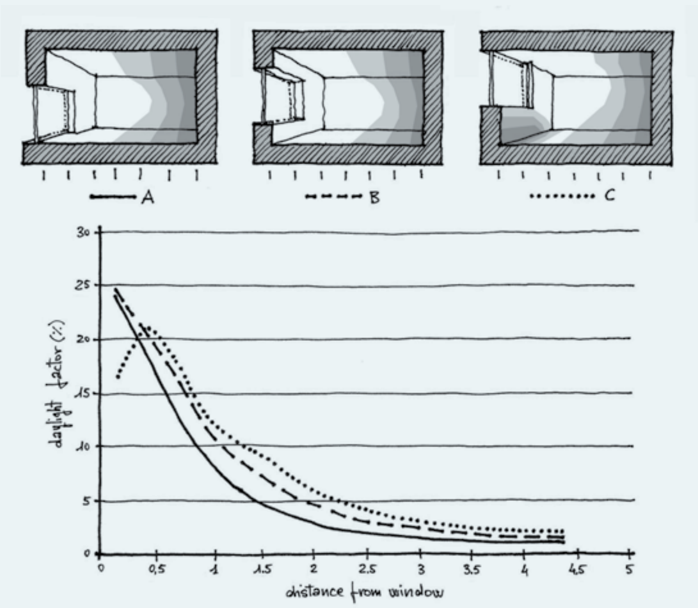
The conflict between glare and useful light should be balanced. If glare is an expected problem, and if an architectural solution for the problem is not possible (or is not accepted), a light transmission coefficient of the glass (visible transmittance) which is a compromise between glare and light must be selected. This is a compromise, however, which increases electrical consumption for artificial lighting and represents a defeat from the design point of view.

To maximize lighting and HVAC energy benefits, a whole building simulation should be conducted in order to evaluate the total glazing area used for daylighting before a daylight scheme is finalised.

4.1.2.2 WINDOW SHAPE AND POSITION

The daylight factor (and therefore the level of illuminance, see Appendix 2) at a point depends - for the same size of the window - on the distance from the window, the type of glass, the presence of curtains or other protections and the position of the window relative to floor level. Figure 4.1-5 shows that the first metre from floor level, has no advantages for the purposes of natural light (and is a disadvantage for solar gains). On the other hand, moving the window to the top, to touch the ceiling, increases the daylight factor.

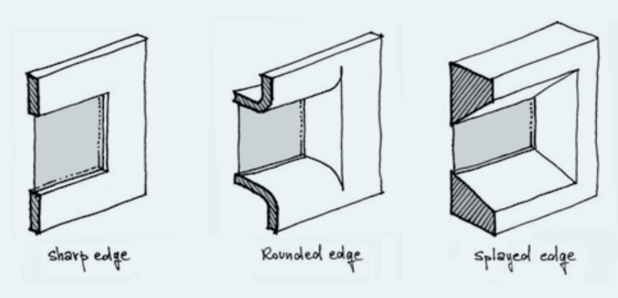
FIGURE 4.1-5 **DAYLIGHT FACTOR ON A VERTICAL PLANE CROSSING THE CENTRE LINE OF THE WINDOW, AT THE HEIGHT OF 0.8 M FROM THE FLOOR**



Sloped surfaces help to soften glare. These surfaces should be light-coloured and provide an intermediate brightness between window and room surfaces, making an easier transition for the eye and thus reducing eye fatigue due to the contrast of luminance (Fig. 4.1-6).

Operable high side-lighting fenestration can be used in combination with operable windows to naturally ventilate the space when the outside air temperature falls within a comfortable range. Natural ventilation can have a positive impact on indoor air quality and can eliminate or significantly reduce the need for mechanical ventilation.

FIGURE 4.1-6 **TRADITIONAL VS. SPLAYED WINDOWS TO REDUCE GLARE**



Clerestory side-lighting can save energy by reducing the use of energy for electric lighting, assuming that appropriate manual or automatic controls are used for the electric lighting system. Clerestory side-lighting improves lighting quality by distributing daylight more uniformly across the space.

When combining view windows and high side-lighting in a space, the clerestories should be continuous along the whole area to be daylit, but view windows can be selectively spaced as needed.

Use separate apertures for view and daylight. A good approach for excellent daylighting and glare control is the separation of view and light windows. Use high transmission, clearer glazing in clerestory windows, and lower transmission glazing in view windows to control glare (Fig. 4.1-7). The daylight windows should be sized to provide the illumination required in the space when the view windows' curtains are drawn.

*A sloping ceiling at the perimete*r raises the window head without increasing floor-to-floor height (Fig. 4.1-8)

Size the windows and select glazing at the same time. Do not waste glass surface where it cannot bring any benefit. It wastes energy and causes discomfort. Window size and choice of glass are interrelated factors. Thus, when sizing a window we need to keep in mind the concept of "Effective Aperture" (Fig. 4.1-9), EA = τ_{vis} x WWR (WWR = Window to Wall Ratio; τ_{vis} = visible transmittance). The same EA value, i.e. the same effect of natural lighting, can be obtained with different glazed areas, depending on the type of glass. A good effective aperture value is between 0.2 and 0.3.

Large windows require better and more expensive glazing. The larger the window, the lower the solar factor and visible transmittance must be. The larger the window, the greater the need for high performance glass.

FIGURE 4.1-7 **SEPARATE APERTURE FOR VIEW AND DAYLIGHT**

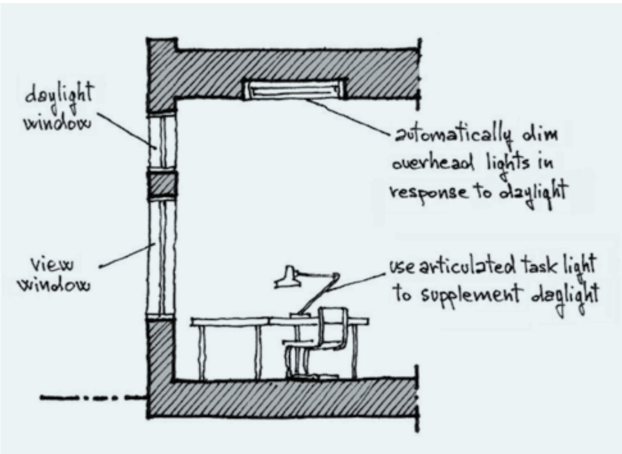


FIGURE 4.1-8 **SLOPING CEILING**

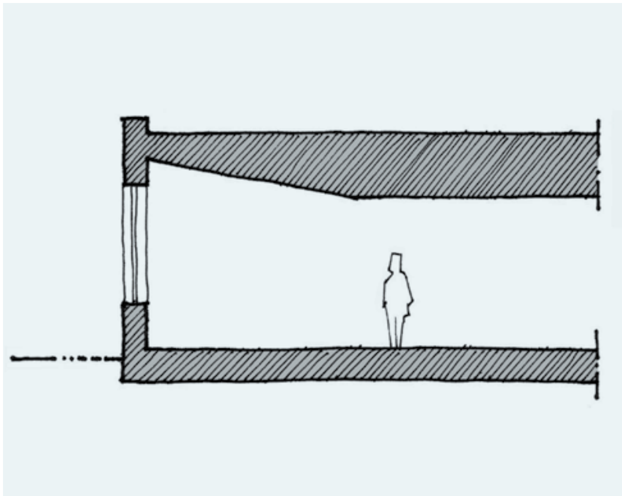
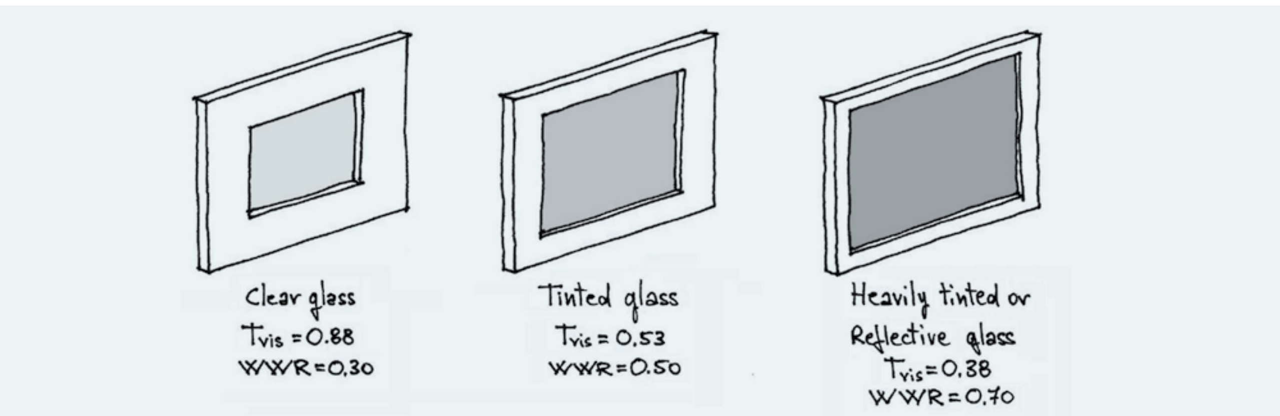


FIGURE 4.1-9 **VARIATION OF THE SIZE GLASS AREA AS A FUNCTION OF THE TYPE OF GLASS, WITH THE SAME NATURAL LIGHTING OBTAINED***



** J. O'Connor, Tips for Daylighting with Windows – The Integrated Approach, Berkeley, Ernest Orlando Lawrence Berkeley National Laboratory, 1997. http://windows.lbl.gov/daylighting/designguide/designguide.html*

4.1.2.3 **GLAZING**

Clear single-pane glass is generally the least expensive type of glazing providing the best colour quality indoors. Check carefully if there is a real need to use other types of glass. In tropical climates high performance low-e glazing may be a waste of money.

Do not believe that tinted glass provides good solar control. Many types of tinted glass block the light more than the heat, and reduce the air conditioning load very little, while forcing the occupants to use more artificial lighting. Tinted glass can create a gloomy atmosphere and it can affect people's mood in residential buildings and productivity and absenteeism in commercial ones. The colour quality of natural light is preserved only with the use of clear glass or glass that is tinted with neutral colours. If it is really necessary to use tinted glass, it should be chosen with great care and with the assistance of an expert. Tinted glass not only reduces natural lighting, but also increases the thermal discomfort of the occupants on sunny days: it absorbs solar energy and heats up, turning the space nearby into a furnace for whoever is close to it.

Spectrally selective types of glass reflect part of the red component of solar radiation, and the resulting light in the space has a slight bluish cast: i.e. is a little' "cold". If you want to retain a good colour rendering of natural light and want to avoid the perception of a "cold" visual environment, selective glass can be replaced by mobile solar protection.

Do not rely solely on the type of glass to reduce solar gains, thermal discomfort and glare. If solar rays enter the building, they create discomfort for the occupants who are in their path and increase the thermal load. External shading systems combined with carefully chosen glass are the best strategies. Even interior shading systems are possible options for reducing solar gains, but result in higher energy consumption than external ones.

Avoid the use of reflective glass as much as possible; it reduces the quality of the outside view and the mirror effect after sunset is unpleasant for the occupants.

4.1.2.4 **SHADING**

Exterior shading makes more difference when used with clear glass; it has much less impact when used with solar-control glazing.

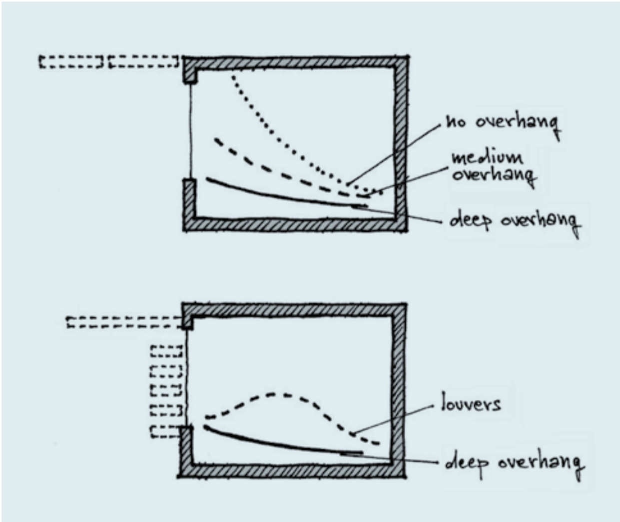
Horizontal overhangs, vertical side fins or a combination of these two devices are recommended on the outside of buildings to shade windows and block direct penetration of sun into a space. Exterior shading devices offer the additional advantage of stopping heat gain before it enters the building.

Horizontal overhangs have the effect of reducing glare and provide a more uniform distribution of light, but also reduce the level of illumination. Horizontal blades in front of the window perform better in this respect (Fig. 4.1-10).

Exterior shading is recommended for windows on all buildings. It is most cost effective when used on low-rise buildings such as schools and offices, where roof overhangs can provide some or all of the shade. Exterior shading is typically more costly in high-rise buildings, but the same design recommendations apply.

The use of solar shading devices often means that the size of the air conditioning system can be reduced. These equipment savings may offset the cost of the shading devices. In addition, fully shaded windows may mean that less expensive glazing can be used.

FIGURE 4.1-10 **FOR THE PURPOSES OF GLARE CONTROL AT EQUAL SUN PROTECTION CAPABILITY, HORIZONTAL BLADES RESULT IN A MORE UNIFORM ILLUMINATION**



Before selecting the external sunscreen to use, it is advisable to:

- check if it would be possible/appropriate to reduce the areas of glass towards values that optimise natural lighting and solar gains;
- size, even as a first approximation, the solar protection;
- check the effects of solar protection on natural lighting, and its impact on energy consumption for artificial lighting;
- check the costs and benefits of mobile sunshades;
- take account of the fact that – when struck by the sun – the sunshade heats up and emits in the

infrared, in turn heating up the glass, which radiates the heat inwards, especially if the solar protection is made of metal or glass. This results in the reduction in heat gain being attenuated. This phenomenon is particularly critical when the sunshade is located in the cavity of double skin glass.

Before selecting the interior sunscreen, it should be considered that interior shading alone has limited ability to control solar gain. All interior systems are less effective than a good exterior system because they allow the sun's heat to enter the building. They also depend on user behaviour, which cannot be relied upon. It is advisable to:

- specify light-coloured blinds or louvres in order to reflect the sun's heat back out. Light-coloured woven or translucent shades are acceptable;
- specify internal curtains operable by the occupants and suitable for the control of glare and for additional shading;
- use components that allow light to penetrate. Blinds and large mesh curtains are a good choice to filter but not completely block the light;
- avoid dark components unless there is external shading. Dark-coloured interior devices offer only small energy savings;
- avoid between glass systems. Several manufacturers offer shading systems (e.g., blinds) located between glazing layers. Some are fixed and others are adjustable. Consider this option carefully: the blinds warm up and, in turn, through infrared radiation, warm the interior glass pane, which radiates energy towards the internal space: the heat gain is still high and thermal comfort low.

4.2 BUILDING SERVICES

Why include building services in a Handbook dealing with architecture?

The answer to this question was already given in 1969 by the architecture historian Reyner Banham in his book "The architecture of the well-tempered environment":

..."The idea that architecture belongs in one place and technology in another is comparatively new in history, and its effect on architecture, which should be the most complete of the arts of mankind, has been crippling.....

....Because of this failure of the architectural profession to – almost literally – keep its house in order, it fell to another body of men to assume the responsibility for the maintenance of decent environmental conditions: everybody from plumber to consulting engineers. They represented 'another culture', so alien that most architects held it beneath contempt, and still do. The works and opinions of this other culture have been allowed to impinge as little as possible on the teaching of architecture schools, where the preoccupation still continues to be with the production of elegant graphic compositions rendering the merely structural aspects of plan, elevation and sometimes section ('Never mind all that environmental rubbish, get on with your architecture')".

Unfortunately this is still true today and must be changed; moreover, the growing concern about environmental issues makes the change terribly urgent.

Sustainable building design implies integrated design, which means that architects and mechanical engineers must interact, just as both have to interact with the energy expert. There is no possibility of interaction if the architect does not have some basic knowledge of the technologies that are used with great expertise by mechanical engineers.

4.2.1 HVAC TYPES AND FEATURES

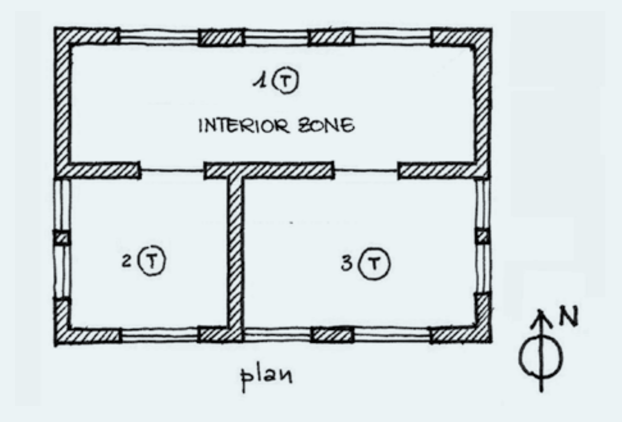
HVAC (Heating, Ventilation and Air Conditioning) systems include a large variety of active technologies designed to provide thermal comfort and appropriate air quality in an enclosed space. A sustainable HVAC system should be capable of controlling air temperature, humidity and air quality, while minimizing the primary energy needed to carry out such tasks.

HVAC systems play a fundamental role in architectural design for several reasons. First of all, they can occupy a not inconsiderable part of the space in the building. Secondly, they constitute an important part of the budget for construction. Thirdly, the operational costs of HVAC can represent a fundamental component of the overall operating costs of a building.

Finally, the success or failure of a building is related to the comfort and feeling of well-being that it is able to provide for the occupants. In this sense, the HVAC system should be considered an integral part of the overall building system and must be designed to work in synergy with a building's passive systems. For these reasons architects should be aware of the principles underlying the layout and the operation of HVAC systems, how energy conversion units work and the function of the principal components. Architects should not leave all the decisions to mechanical engineers; they should be able to interact with some understanding of the technologies involved: this is the basis on which integrated design is founded.

An HVAC system must be designed to provide accurate control of all the comfort parameters of a thermal zone. A thermal zone is defined as an individual space or group of neighbouring indoor spaces with similar thermal loads, serviced by the same mechanical equipment and controls. Typically, differences in orientation, scheduling or occupancy require the definition of separated thermal zones, as illustrated in figure 4.2-1, in order to manage the HVAC system properly.

FIGURE 4.2-1 **EXAMPLE OF A THERMAL ZONES DIVISION IN A LARGE OFFICE BUILDING**



The functions of an HVAC plant can be accomplished by means of different configurations and components, which can be generally organized in five main subsystems:

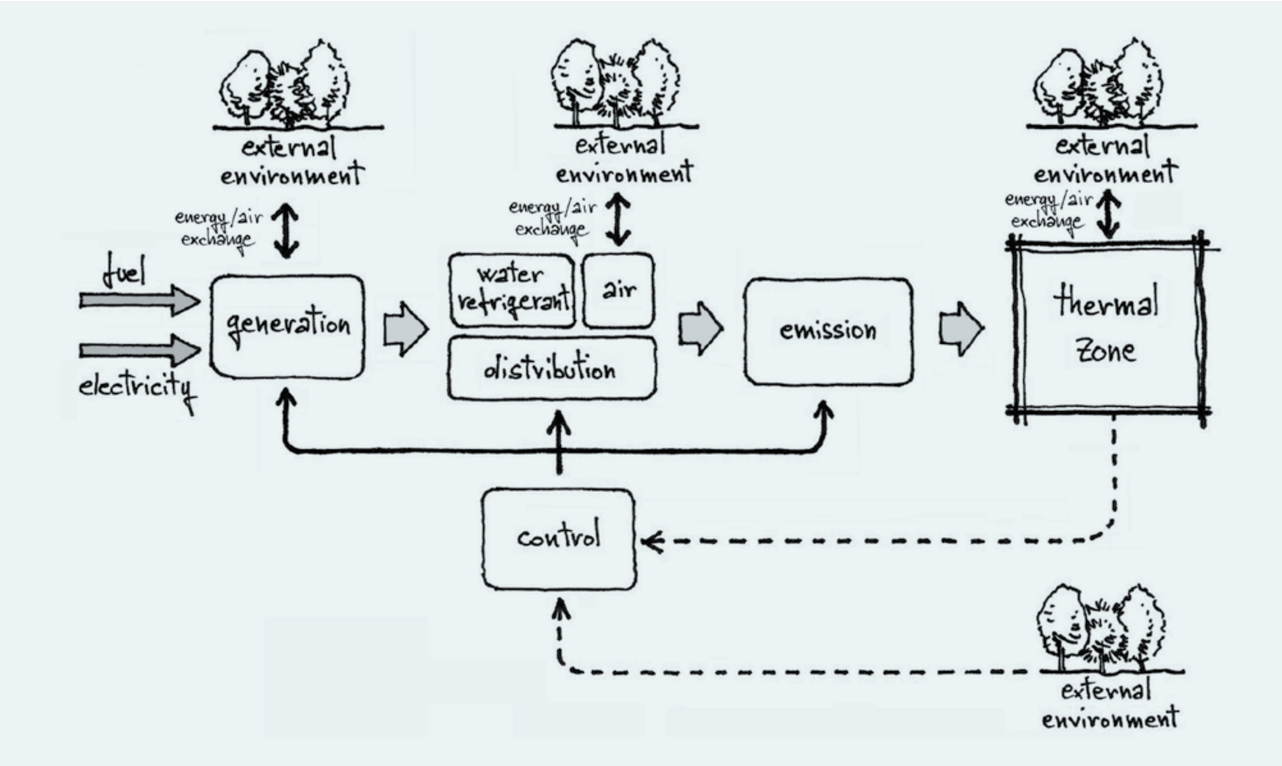
1. Generation subsystem, which produces or subtracts thermal energy;
2. Distribution subsystem, which transfers the thermal energy produced to the thermal zones of the buildings, by means of a heat transfer fluid;
3. Emitting units, which exchange thermal energy within the thermal zone;
4. Ventilation subsystem, which has to provide the optimal air exchange rate in the thermal zone;
5. It can be fully/partially integrated into the above mentioned subsystems or separated from them;
6. Control subsystem, which controls the operation of the subsystems according to users' inputs and/or specific schedules and/or information coming from the thermal zones, such as air temperature and relative humidity, and/or parameters measured by outdoor sensors.

A general scheme of the architecture described above is shown in figure 4.2-2.

In centralized plants the different subsystems are typically well separated, with a tree structure that comprises a central generation subsystem, normally placed in a mechanical equipment room, and a distribution subsystem branching towards the emitting units, located in different rooms/zones.

Otherwise, in local stand-alone systems all the subsystems, or at least some of them, are compacted into self-contained equipment units that work independently and are located in the thermal zones or next to them. Compact systems are generally used in small buildings.

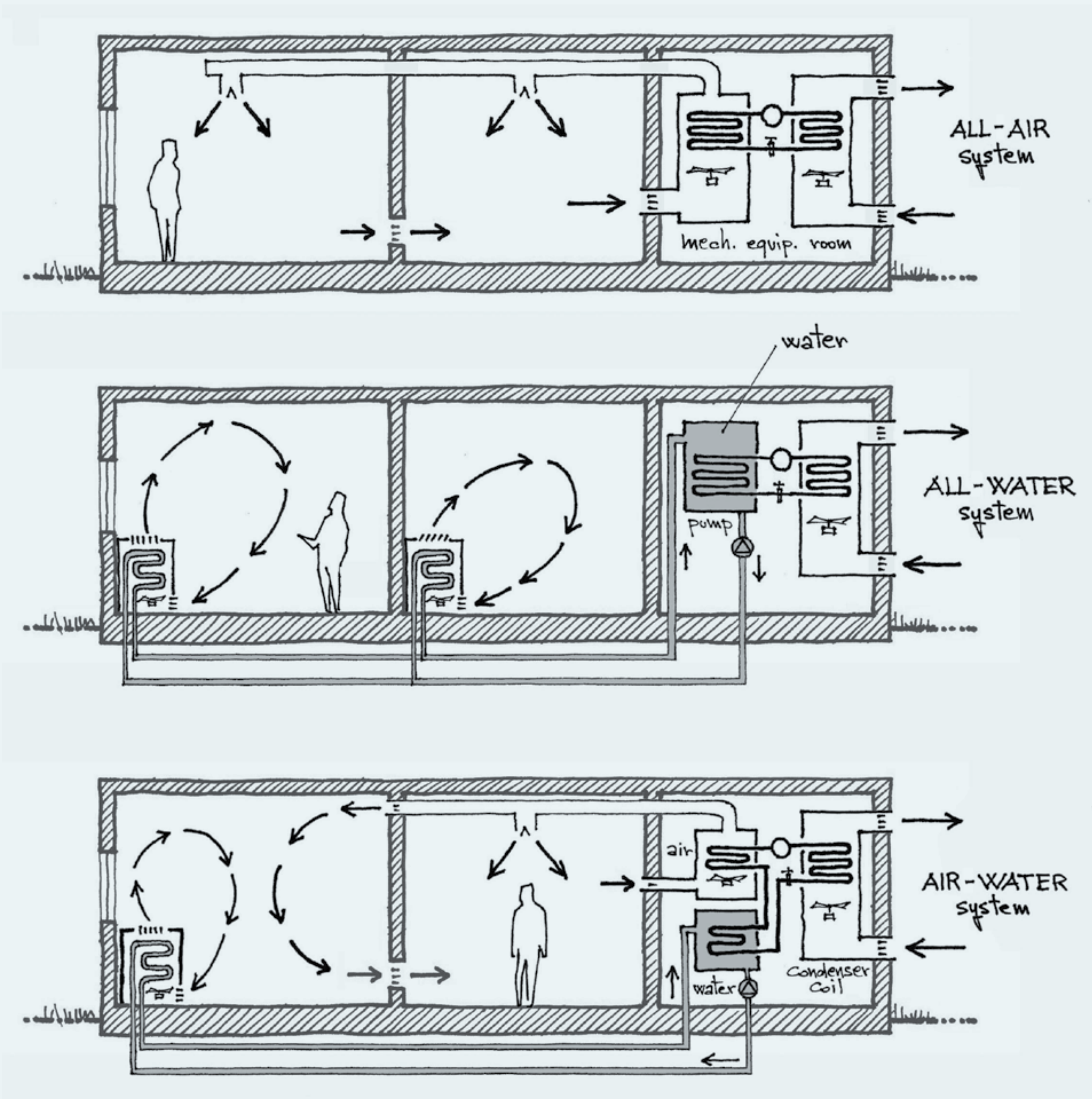
FIGURE 4.2-2 **GENERAL ARCHITECTURE OF AN HVAC PLANT**



HVAC systems are categorized according to the type of fluid used to transfer thermal energy, as follows (Fig. 4.2-3):

- all-air systems: they provide HVAC using only air as fluid; the air flow channelled to a thermal zone provides both ventilation and cooling;
- all-water systems: only water is used; cold water is distributed to the terminals and ventilation must be supplied separately through openings or windows;
- direct refrigerant systems: instead of water, a refrigerant fluid is distributed to the terminals; in this case ventilation must be supplied separately through openings or windows;

FIGURE 4.2-3 **SCHEMATIC DIAGRAM OF ALL-AIR, ALL-WATER AND AIR-WATER SYSTEMS**



- combined systems: they are a combination of two or more of the above mentioned categories; the most common are the air-water systems, where sensible cooling is usually managed by the hydronic system while air provides humidity control and ventilation.

4.2.1.1 HYDRONIC SYSTEMS

In hydronic systems water is used to transfer thermal energy. Pipes and pumps must be provided to distribute cooled water from the generator to the terminal units. The basic configuration is a two-pipe system: a main-flow pipe, in which water flows from the generator to the terminal units, and a return pipe. Water pipes in HVAC distribution systems must be insulated to reduce thermal losses and avoid condensation.

The main advantage of hydronic configurations is that piping requires very little space compared to air ducts and the amount of energy required by pumps is small in comparison with fans. Moreover, if the water distribution subsystem is well designed, it can be absolutely noiseless. In general, it is essential to provide variable-flow electric pumps, so that their energy consumption is proportional to the thermal energy needs of each part/zone of the building.

Once thermal energy is carried by water into the building's thermal zones, it must be exchanged within the air conditioned spaces through several types of water terminal units.

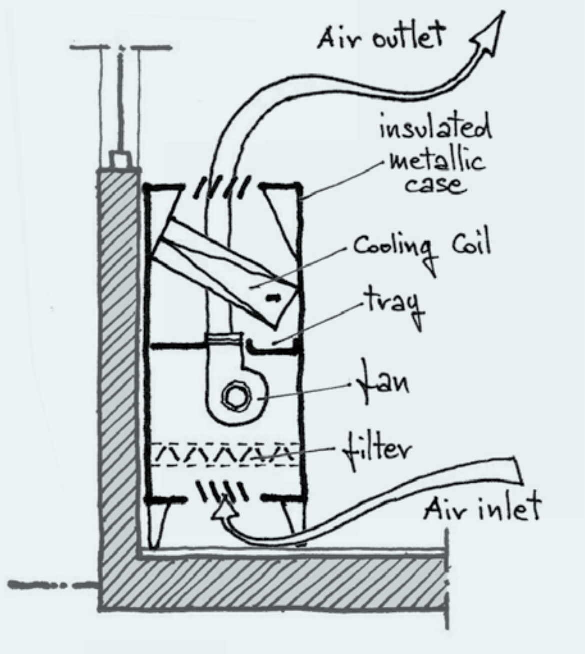
Water terminal units

In water-based systems a variety of terminal units can be used: fan-coils, active and passive chilled beams and radiant ceilings[35].

Fan-coil units

A fan-coil is a terminal unit with a cooling coil, a circulation fan and a filter (Fig. 4.2-4). Fan-coil units can be installed in suspended ceilings or along walls. Individual fan-coils are connected to the water distribution system and the control of the unit is achieved either by varying the water flow and/or fan speed; the control can be centralized or decentralized (personalized at room level), depending on the type of fan-coil. When hot and humid air circulates through the cooling coil there is condensation of the water vapour, which must be collected in a tray and drained away: each fan-coil must thus be connected to a drainage system. Fan-coil systems thus provide some air dehumidification, which is a secondary effect of cooling and, typically, cannot be controlled independently. For this reason, fan-coil systems are frequently combined with an air system providing separate ventilation and air handling (Fig. 4.2-5).

FIGURE 4.2-4 **FAN-COIL UNIT**



35 *Radiators are not included in the list since heating only is not an option in commercial buildings in EAC countries and is not a competitive option in residential buildings in the High Upland climatic zone.*

FIGURE 4.2-5 **FAN COIL AND PRIMARY AIR SYSTEM**

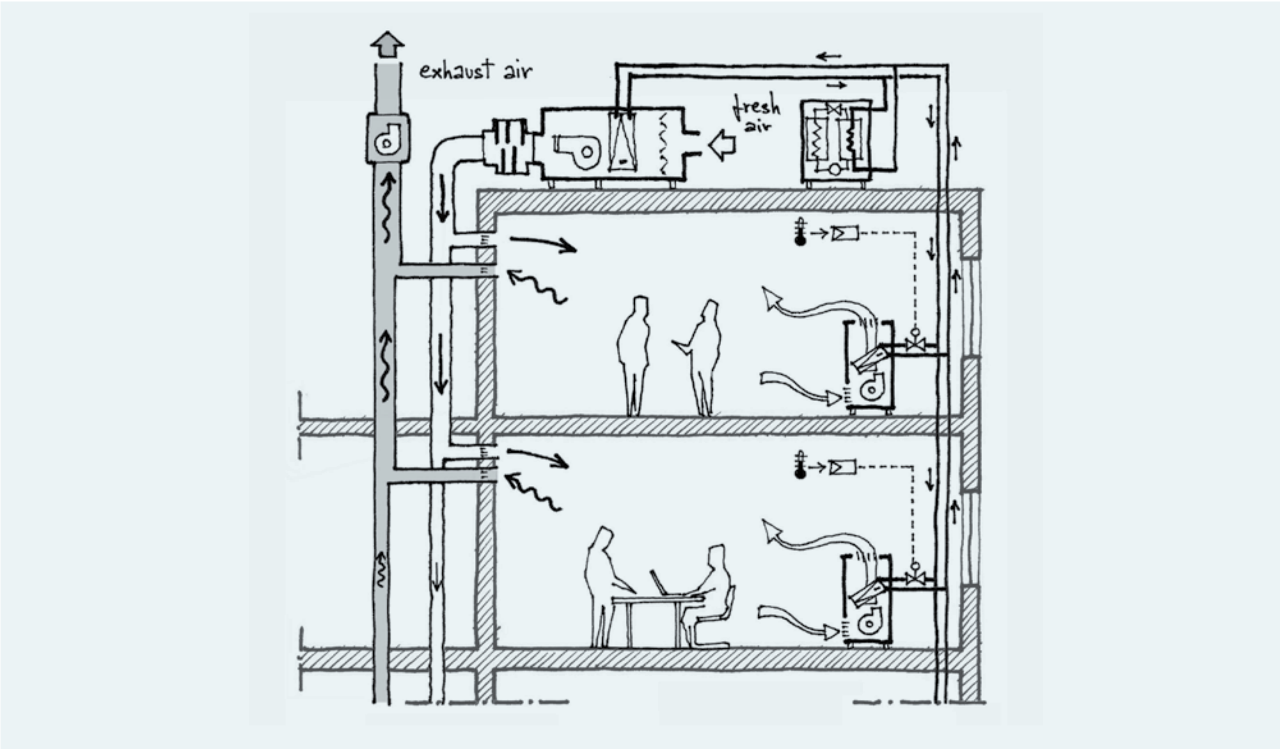
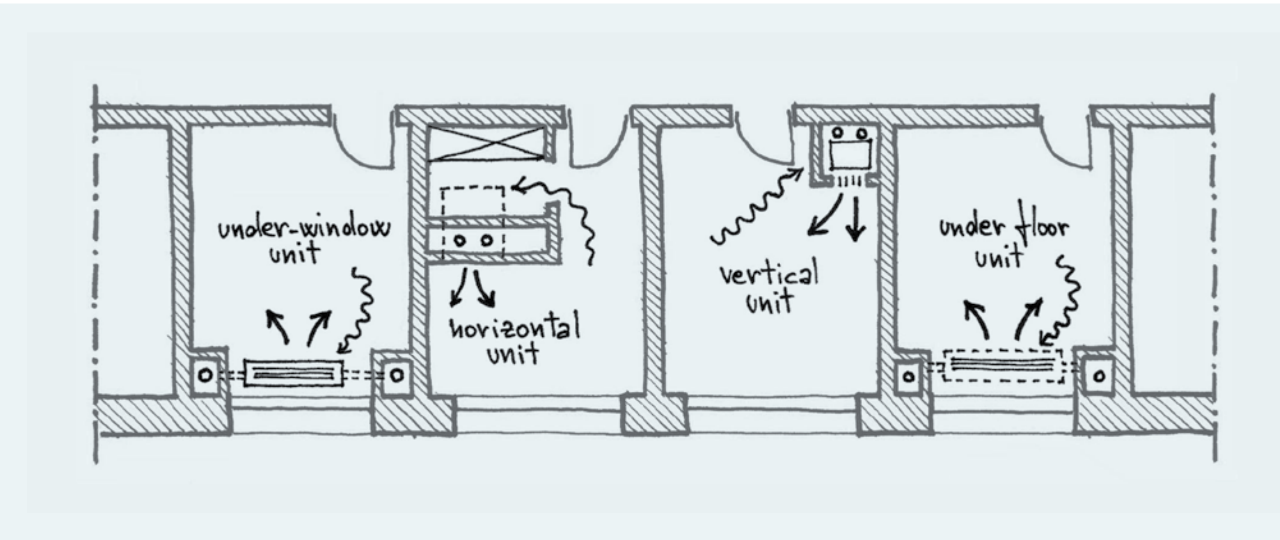


FIGURE 4.2-6 **FOUR DIFFERENT FAN-COIL USES**



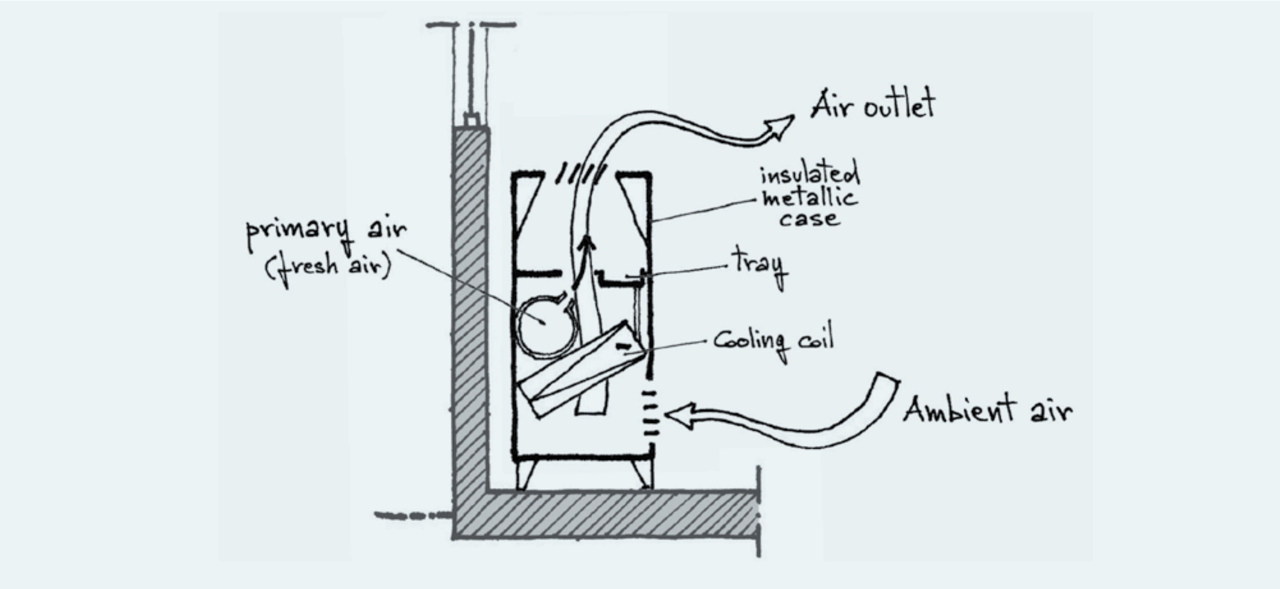
The specific room spaces for fan-coils must be carefully considered as noise due to their fan may be a concern for occupants. Otherwise, these units are very flexible and a variety of products is available on the market, providing several aesthetic and technical solutions (Fig. 4.2-6), which are easily adaptable to heterogeneous contexts.

In general, fan-coils are appropriate for buildings with small thermal zones, where high flexibility in thermal needs is required.

Induction Units

Induction terminal units have no fans. Air movement through coils in the terminal unit is induced by high-pressure air, called "primary" air, that comes from a central air handling unit. The primary air is passed through an array of nozzles in the terminal unit that create a Venturi effect, or vacuum. The vacuum recirculates air from the space through the terminal unit coil. The space air, called "secondary air," mixes with the primary air and is discharged into the space (Fig. 4.2-7).

FIGURE 4.2-7 **INDUCTION UNIT**

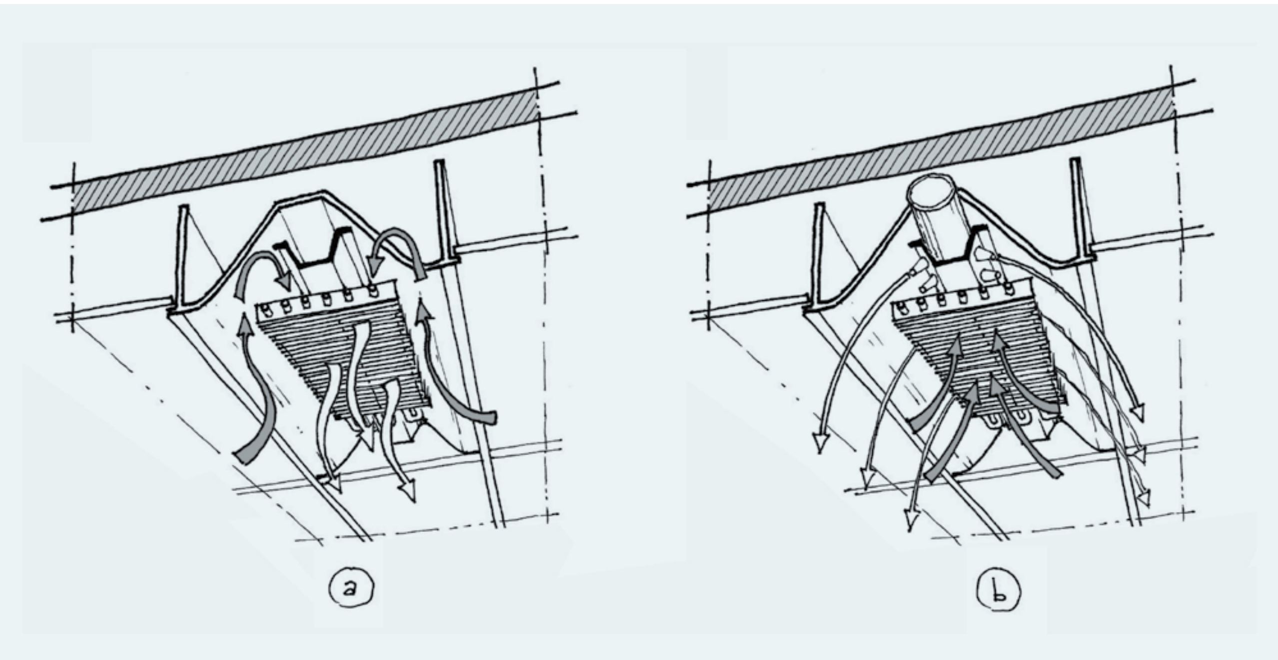


Chilled beams

A chilled beam is a type of terminal unit where water pipes are passed through a "beam" (a heat exchanger) suspended a short distance from the ceiling or integrated into the false ceiling of a room. As the beam chills the air around it, the air becomes denser and falls to the floor. It is replaced by warmer air moving up from below, causing a constant convection flow and cooling the room (Fig. 4.2-8, left). Therefore, in cooling mode cold beams can work simply by convection. This type of chilled beam is called "passive".

Another type of chilled beam is "active" (Fig. 4.2-8, right); while the passive type relies solely on natural convection, the active type works as the induction unit. Active chilled beams are more effective for cooling than passive beams, because of the increased convection and air circulation within the building zone, and because they are coupled with the ventilation system, providing at the same time temperature and humidity control (ventilation air properties are first managed in an air handling unit and then channelled to the beam), but they consume more energy to operate.

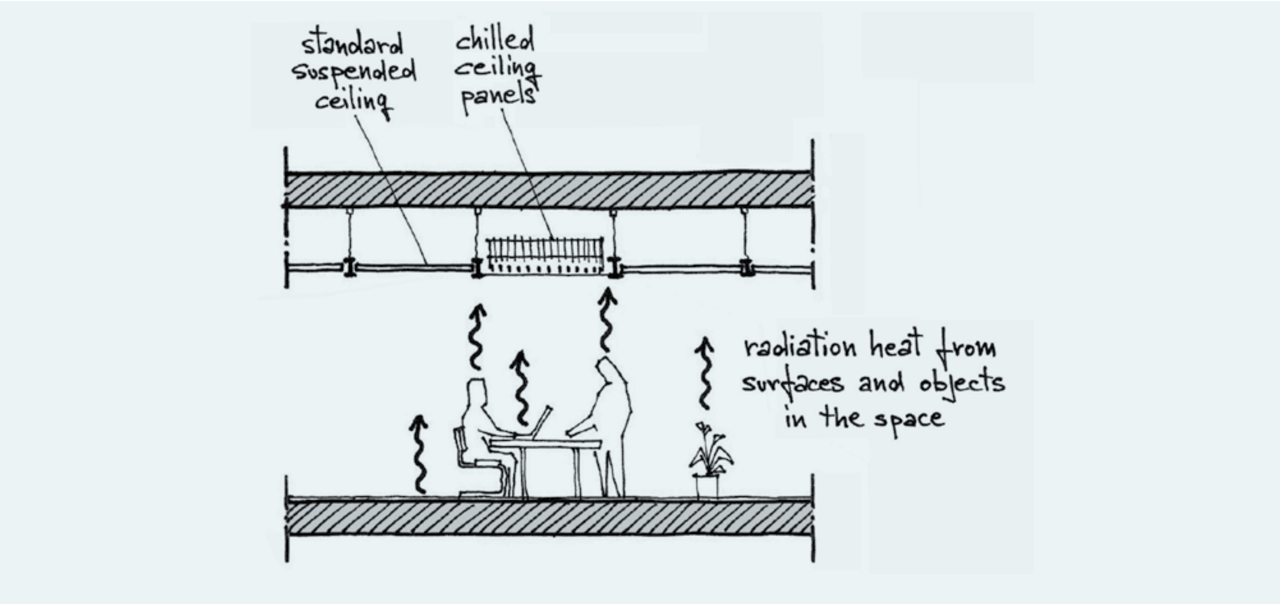
FIGURE 4.2-8 **CHILLED BEAMS WORKING PRINCIPLE. PASSIVE (LEFT); ACTIVE (RIGHT)**



Radiant ceilings

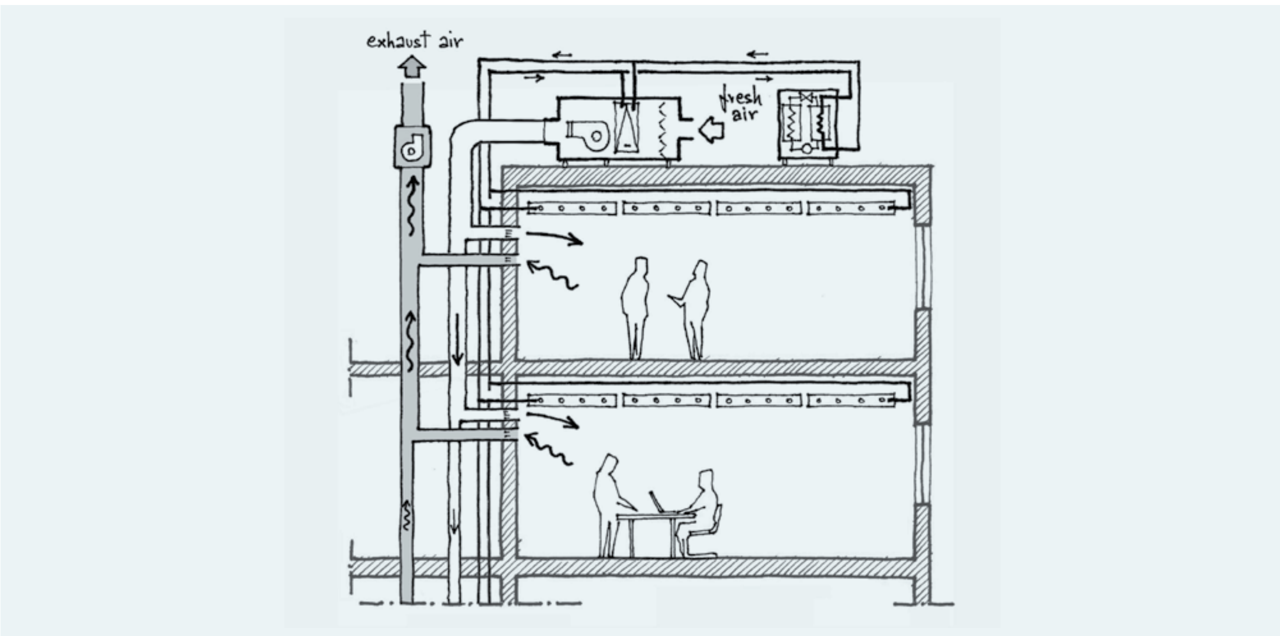
Radiant ceilings consist of panels with embedded pipes (Fig. 4.2-9). Pipes can be either embedded in customized construction elements or in pre-cast construction components, such as false ceilings.

FIGURE 4.2-9 **RADIANT CEILING**



This type of cooling system is virtually maintenance-free and allows energy saving as long as water temperature is higher than in fan-coil systems, with reduced losses in the distribution subsystem and higher efficiency in generating chilled water. Radiant ceilings, by performing the cooling effect primarily through radiation, can provide a comparable comfort level at higher internal air temperatures, lowering the mean radiant temperature, thus enabling a more efficient operation. However, a disadvantage is that accurate humidity control is required to avoid condensation. Since these systems have no condensation drain, when the water circulated in the pipes is too cold and internal humidity is not controlled, serious condensation problems may occur, especially in hot humid environmental conditions. For this reason, such water terminal units must necessarily be combined with a good air handling system (Fig. 4.2-10).

FIGURE 4.2-10 **RADIANT CEILING AND PRIMARY AIR**



4.2.1.2 **AIR SYSTEMS**

In air systems, air is ducted into the different thermal zones of the building to transfer thermal energy and/or to provide ventilation.

Several materials are commonly used to construct ducts, in particular metal sheets (galvanized steel, aluminium) or multi-layer composites. Insulation is placed around ducts to avoid, as far as possible, thermal losses and condensation. The most common shapes of ducts have rectangular, square, circular or oval section. A circular section is the most economical with respect to material and pressure losses, but a rectangular section is more suitable for architectural integration.

Ductworks are usually completed with accessories such as dampers, splitters, and turning vanes. Dampers are used to control air flow in response to changing building loads and required ventilation rates for internal air quality. Air systems are able to control temperature, humidity and concentration of pollutants. Therefore, they are extremely versatile in terms of possible application; it should be remembered however, that air -as an energy carrier- is not as efficient as water and this system may require extensive building volume for ductworks, depending on the specific end-use. For this reason, air systems can be coupled with water systems to reduce both sizing and energy consumption due to the air handling process.

In general, different design schemes can be adopted for air distribution systems: the most common are single duct, multi-zone, dual duct and VAV (Variable Air Volume).

Single-duct systems

In single-duct systems, dehumidified air at an appropriate temperature is circulated throughout the building in a single branching duct (Fig. 4.2-11). Return air can use either a return air duct or travel in a plenum. The air delivered to all spaces within the building flows in a common duct and in some cases may be controlled by dampers at the duct outlets, but temperature and/or humidity cannot be independently controlled. For this reason, this system is appropriate for small buildings or for buildings with few zones.

Single-duct systems can also integrate terminal reheat systems: a single duct for air supply is combined with some type of heating device, such as hot water coils, located downstream near each zone. A thermostat in each zone controls the heat output of the reheat coil to produce comfortable conditions. If, however, the supply air is conditioned to cool the zone with the greatest cooling load, it may be too cold for other zones. The common duct therefore supplies the air stream with the coldest temperature required, and then heat is added to adjust the temperature of the air stream depending on the needs. Any zone requiring less than maximum cooling will have the temperature of its supply air increased by its terminal reheat device. It is obvious that cooling all supply air to the lowest temperature required and then reheating most of the air to produce comfortable conditions is a waste of energy and so this solution should preferably be avoided.

Multi-zone systems

Multi-zone air configurations are composed of an individual supply air duct for each thermal zone in the building (Fig. 4.2-12). Cool air and warm air (return air or heated air) are mixed to suit the needs of each zone. Once mixed, air for a particular zone is supplied through separate ducts to the different zones.

A key advantage of the multi-zone control approach is the capability of supplying adequate air conditioning to several zones, usually avoiding the energy waste associated with the terminal reheat system. The drawback from both the economic and architectural (space, aesthetic effect, etc.) points of view is the need for many separate ducts for the different zones.

Dual-duct systems

A central unit provides two conditioned air streams (a "cold" deck and a "hot" deck). These air streams are distributed in the building by separate and parallel ducts; a mixing box is provided for each zone (Fig. 4.2-13). Under the control of the zone thermostat, the air streams are mixed in the terminal box to provide a supply air temperature at the required temperature and humidity conditions in each zone.

FIGURE 4.2-11 **SINGLE-DUCT CONFIGURATION**

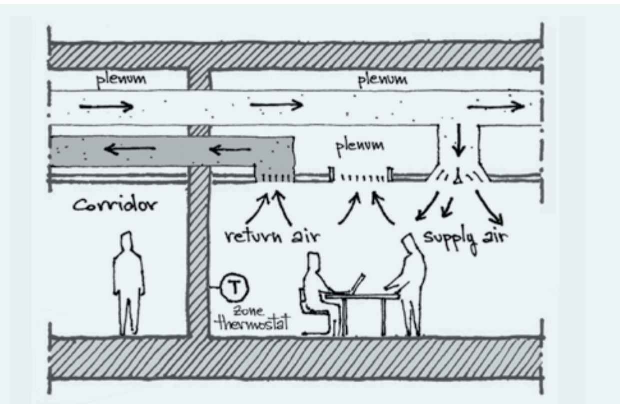


FIGURE 4.2-12 **MULTI-ZONE CONFIGURATION**

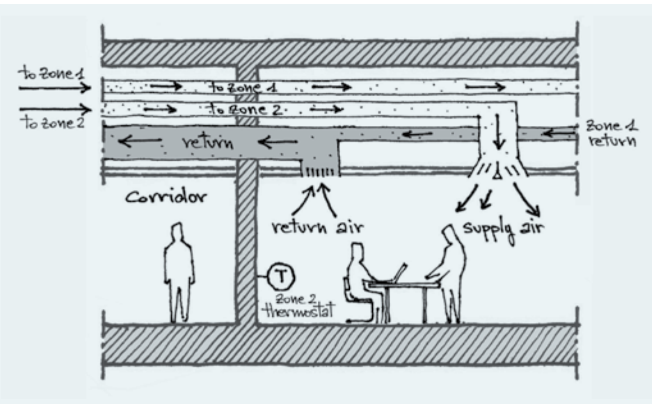


FIGURE 4.2-13 **DUAL-DUCT CONFIGURATION**

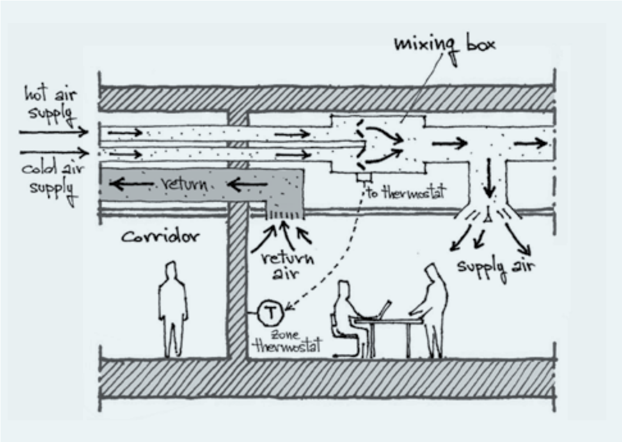
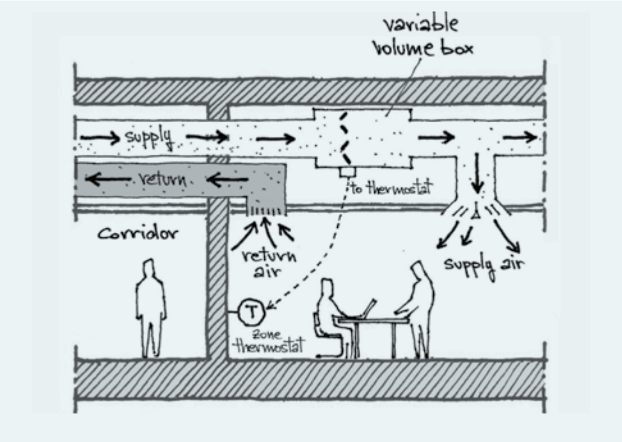


FIGURE 4.2-14 **SINGLE-DUCT VAV**



In principle, a dual duct system has the same advantages and disadvantages as a multi-zone system, but it can be considered more flexible to changes in zoning requirements.

Variable Air Volume (VAV) systems

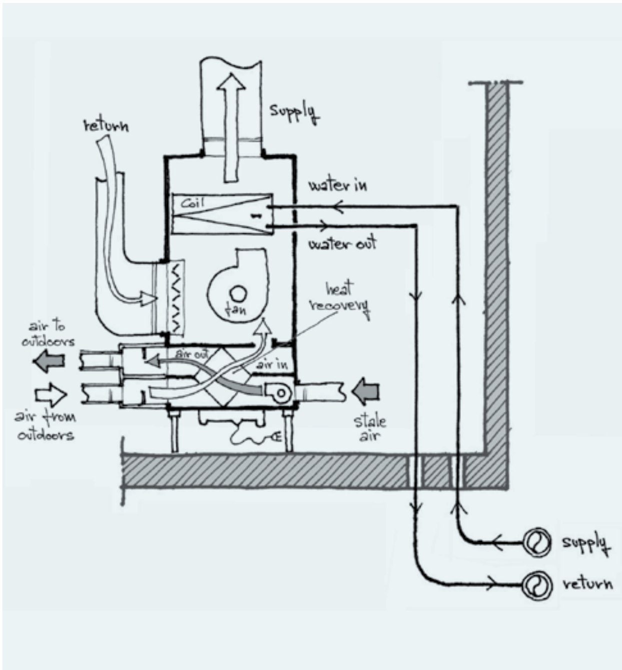
Both single and dual-duct configurations can be operated either with constant air volume or with variable air volume (VAV). In this second case, the air flow supplied to a space varies in response to the changing load (Fig. 4.2-14). This is a major operational difference from the constant volume systems, in which supply temperatures are changed in response to zone loads but ventilation rates are kept constant for each zone. This solution opens up a number of energy-efficiency options. For example, a single central unit supplies air through a common duct pathway to all conditioned spaces and each zone is provided with a VAV box (terminal control box) that adjusts the volume of the air supply; in this way both air temperature and flow rate can be varied separately in response to the zone requests.

4.2.1.3 **AIR HANDLING UNITS**

Air handling units (AHU) are equipment packages, usually pre-assembled but sometimes site-built, containing several components necessary for the operation of an air-based HVAC systems (Fig. 4.2-15). In particular, they are used to perform air handling processes such as heating, cooling, dehumidification, humidification and heat recovery. They can be either centralized, thus servicing the whole air distribution subsystem, or decentralized, i.e. subdivided into multiple units nearby the different building zones and connected to them. Due to high air relative humidity levels, the design and dimensioning of AHU in tropical climates must be carried out carefully. An air handling unit assembly consists of a sheet metal enclosure, a fan providing the pressure for air circulation, a cooling coil for sensible cooling and dehumidification, a heat recovery unit and, if necessary, a heating coil for reheating.

Control devices such as mixing dampers and valves are often part of air handling units.

FIGURE 4.2-15 **SCHEMATIC OF AN AHU (WHEN USED FOR SPACES WITH HIGH INTERNAL LATENT LOAD (THEATRES, CONFERENCE ROOMS, BALL-ROOM, ETC.) A REHEAT COIL MAY BE NECESSARY AFTER THE COOLING COIL)**



4.2.1.4 **ENERGY RECOVERY**

An energy recovery ventilator (ERV) is a type of mechanical equipment that features a sensible and/or latent heat exchanger combined with a ventilation system, which reclaims energy from exhaust airflows. If only sensible heat needs to be recovered, a run-around coil heat recovery can be used; it works by circulating liquid between heat-exchange coils in extract and inlet ducts. An incorporated heat pump can transfer energy efficiently from cold extract to warm intake, as illustrated in figure 4.2-16.

FIGURE 4.2-16 **RUN-AROUND COIL HEAT RECOVERY SYSTEM**

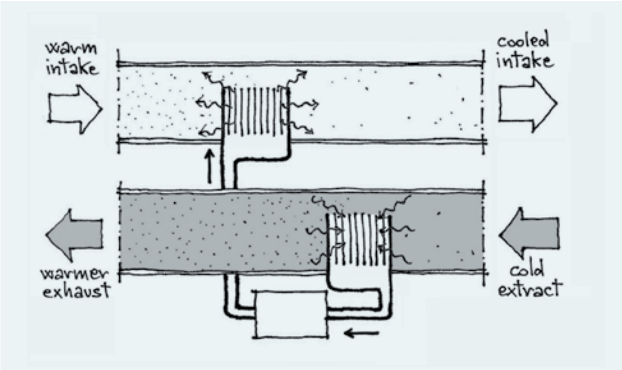
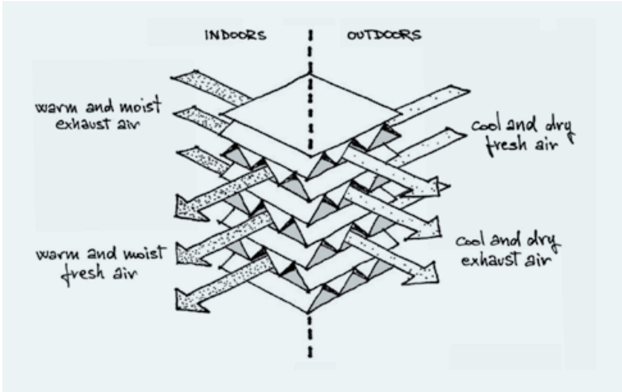


FIGURE 4.2-17 **CROSS FLOW HEAT EXCHANGER**



In commercial buildings in tropical and subtropical regions, air-conditioning may be necessary throughout the year, and the latent cooling load is a large part of the total. For this reason, in order to increase energy efficiency, the recovery of the enthalpy (both sensible and latent energy) of the exhaust air is essential and can usually be performed by using a fixed plate energy exchanger (Fig. 4.2-17) or an enthalpy wheel (Fig. 4.2-18). In the first, two air-streams (inlet and outlet) flow in adjacent but separated ducts and exchange sensible and latent heat by using special materials which transfer sensible heat and are water vapour-permeable.

An enthalpy wheel consists of a rotating cylinder filled with an air permeable material with a large surface area, which is the medium for the sensible energy transfer. As the wheel rotates between the ventilation and exhaust air streams it picks up heat and releases it into the colder air stream. At the same time, the use of desiccant materials inside the wheel, such as silica gel, allows the transfer of moisture through the process of adsorption, which is predominately driven by the difference in the partial pressure of vapour within the opposing air-streams. Enthalpy wheels are the most effective devices for energy recovery but accurate system design and careful selection of appropriate components are needed in order to guarantee the wheel's durability.

FIGURE 4.2-18 **ENTHALPY WHEEL HEAT RECOVERY SYSTEM**

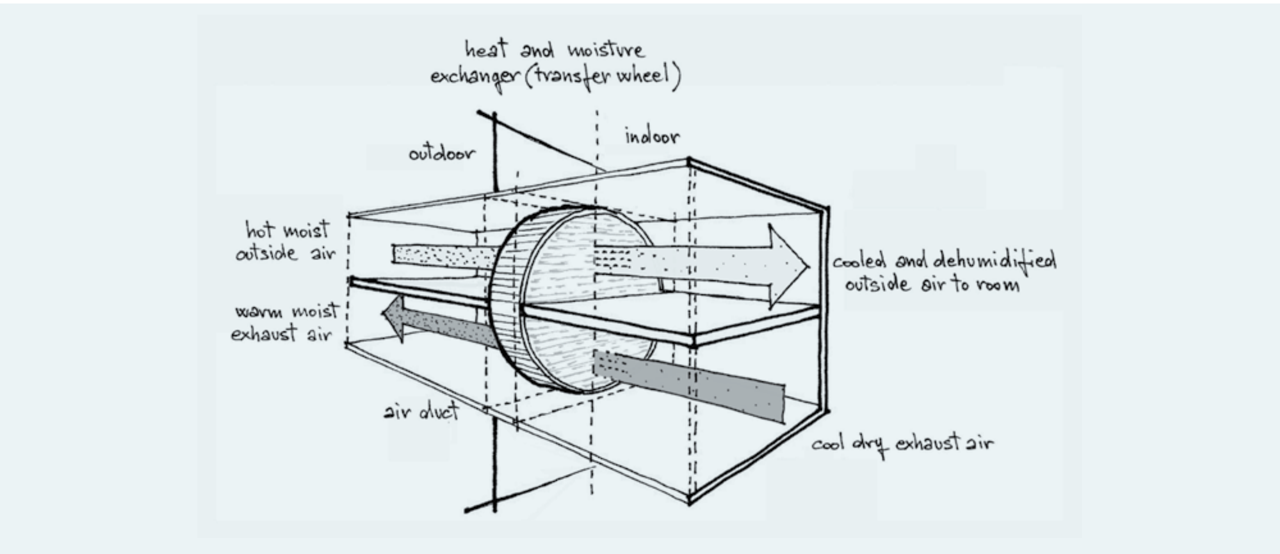
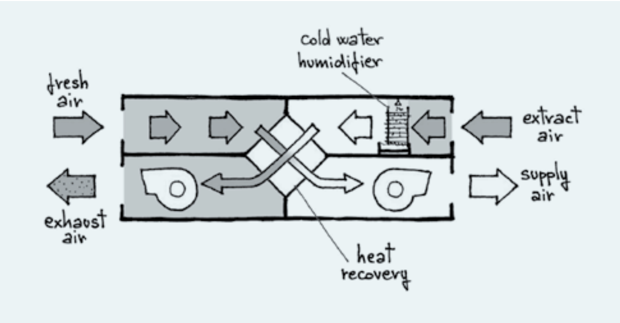


FIGURE 4.2-19 **EVAPORATIVE COOLING HEAT EXCHANGER**



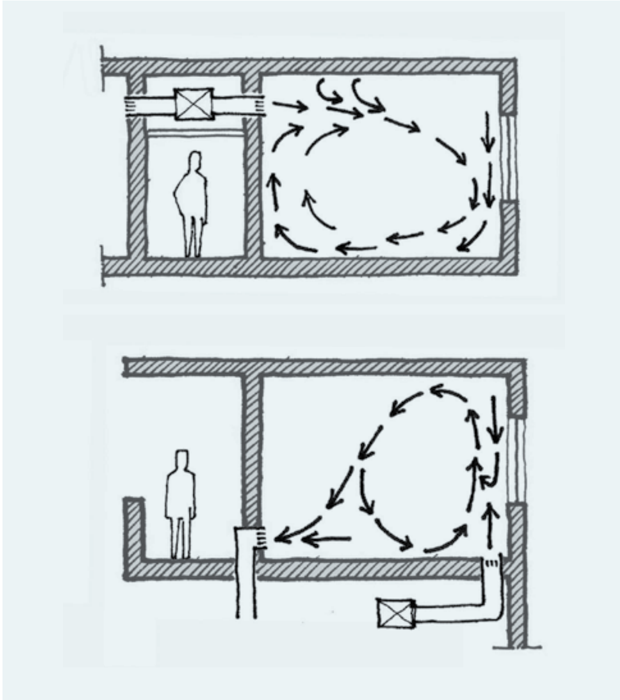
Evaporative cooling can be used to enhance heat recovery; in evaporative cooling the heat exchanger's exhaust air is cooled by spraying water on it before it enters the heat exchanger (Fig. 4.2-19).

4.2.1.5 AIR TERMINAL UNITS

Air is typically supplied to zones through ducts that terminate with different types of registers, grilles or diffusers. Such air terminal units can be placed in different parts of the room (Fig. 4.2-20). The position of supply-air outlets affects the comfort level for occupants. It has to ensure that the air stream circulates homogeneously in each space without striking people directly. Inlet and outlet air terminals should also be positioned taking into account the most economic and easiest routes for ducts according to building structure.

In general, in spaces with normal height ceilings good stratification typically occurs; for this reason a displacement ventilation technique, which supplies low-velocity cool air at floor level and extracts warm air from ceiling outlets, can be particularly efficient.

FIGURE 4.2-20 **HIGH AIR TERMINAL OUTLET (A) AND FLOOR AIR OUTLET (B)**

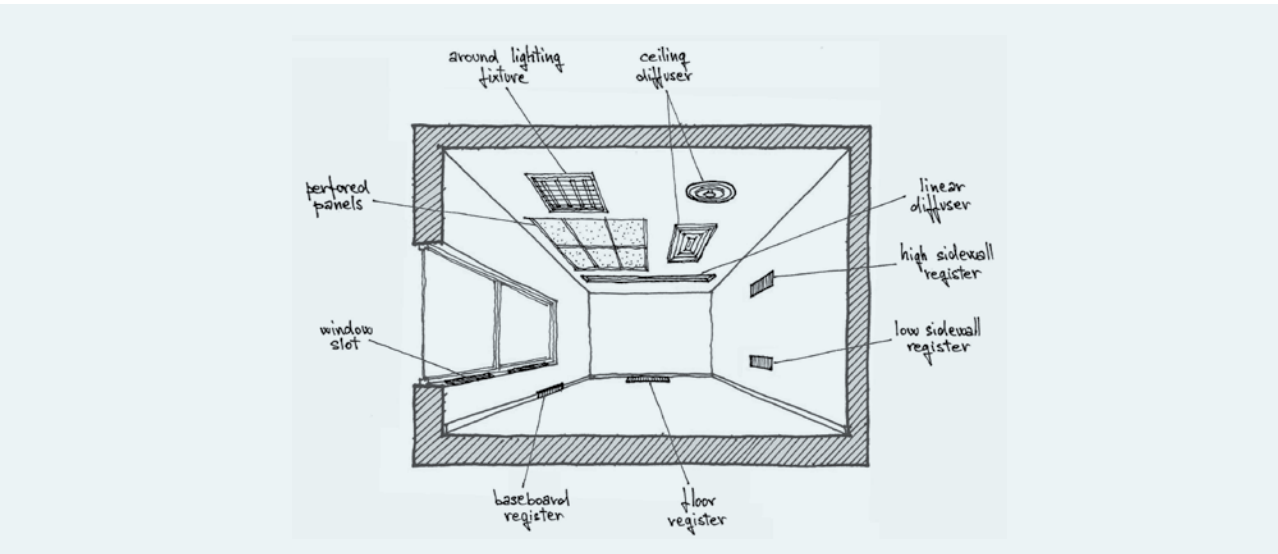


Several types of air terminal devices are available (Fig. 4.2-21). The most common are:

Grille

A grille is an opening with several slits in a wall or metal sheet or other covering for the air inlet or outlet. Usually, supply grilles have adjustable vanes for controlling the direction of the air entering a room while return air inlets simply collect exhaust air from a zone.

FIGURE 4.2-21 **DIFFUSER AND REGISTER TYPES**



Register

A register is a grille with a damper that allows controlling, directing and diffusing the amount of air entering a room. Registers may direct air in one, two, three or four different directions.

Diffuser

A diffuser is a device designed specifically to introduce supply air into a space, with a good mixing of the supply air with the room air and minimum draughts that would cause discomfort for occupants. Diffusers should be selected carefully, as they are the point where the effect of an HVAC system is transferred to building zone/room. Diffusers are intended for ceiling installation and are available in many shapes, sizes, styles, finishes, and capacities. Good air diffusion is particularly important for low-ceilings, for example, in office buildings.

4.2.1.6 **DIRECT REFRIGERANT SYSTEMS**

Direct refrigerant, called also direct expansion (DX) systems are characterized by the absence of water pipes and/or of air ducts to transfer heat from/to the building. In such systems, refrigerant is used as a heat transfer medium between the outdoor unit/part of the system and the internal spaces (for this reason these are called split systems). Such solutions are usually suitable for small or medium size buildings, or for those contexts in which it is difficult to install ducts and/or pipes(for example historical buildings).

A multi-split system (Fig. 4.2-22) is generally composed of an exterior unit, consisting of compressor and condenser elements, and an interior unit, consisting of evaporator and expansion valve elements, and typically can work in heating or cooling mode. The two parts of the system are connected by a refrigerant distribution pipe, thus guaranteeing better flexibility with respect to window air conditioners, unitary air-conditioners and packaged rooftop units. The internal evaporator unit can also be provided as a self-contained element, with different dimensions and features, similar to fan-coil units but fed by the refrigerant. Moderate capacity split systems with multiple evaporator units are available on the market. Modern split systems can also have variable refrigerant flow (VRF), which modulates the amount of refrigerant being sent to each evaporator. By operating at varying speeds, VRF units allow a substantial energy saving at part-load conditions and can also represent an interesting technical solution for many small-size applications.

The application of split systems can be considered when different cooling loads are required in neighbouring spaces and a central system is not suitable. Table 4.2-1 summarises the advantages and disadvantages of multi-split systems compared with centralised HVAC systems.

Packaged rooftop air-conditioner

A packaged rooftop air-conditioner (Fig. 4.2-23) typically comprises a vapour compression refrigeration unit cycle, an air handling unit (fan, filter, dampers) and control devices. This kind of system, as suggested by its name, is placed on the flat roof of a building and conditioned air is directly injected into the space through short ducts. The typical capacity for a rooftop packaged unit is much bigger than for a unitary air-conditioner and, thanks to its bigger size compared to window air conditioners, efficiency is generally higher. Moreover,great efforts have been made by manufacturers in recent years to improve energy efficiency. On the other hand, drawbacks related to aesthetics, noise and space utilization must be considered. The use of a packaged rooftop air-conditioner could be considered in commercial buildings where air conditioning of large enclosed spaces is required. The performance of the system when there are high outside air temperatures and humidity must also be carefully analysed.

FIGURE 4.2-22 **MULTI-SPILT SYSTEM**

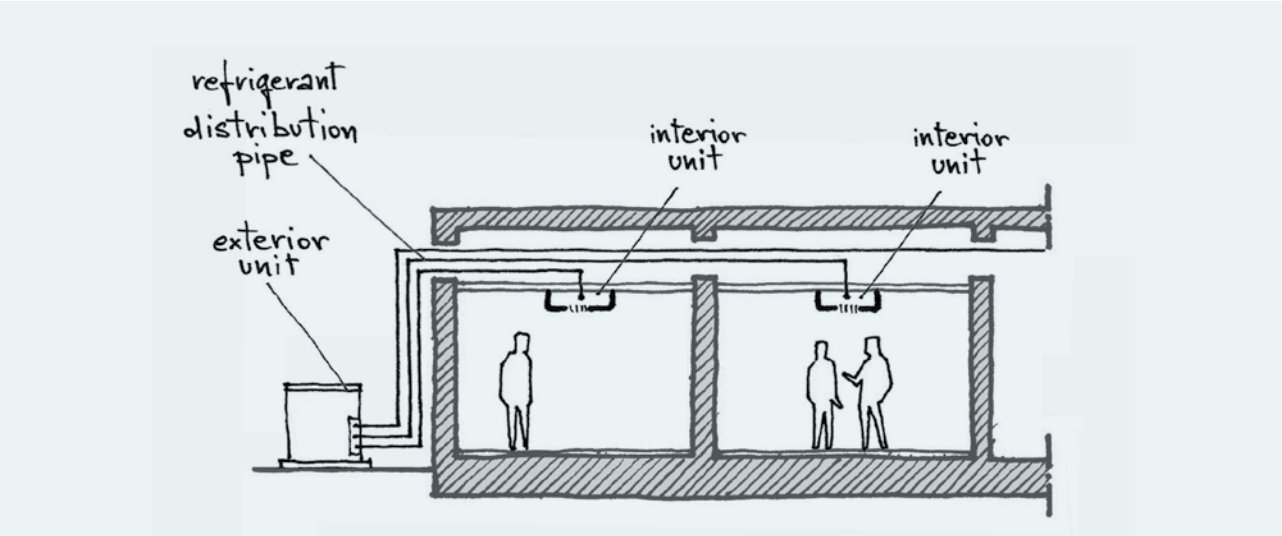
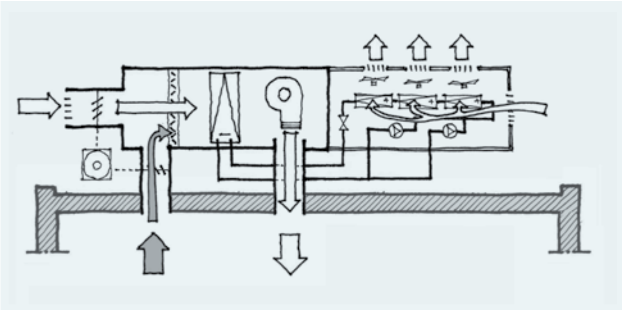


TABLE 4.2-1 **CENTRALISED VS. DECENTRALISED HEATING AND COOLING SYSTEMS**

	Centralised systems	Direct Expansion or split systems
Building Space Requirements	Separate building space is required to house the components (chillers, pumps, AHU's, etc.) In addition, space is required outdoors for condensing units or cooling towers.	No separate space is required for plant. The local systems are smaller in size.
Aesthetics	They are generally designed as concealed systems, but extra space dedicated to ducting is necessary.	The appearance of local units can be unappealing but if same extra space is dedicated (false ceilings), these units can be concealed.
Zoning	Central HVAC systems may serve multiple thermal zones and have their major components located outside the zone(s) being served, usually in some convenient central location.	A local HVAC system typically serves a single thermal zone and has its major components located within the zone itself or directly adjacent to the zone. Multiple units are required for multiple zones.
Air Quality	The quality of air conditioning is comparatively superior, with better control over temperature, relative humidity, air filtration, and air distribution.	The air quality is not comparable to central systems. These systems typically cannot provide close humidity control or high efficiency filtration.
Controls	These require a control point for each thermal zone. The controls are field wired and are integrated in a central control panel. The controls are complex and depend on the type of system. Constant air volume (CAV) systems serving multiple zones rely on reheat coils to control zone temperature. Energy is wasted due to simultaneous cooling and heating. Space temperature control can also be achieved with variable air volume (VAV) systems, which may or may not have a reheat coil.	Local units are off-the-shelf items complete with integrated controls. They usually have a single control point, which is typically only a thermostat. With the zone- control ability of the compact systems, only occupied spaces are maintained at a comfortable level, and conditioning for the rest of the building is turned down or shut off. Savings in fan energy are limited in systems with on/off controls for the compressors; systems with variable speed compressor motors are far more efficient and are capable of avoiding temperature fluctuations in the conditioned space.
Efficiency	Central systems usually operate under part load conditions, and localized areas cannot be isolated for complete shut down under any condition. In a central system, the individual control option is not always available. If individual control is desired, the system should be designed as a variable air volume system with localized thermostats.	In a building where a large number of spaces may be unoccupied at any given time, such as a dormitory or a motel, local systems may be totally shut off in the unused spaces, thus providing huge energy saving potential. As a self-contained system, a local HVAC system may provide greater occupant comfort through totally individualized control options.
Refrigerant Containment	Central plant systems provide an excellent means to contain all the refrigerant within the chiller housing and plant room. It is possible to detect any minor leaks within the localized plant room and take remedial action to arrest the leak.	Unlike central systems, Direct Expansion systems pose a greater risk of refrigerant leaks to the atmosphere. With Direct Expansion systems installed in several localized areas it may be very difficult or impossible to detect these leaks, especially in split systems with long pipe runs using high pressure refrigerant.
Operations and Maintenance (O&M)	Large central systems can have a useful life of up to 25 years. Central systems allow major equipment components to be kept isolated in a mechanical room. Grouping and isolating key operating components allows maintenance to occur with limited disruption to building functions.	Local systems can have a useful life of up to 15 years. Maintenance of local systems may often be relatively simple but maintenance may have to occur directly in occupied spaces.
Cost	The initial purchasing and installation cost of a central air conditioning system is much higher than that of a local system. Extra cost benefits can be achieved due to the potential for energy efficiency measures like thermal heat recovery, economizers, energy storage systems and etc.	Packaged and split units have much lower initial costs than a central system. The potential for adoption of high-tech energy efficiency measures is very limited.

Source: *adapted from: Energy Conservation Building Code User Guide, Bureau of Energy Efficiency, 2009*

FIGURE 4.2-23 **PACKAGED AIR CONDITIONER**



4.2.1.7 CONTROL SYSTEMS

The control systems regulate the operation of the HVAC and must be generally applied to all previous types.

The word "control" is used in a general sense, from local (room level) manual control, to centralized (building level) computerized control. The control of an HVAC system is critical to its successful operation because the aim of the HVAC is to maintain comfortable conditions by monitoring the thermal load of each building zone and adjusting it. Incorrect zoning of buildings may result in a poorly controlled HVAC system with high energy use and low levels of comfort for the occupants, due to the difficulty in managing the variations in internal environmental conditions. The basic control element in a thermal zone is, of course, the thermostat (set-point for internal temperature). One problem for this type of control is short cycling (frequent on/off), which keeps the system operating inefficiently and wears the component out quickly. The longer the time between cycles, the wider the temperature swings in the space. An alternative control, to obtain adequate comfort without excessive wear on the equipment, is modulation or proportional control. In this system, if only a fraction of the cooling capacity of the generator is needed, the flow rate is proportionally decreased or the temperature of the thermal fluid is increased. Usually proportional control and modulation are carried out by using multiple sensors, such as external and internal air temperature/humidity sensors, occupancy sensors, CO_2 level sensors etc. The information collected must be analysed by the HVAC controller, which then sends command signals to the different subsystems.

4.2.2 EFFICIENT ENERGY CONVERSION TECHNOLOGIES

According to the second principle of thermodynamics, heat can flow spontaneously and with continuity only from a hotter to a colder body; the reverse operation, i.e. moving heat with continuity from a lower temperature to a higher temperature cannot happen spontaneously, and a thermodynamic cycle powered by mechanical or chemical energy is needed.

This explains why heating technologies are very old (from the open fire to the fireplace, to the stove, to the boiler), while cooling technologies are relatively new: the first refrigeration machines were developed in the middle of 19^{th} century, after the scientific advancements in thermodynamics took place.

The second principle of thermodynamics teaches us another important lesson: if the aim is to produce heat at about 20 °C – the comfortable temperature we want to have in a room – it is far more efficient to "lift" or pump up heat from lower (external) temperature to higher (room) temperature than to produce heat at very high temperature (as in a fire or in the burner of a boiler) and use it at a lower one, the ambient temperature.

Finally, the second principle of thermodynamics tells us that a very efficient way to power a low temperature (< 100 °C) device is to use the waste heat that is unavoidably released in the operation of a thermal engine producing mechanical power.

Efficient energy conversion technologies are those based on the exploitation of the second principle of thermodynamics.

4.2.2.1 REFRIGERATING MACHINE AND HEAT PUMP

The refrigerating machine (Fig. 4.2-24) is the basis of the ordinary domestic refrigerator, extracting heat from an insulated box, at a low temperature, and exchanging it with the surrounding environment, at a higher temperature. The same process can be used to extract heat from a room and release it into external air, the ground or a river. In the heat-pump mode the process is simply inverted and heat is extracted from the surrounding environment and transmitted to the building.

There are two main types of refrigerating machine: vapour compression and absorption. The first uses mechanical work (e.g. electricity) to operate its thermodynamic cycle, the second uses heat (typically > 80 °C) as energy source.

Vapour compression refrigerating machine

Vapour-compression refrigerating machines use a medium (refrigerant) that absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. All such systems have four components: a compressor, a condenser, a thermal expansion valve (also called a throttle valve), and an evaporator (Fig. 4.2-25). Circulating refrigerant enters the compressor as a saturated vapour and is compressed to a higher pressure, and consequent higher temperature. The hot, compressed vapour goes through a condenser where it is cooled and condensed into a liquid by flowing through a coil or tubes cooled by air or water. In the condenser the circulating refrigerant rejects heat from the system and the rejected heat is carried away by either water or air.

FIGURE 4.2-24 **OPERATING PRINCIPLE OF A REFRIGERATING MACHINE**

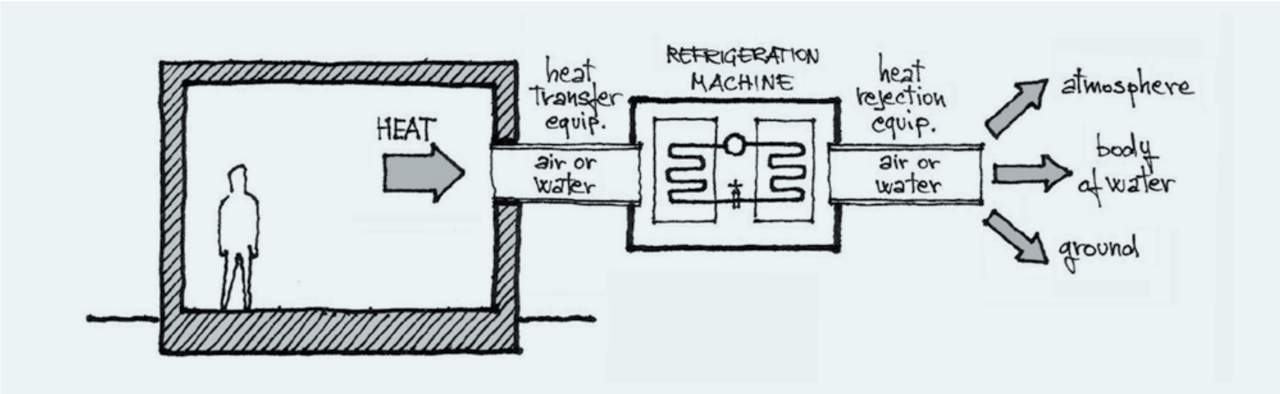
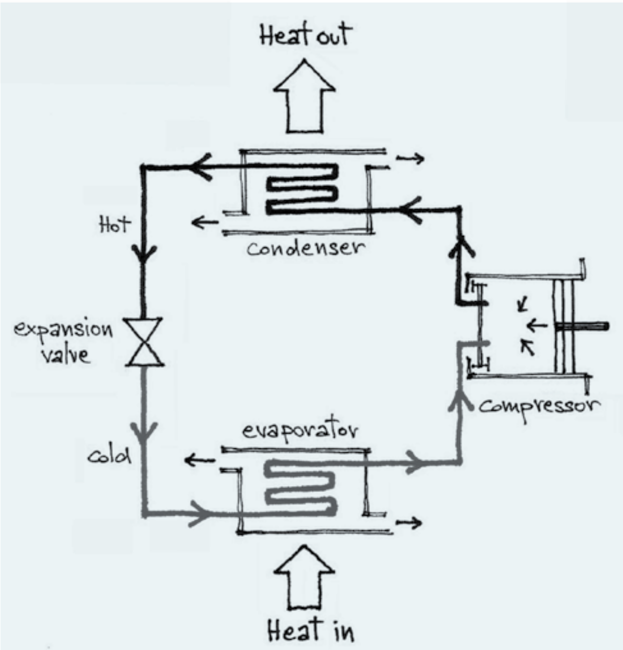


FIGURE 4.2-25 **VAPOUR-COMPRESSION REFRIGERATION CYCLE**



The condensed liquid refrigerant is next routed through an expansion valve where it undergoes an abrupt pressure reduction. That pressure reduction results in the evaporation of a part of the liquid refrigerant. The evaporation lowers the temperature of the liquid and vapour refrigerant mixture.

The cold mixture is then routed through the coil or tubes in the evaporator, where heat is subtracted from the environment (the refrigerator volume, ambient air or water) by the evaporation of the liquid part of the cold refrigerant mixture; the heat subtraction from the environment causes its cooling. The evaporator is where the circulating refrigerant absorbs and removes heat that is subsequently rejected in the condenser and transferred elsewhere by the water or air used in the condenser.

To complete the refrigeration cycle, the refrigerant vapour from the evaporator is again a saturated vapour and is routed back into the compressor.

According to above-described operating principle, the greater the temperature difference between condenser and evaporator, the greater the required pressure difference and consequently the more energy needed to compress the fluid. Thus the amount of thermal energy moved per unit of input work required decreases with increasing temperature difference.

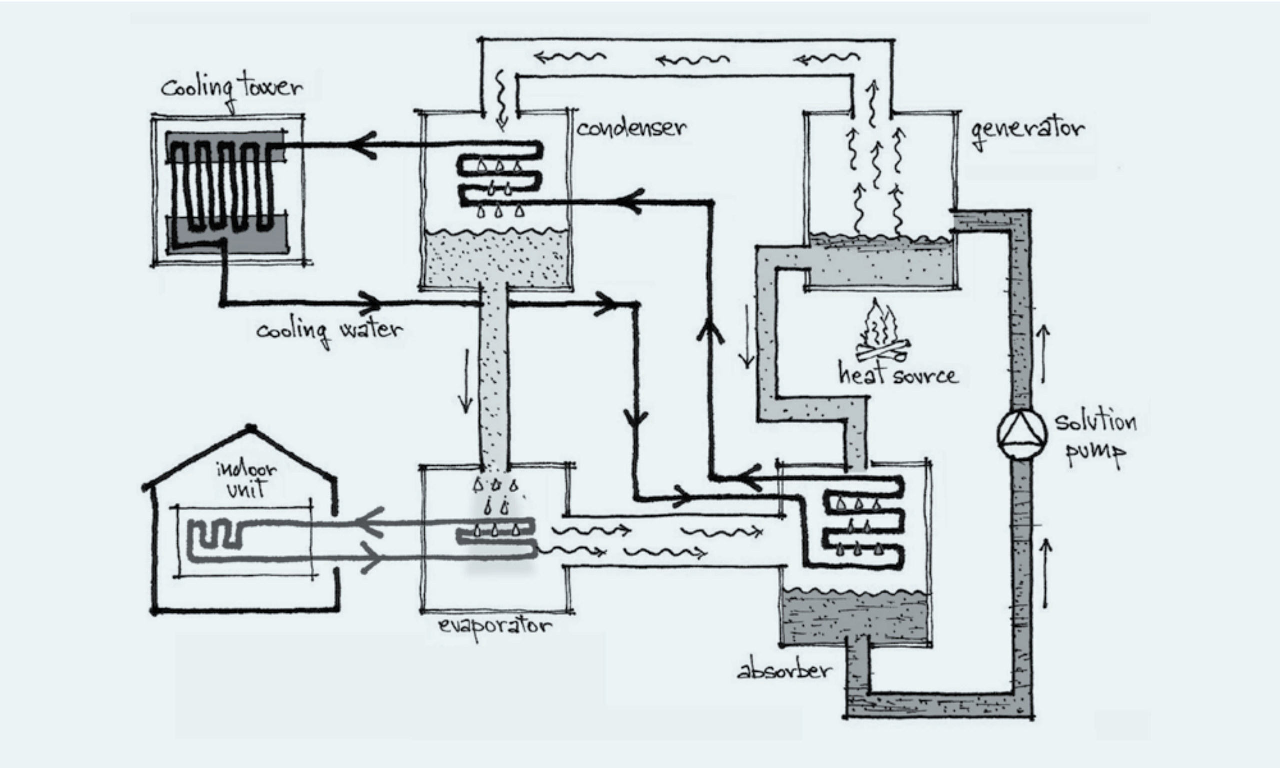
Absorption chiller

The absorption chiller (Fig. 4.2-26) requires no compressors or other moving parts to operate the thermodynamic cycle but uses a source of heat and a regenerator in place of compressor. A refrigerant solution (e.g. Lithium Bromide/Water, Water/Ammonia) is circulated between the regenerator (or simply generator), the condenser, the evaporator, and the absorber. The diluted refrigerant solution is pumped into the generator and is heated by a heat source, raising its temperature until it partially vaporizes and flows to the condenser. The remaining concentrated part of the solution flows down to the absorber chamber.

In the condenser, the cooling water absorbs the condensation heat from the vaporized part of the solution, changing it into a liquid. The liquid refrigerant flows from the condenser to the evaporator through expansion piping. During this transit the liquid refrigerant experiences a drop in pressure and temperature.

The refrigerant fluid is then pumped to the evaporator and sprayed on a heat exchanger, through which the water to be chilled flows before reaching the indoor unit. At low evaporator pressures, the liquid refrigerant vaporizes, removing energy from the chilled water. Then the vaporized refrigerant flows from the evaporator to the absorber.

FIGURE 4.2-26 **ABSORPTION REFRIGERATION MACHINE CYCLE**



In the absorber, the concentrated liquid solution absorbs the vaporized refrigerant and the cooling water removes the vapour absorption heat. As the refrigerant vapour is absorbed the concentrated solution returns to a diluted state and is pumped to the generator, completing the refrigerant cycle.

The efficiency of the absorption cycle is much lower than that of the compression cycle, but absorption chillers can use waste heat from cogeneration or solar thermal energy.

In general, depending on the fluid used to condense the refrigerant, i.e. the fluid to which the heat is transferred, and also on the fluid cooled by the internal evaporator coil, there may be four types of refrigeration machines/heat pumps:

- air to air: the refrigeration machine cools the room air directly through an evaporator and transfers heat to the external environment by means of an air cooled condenser;
- air to water: the refrigeration machine cools the room air directly and transfers heat to the external environment by means of a water cooled condenser. The water can come from a closed loop circuit (ground-coupled heat exchangers, cooling tower) or an open loop circuit (lake, river or ground water);
- water to water: the refrigeration machine draws heat from the internal water circuit (water distribution system with hydronic terminal units) and transfers it to the external environment by means of a water cooled condenser;
- water to air: the refrigeration machine draws heat from the internal water circuit and transfers it to the external air by means of an air cooled condenser.

The efficiency of a vapour compression machine is given by the ratio between the thermal energy transferred by the system and the electricity consumption. This relationship is usually called COP (Coefficient Of Performance) in heating mode and EER (Energy Efficiency Ratio) in cooling mode. COP and EER varies according to system technology but mainly depends on the temperature difference between evaporator and condenser, that is between the inlet air in the thermal zone and the external thermal sink. Good mean-yearly COP/EERs should be higher than 3 for air-condensed machines, while water-condensed systems can reach values greater than 5.

The efficiency of absorption machines is dependent on the temperature of the heat source: the higher the temperature, the higher the efficiency of the system. In this sense, the EER of an absorption machine varies depending on the type of heat pump and the operating conditions and has, in general, a value lower than 0.6; double-effect machines can be used only in the presence of high-temperature sources (>160-180 °C), with an EER up to 1.2.

Condenser cooling systems

Heat from the condenser of a vapour compression or absorption chiller can be extracted in two ways: with air or with water. In the first case, air cooled condensers are used; in the second case, if a continuous flow of cold water form a river, lake, sea or water table is not available, a cooling tower is used.

Air-cooled condensers reject heat from the refrigerant by sensible heating of the ambient air that flows through them (Fig. 4.2-27). The low specific heat of air results in a large volume flow rate of air required, with corresponding high fan power and large condenser plan area.

The net result of the use of an air-cooled condenser is a saving of water, but at the expense of increased power consumption by the compressor and the condenser.

Open cooling towers (Fig. 4.2-28) expose the condenser cooling water coming from the chiller plant directly to the atmosphere. This warm water is sprayed over a fill in the cooling tower to increase the contact area, and air passes through the fill. Most of the heat is removed by evaporation. The cooled water remaining after evaporation drops into the collection basin and is returned to the chiller's condenser.

FIGURE 4.2-27 **AIR COOLED CONDENSER**

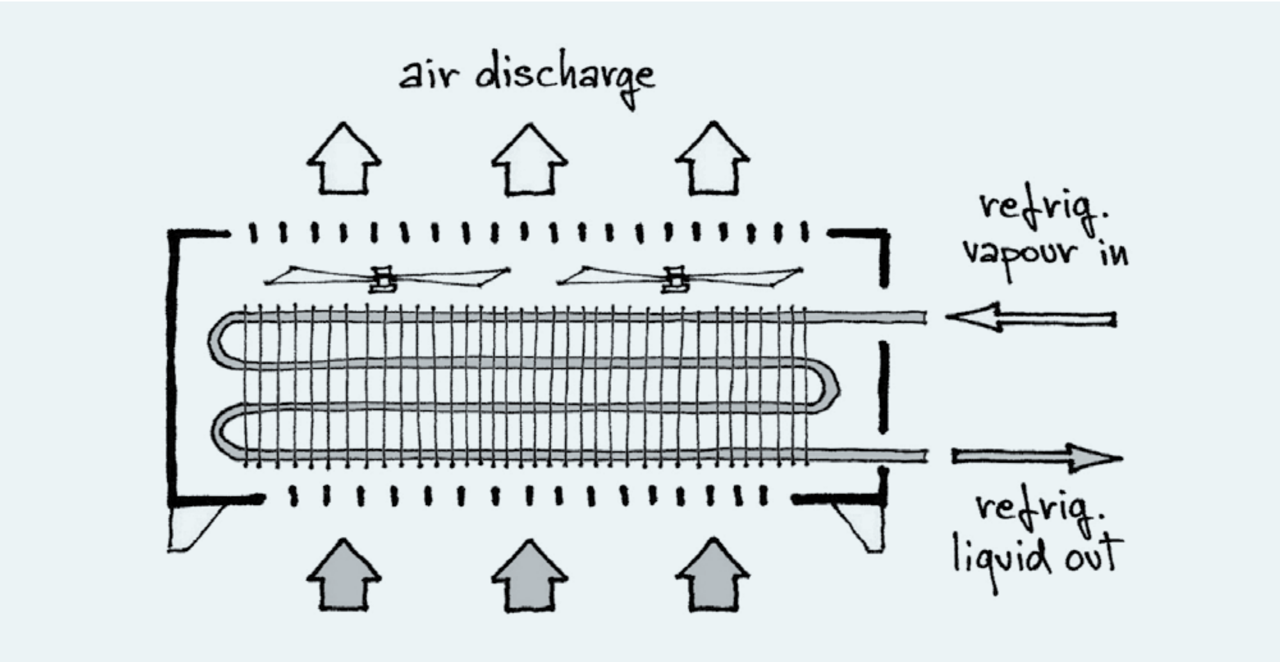
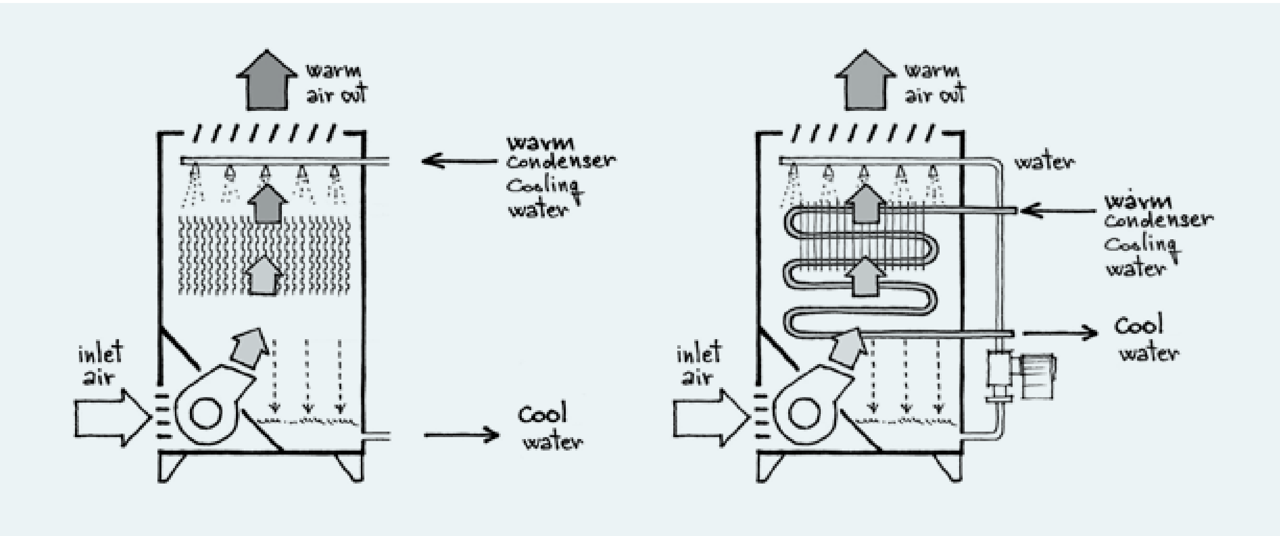


FIGURE 4.2-28 **OPEN COOLING TOWER (LEFT); CLOSED COOLING TOWER (RIGHT)**



A closed cooling tower (Fig. 4.2-28, right) circulates warm water from the chiller plant through tubes located in the tower. In a closed tower, the cooling water does not come in contact with the outside air. Water that circulates only within the cooling tower is sprayed over the tubes and a fan blows air across the tubes. This cools the condenser water within the tubes, which is then recirculated to the chiller plant.

The effectiveness of a cooling tower depends on the external environmental conditions (wet bulb temperature of external air); therefore in hot humid climate cooling towers are not as effective as in hot dry climates, but in the latter water availability may be a problem.

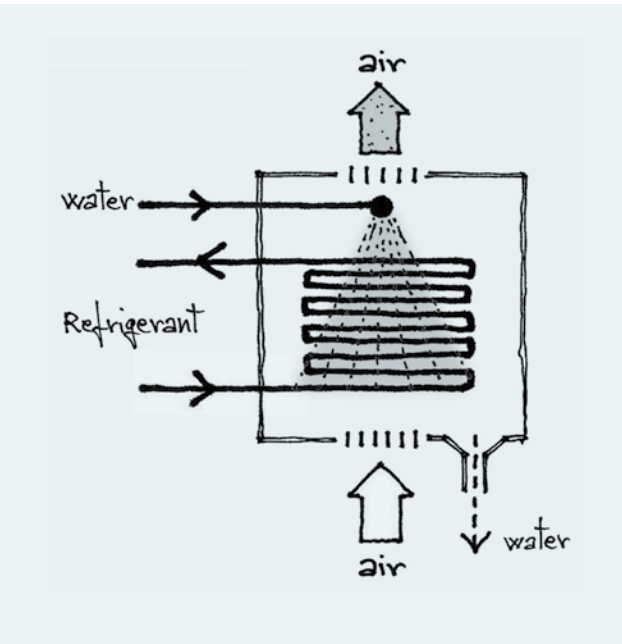
Means for improving energy efficiency of air cooled condensers

Several systems have been developed for improving the energy efficiency of air cooled condensers,.

Evaporative Condenser

An evaporative condenser (Fig. 4.2-29) is a device for cooling the refrigerant in the condenser coil by evaporating water. Water is sprayed on the condenser coil and evaporates, cooling the coil.

FIGURE 4.2-29 **SCHEME OF EVAPORATIVE CONDENSER**



Evaporative pre-coolers

Typical air-cooled condensers lose efficiency significantly during hot outdoor conditions. Evaporative pre-coolers reduce air conditioner loads by cooling the air that surrounds air conditioner condensers. The evaporative cooling technique described below (Fig. 4.2-30) is used to cool the air that goes to cool the air condenser. Since the cooler and moister air is passed over the condenser, the moisture is not added to the space. The cooler air passed across the condenser coil improves heat transfer efficiency, allowing the system to operate with much greater efficiency during peak conditions.

Peak demand can be reduced by 40%. These systems provide the greatest benefit in climates that necessitate a significant number of hours of cooling in outdoor temperatures of 35 °C or greater. Although these systems are relatively common in larger cooling plants, products are now available for residential and light commercial applications.

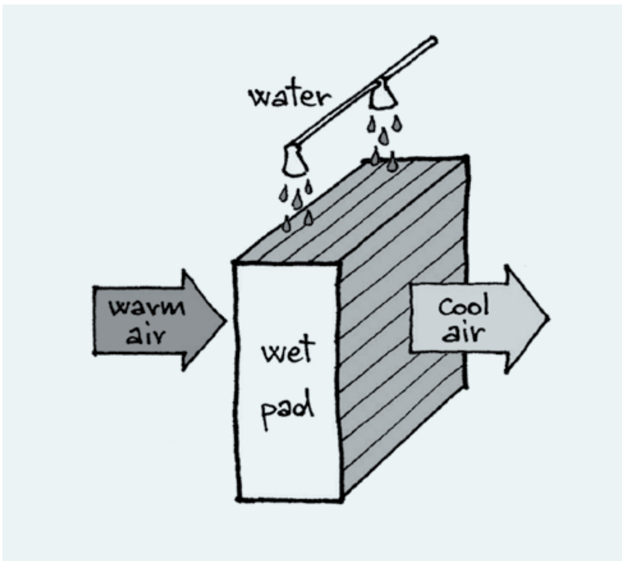
4.2.2.2 EVAPORATIVE COOLERS

In hot-arid and semi-arid climates there are seasons and periods of the day in which air humidity is very low and air temperature high. In these conditions evaporative coolers can be very effective and energy efficient. There are many types of evaporative coolers available on the market.

Direct

In direct evaporative coolers outside air is blown through a water-soaked medium (usually cellulose) and cooled by evaporation (Fig. 4.2-30). The cooled air is circulated by a blower.

FIGURE 4.2-30 **DIRECT EVAPORATIVE COOLING.**



The air, cooled by 10 to 20 °C as it crosses the water-soaked pad, is then directed into the room, and pushes warmer air out through windows.

When an evaporative cooler is being operated, windows are opened part way to allow warm indoor air to escape as it is replaced by cooled air. Unlike air conditioning systems that recirculate the same air, evaporative coolers provide a steady stream of fresh air into the room.

Evaporative coolers cost about one-half as much as central air conditioners and use about one-quarter as much energy. However, they require more frequent maintenance than refrigerated air conditioners and they are suitable only for areas with low humidity.

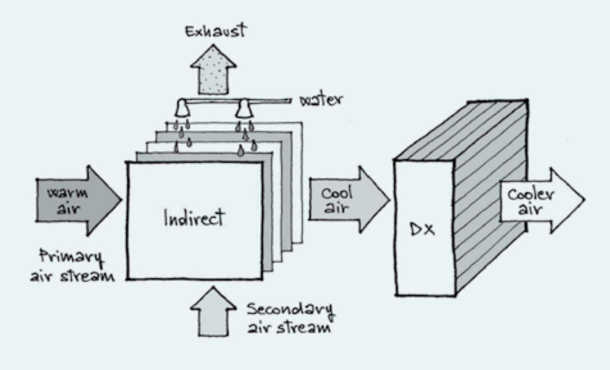
Evaporative coolers are rated by the airflow that they deliver. Most models range from 5,000 to 40,000 m³/h. Manufacturers recommend providing enough air-moving capacity for 20 to 40 air changes per hour, depending on climate.

Evaporative coolers are installed in one of two ways: the cooler blows air into a central location, or the cooler connects to ductwork, which distributes the air to different rooms.

Indirect

With direct evaporative coolers, if outdoor air humidity is not very low, indoor air humidity can be too high to be comfortable. This drawback can be attenuated with the indirect evaporative coolers (Fig. 4.2-31). With indirect evaporative cooling, a secondary air stream is cooled by water. The cooled secondary air stream goes through a heat exchanger, where it cools the primary air stream. Indirect evaporative cooling does not add moisture to the primary air stream.

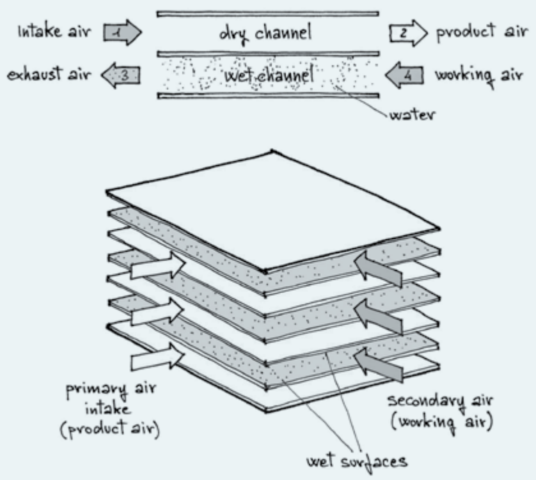
FIGURE 4.2-32 **TWO-STAGE EVAPORATIVE COOLER**



second stage, the pre-cooled air passes through a direct evaporative cooler. Because the air supply to the second stage evaporator is pre-cooled, less humidity is added to the air. The result is cool air with a relative humidity between 50 and 70%, depending on the climate, which represents a very good performance if compared to a traditional direct system, which produces about 80-90% relative humidity air.

Such two-stage systems (referred to as indirect-direct or IDEC systems) can meet the entire cooling load for many buildings in arid to semi-arid climates.

FIGURE 4.2-31 **INDIRECT EVAPORATIVE COOLING**



Two-stage

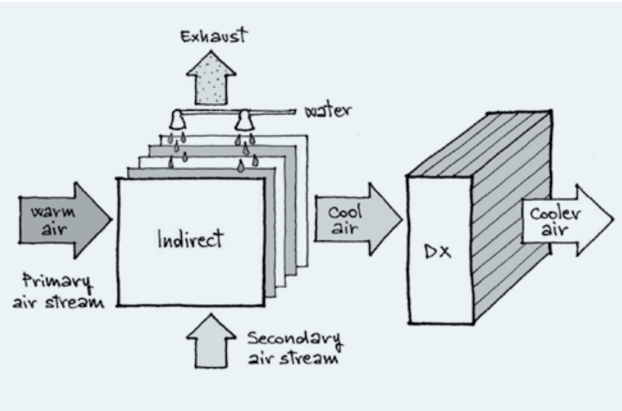
Two-stage evaporative coolers (Fig. 4.2-32) are newer and even more efficient. They use a pre-cooler, more effective pads, and more efficient motors, and do not add as much humidity to the rooms as single-stage evaporative coolers. In the first stage of a two-stage cooler, warm air is pre-cooled in an indirect evaporative cooler. In the

Two-stage evaporative coolers can reduce energy consumption by 60 to 75% over conventional air conditioning systems, according to the American Society of Heating and Engineers (ASHRAE). Yet this relative improvement depends on location and application.

Indirect evaporative cooling coupled with DX backup

Indirect evaporative cooling can be coupled with conventional DX (direct-expansion) cooling to lower refrigeration loads in order to meet cooling demand during hot and but not very dry outdoor conditions (Fig. 4.2-33). In indirect evaporative coolers with DX back-up, the primary air stream is cooled first with indirect evaporative cooling; most of the time, this cools the primary air stream to the desired temperature. When more cooling is required, the supplemental DX module cools the air further to reach the desired temperature.

FIGURE 4.2-33 **INDIRECT EVAPORATIVE COOLING COUPLED WITH DIRECT-EXPANSION (DX) COOLING SYSTEM**



Since the systems use 100% outside air for cooling, they can also be paired with heat recovery to capture some of the energy that is lost in the exhaust air stream and reduce the ventilation cooling load.

Water Use and Water Treatment

Water is used with evaporative systems to both replace the evaporated water and to purge dissolved minerals that accumulate as water evaporates. Water treatment is a concern, especially for areas where only hard water (rich in minerals) is available. Mineral deposits will accumulate in the sump and eventually cause scaling on the pads.

One option is a bleed-off system, which diverts a small amount of water to dilute mineral concentrations. The bleed rate depends upon water hardness and airborne contaminant levels and can range from 5% to 100% of the evaporation rate.

A blow-down system will periodically dump water from the sump while the cooler is in operation. The discharged water can be used to water gardens. Blow-down systems have an advantage over bleed-down systems in that they discharge accumulated dirt and debris that collects at the bottom of the sump, and they often use less water than continuous bleed systems.

A third option is water treatment. Water treatment is often recommended for systems with rigid media due to high replacement costs. Other treatment mechanisms include electromagnetic, electrostatic, catalytic and mechanical.

If rainwater is collected during the wet season and stored, can be used effectively for evaporative cooling, eliminating or minimising the problem of the dissolved minerals accumulation.

Disadvantages of evaporative coolers

Evaporative coolers require simple maintenance about once a month.

By their nature, evaporative coolers also continually use water; in areas with limited water supplies, there should be some concern about the water-use impact of adding an evaporative cooler.

The evaporative cooler water tank is a common place for mosquitoes to breed. To avoid this a chemical larvicide must be used or, better, water tanks sealed to prevent mosquitoes from depositing eggs.

Odours and other outdoor contaminants may be blown into the building unless sufficient filtering is in place.

Mould and bacteria may be dispersed into interior air from poorly maintained or defective systems, causing Sick Building Syndrome or Legionnaire's Disease if provisions for killing the germs are not made (such as germicide lamps).

Asthma patients may need to avoid poorly maintained evaporatively cooled environments.

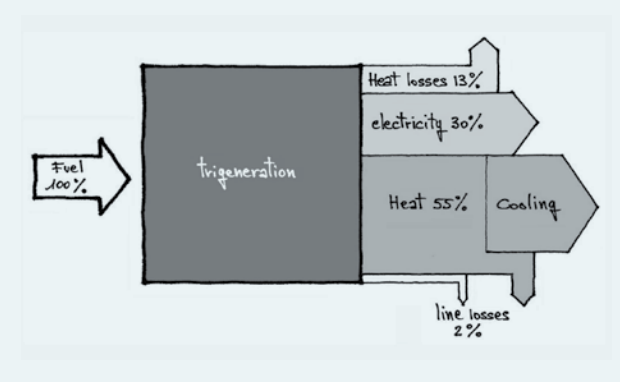
4.2.2.2 TRI-GENERATION SYSTEMS

Tri-generation or CHCP (combined heat, cooling and power) refers to the simultaneous generation of electricity and useful heating and cooling. The most common technical configuration is made up of a reciprocating engine or a micro-turbine powering an alternator, and an absorption chiller which is powered by the waste heat from the generator. This system can be economically viable in contexts where there is a constant need for thermal energy that can be used both for cooling and for producing DHW, and where availability of electricity from the grid is not always guaranteed. In such cases, if the whole system is correctly designed, it can be more efficient, in terms of primary energy needs, than an air-cooled electric refrigerating machine powered by the grid. In general it must also be noted that the lower the efficiency of national electricity generation , the more the use of tri-generation systems should be considered in preference to electric chillers, especially if heat is also needed and is usually produced using electric water heaters.

Finally it must be noted the electricity generator can also be powered by bio-fuels, such as bio-ethanol or bio-diesel, where available, further decreasing the primary energy consumption.

In figure 4.2-34 energy flows in a typical tri-generation system are illustrated.

FIGURE 4.2-34 **ENERGY FLOWS IN A TYPICAL TRI-GENERATION SYSTEM**



The configuration described is that of a typical tri-generation system. A further upgrade can be obtained by adding a vapour compression refrigeration unit working in parallel with the absorption refrigeration unit; in this way, through adequate system design and a controlled operating scheme, electricity and thermal energy fluxes can be balanced according to building needs and boundary conditions, maximizing both overall energy performance and economics by appropriate dispatch of the energy produced.

4.2.2.3 DECENTRALIZED DEVICES

For cooling a room, the simplest and most common solution is based on direct expansion systems: window air conditioners and, more popular nowadays, the so-called split systems.

Window air conditioners

A window air conditioner is a packaged direct refrigerant unit comprising a vapour compression refrigeration unit, a fan, a filter and appropriate controls. It is designed for installation in a framed or unframed opening in a building construction element, typically a window or a wall. The two main elements used for heat exchange, the evaporator and the condenser are placed respectively on the interior and on the exterior part of the building. They can be used for both heating and cooling if the refrigeration unit can be used with reverse cycle. However, this element has several drawbacks concerning performance, aesthetics, noise, space utilization and air infiltration.

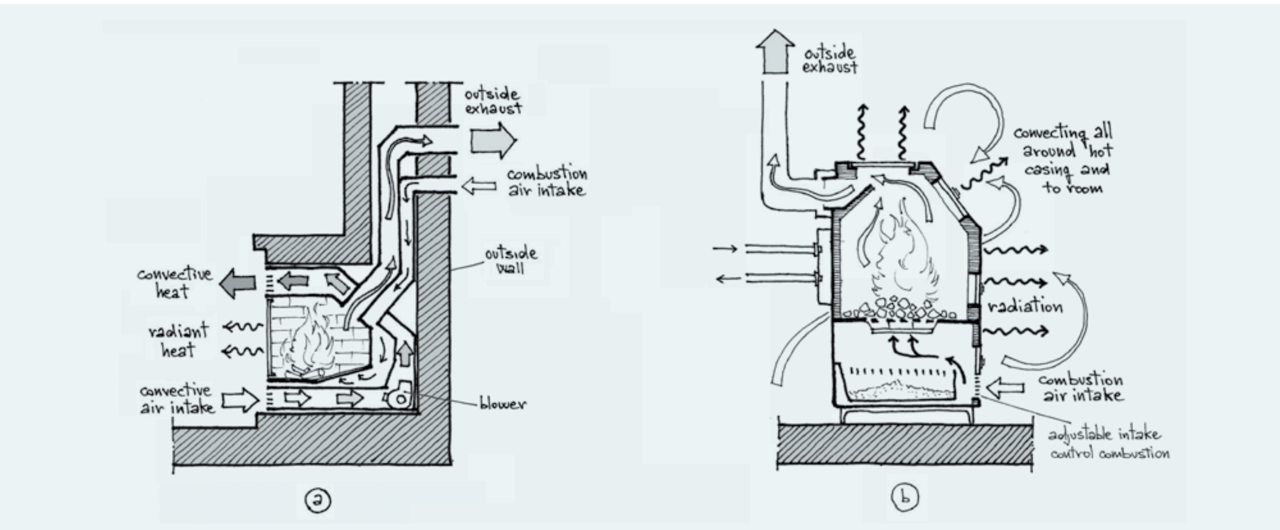
The use of window air conditioners should be limited to provisional installations or in such contexts where other technical solutions cannot be used because of technical constraints.

Split systems

A development of the window air conditioner is the split system. A split system is generally composed of an exterior unit, consisting of compressor and condenser elements, and an interior unit, consisting of evaporator and expansion valve elements; the two units, which can be many metres away from each other, are connected by pipes which carry the refrigerant.

Heating in the EAC is not generally necessary, but in some contexts, such as residential buildings located in a high upland climate, some decentralized heating devices are needed.

FIGURE 4.2-35 **FIREPLACE WITH FORCED-VENTILATION (A) AND WOOD-STOVE (B)**



Evaporative coolers

In hot arid and hot semi-arid climates evaporative coolers are a sensible alternative or complement to window air conditioners and to split systems.

Fireplace

A fireplace is, as its name suggests, a location where on-site combustion is used as a means of producing heat. The typical fireplace consists of a niche constructed of non-combustible materials that will withstand the temperatures generated during the combustion process. Adding fans to circulate heated air can increase its efficiency (Fig. 4.2-35a), which is typically low due to the large losses through the chimney. A fireplace is a local heating device directly providing heat to a limited area of a building. Problems related to low-efficiency and high environmental pollution of the smoke produced by fireplaces, especially if naturally vented, must be carefully taken in account.

Wood Stove

Wood stoves (Fig. 4.2-35b) are on-site combustion devices, normally self-contained, that are more efficient than fireplaces. Better control of the supply of air permits more complete combustion, resulting in improved resource utilization.

Recently, many technical solutions using woodchips are available in the market. These systems can have an automatic woodchip loading system, electronic combustion control and can easily heat large spaces, also reducing the pollution due to incomplete combustion.

In many cases wood stoves can also integrate other functions, such as cookers and an oven, and their use in residential contexts can be considered, if biomass is locally available.

4.2.3 DHW PRODUCTION

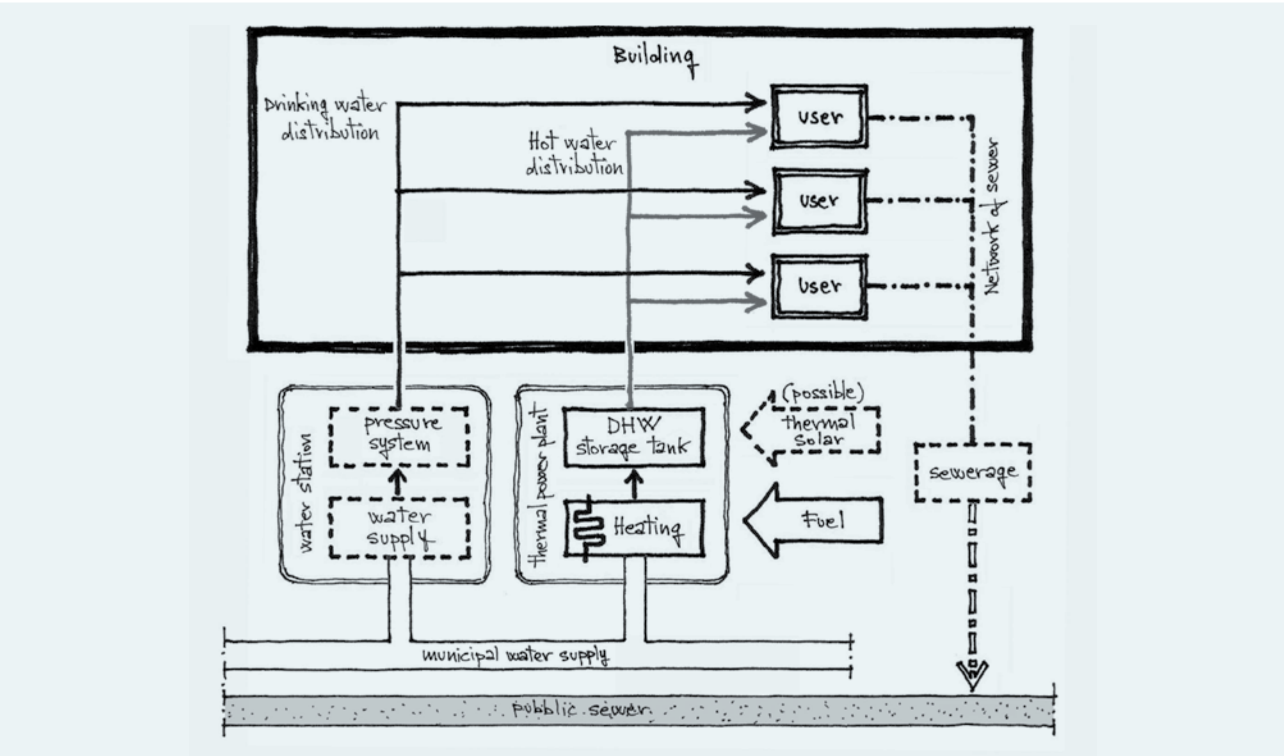
The amount of energy consumed by DHW (Domestic Hot Water) systems may be significant in many types of users such as hotels, sports centres, gyms, hospitals, and in residential buildings.

Water coming from the municipal water supply must have sufficient pressure to reach the most disadvantaged users and it must come out of the dispensing tap with a certain residual pressure. If the pressure is insufficient (which is often the case in tall buildings) it is necessary to install an appropriate pumping system. There may be one or two distribution circuits depending on how the hot water is produced. The network is single (only cold water) if water heating takes place locally (domestic water heaters); it is double if DHW production is centralised, as shown in figure 4.2-36.

4.2.3.1 DHW SYSTEMS AND LEGIONELLA

The production of hot water may be a source of risk for dissemination of gram-negative aerobic bacteria, known as legionella. The infection is contracted through aerosols, i.e. when inhaling contaminated water in small droplets.

FIGURE 4.2-36 **SCHEMATIC DIAGRAM OF A CENTRALISED DHW SYSTEM**



Hot water circuits may favour the growth and dissemination of legionella, because the bacterium proliferates at temperatures of between 15 °C to 50 °C (at temperatures up to 22 °C the bacterium exists but is inactive). There are critical places in the DHW systems: inside the pipes, especially if they are old and have deposits inside, in storage tanks, in shower heads or in taps. Additional sources of risk are storage tanks normally present in solar hot water production systems, whose normal operating temperature is around 50 °C.

To avoid/reduce the risk of legionella it is advisable that stored and circulating water is heated to 60 °C and over from time to time, to kill any bacteria.

4.2.3.2 CORRECT USE OF POTABLE WATER

The basic utilities are obviously essential in every building, but over the last several decades people have realised that water is rapidly becoming a precious resource. While the total amount of water in its various forms on the planet is finite, the amount of fresh water, of quality suitable for the many purposes for which it may be used, is not uniformly distributed.

Drinking water is a precious resource and saving it is one of the features of a sustainable building. Reduction in the use of drinking water can be obtained in two ways:

- by using it more consciously (for example installing saving devices such as aerator valves, taps with timers, etc.);
- by replacing drinking water with non-potable water for the uses for which drinking water quality is not needed (e.g. for toilets, irrigation, etc.).

The first strategy requires the introduction of devices to reduce the quantity of water used, whilst still maintaining the quality of service.

TABLE 4.2-2 **IMPROVING THE PERFORMANCE OF DHW SYSTEMS**

Measure	Description, tips and warning
Reduction of water consumption	Check the plumbing system and the DHW system, in order to find possible further measures to reduce the consumption of potable water. The most common equipment strategies are as follows: • lavatory taps with flow restrictions; • infrared tap sensors; • water efficient shower heads; • timers on taps; • dual-flush toilets. A reduction in the consumption of water depends very much upon end-user behaviour: any form of communication, education and information given to the users is useful. Some of the measures listed above are cost-effective as retrofit actions in existing buildings only if they are part of a planned renovation of the system.
Installation of potable water meters	A reduction in the consumption of cold or hot water can be obtained with the installation of individual meters. In this way the end-user pays for the individual consumption of water and thus has incentives to save.
Insulation of DHW storage tank	Inadequate thermal insulation of the storage tank in a building causes an increase in heat losses through the walls of its casing. Replace existing insulation with a thicker layer of insulating material.
Replacement of electric boilers for hot water production	The direct thermal use of electricity by Joule effect is not sustainable and should be avoided. Electric boilers should be replaced by fuel fired boilers or, better, heat pumps.
Installation of DHW heat pumps	Existing inefficient water heaters (e.g. gas boilers, electric boilers, gas or electric geysers) should be replaced with heat pumps. With this type of equipment hot water is produced with high energy efficiency. DHW heat pumps could be used to replace electric boilers in locations where fuels (e.g. gas) are not available: electricity is used but in a more efficient manner, especially in hot climates, where the electricity consumption is reduced by a factor of four, compared with an electric (resistance) water heater.
Solar systems for DHW production	In some cases the use of solar energy for DHW production is the best way to produce hot water with dramatic reductions in energy consumption. Because of the high values of solar radiation in the EAC, it is not necessary to install high performance solar collectors. For residential uses compact solar water heaters are preferable to traditional ones, because they do not normally require any electrical connections.

In the second case it is necessary to provide a dual supply system, one for drinking water and one for non-potable water.

We define as *drinking water* water that can be used for human consumption without harmful consequences to health.

Non-potable water is water that, while not corresponding to the chemical, physical and biological characteristics of drinking water, does not contain anything that is polluting or otherwise dangerous. The distinction between drinking water and non-potable water is defined in local health regulations, compliance with which is monitored by the responsible authority .

Non-potable water may be used in many ways and the list below gives some examples:

- urinals or vessels;
- industrial laundries and industrial cleaning in general;
- watering of plants;
- supply of fountains, ornamental pools and similar;circuits of cooling towers; circuits for heating or cooling of other fluids;
- fire systems (hydrants, sprinklers, etc.).

The distribution of non-potable water must be distinct from that of drinking water at each point of the related piping and terminals.

No connections are allowed between a drinking water supply and a distribution system for non-drinking water even when equipped with shut-off valves. All components of the distribution networks of non-potable water should be clearly and indelibly marked with words and symbols in accordance with local regulations.

4.2.4 ARTIFICIAL LIGHTING

Lighting is an important factor in minimizing overall energy consumption. In industrialized countries, lighting accounts for 5–15% of the total electric energy consumption.

Besides direct savings, indirect energy savings can be made due to reduced consumption of electricity for air conditioning.

The energy consumption of a lighting installation is heavily dependent on the type of lamps used, luminaires and lighting controls (daylight, presence detection, dimming, etc.). Nevertheless, the electrical power load of a lighting installation is often a first and significant factor in energy consumption.

4.2.4.1 LAMPS

Lamps can be divided into three main groups: incandescent, discharge and light emitting diode (LED). The light of incandescent lamps is generated by a filament heated to a high temperature by an electric current. Discharge lamps have no filaments, but produce light through the excitation of the gas contained between two electrodes. A light-emitting diode (LED) is a semiconductor light source. It is like a photovoltaic cell operating backwards: instead of light generating electricity, electricity generates light.

The factors that characterize light sources are (see also Appendix 2):

- luminous flux, expressed in lumen;
- luminous efficacy[36],expressed in lm/W;
- duration, usually expressed in number of operating hours passed before the luminous flux is reduced to a certain percentage of the initial one[37];
- luminance, expressed in cd/m^2;
- colour appearance, or colour of the light: the colour impression one gets looking at the source itself;
- colour temperature;
- colour rendering;
- physical dimension.

Incandescent lamps are characterized by high compactness, low luminous efficacy, short duration, high luminance, good appearance and colour rendering, and low colour temperature. Because of their low luminous efficacy, the production of incandescent lamps is going to be phased out all over the world. Fluorescent lamps have higher luminous efficacy, longer life and lower luminance, but their colour rendering is worse than that of incandescent lamps.

In this section, only the lamps used for interior lighting are considered.

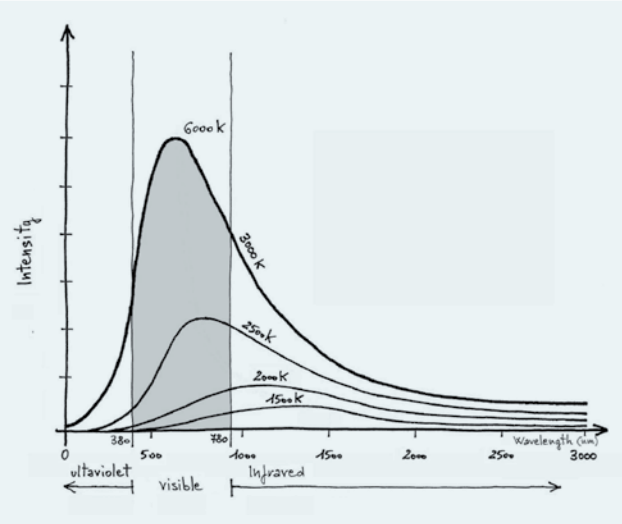
Incandescent lamps

A tungsten wire heated by Joule effect, i.e. by effect of the electricity passing through it, emits electromagnetic radiation, first in the far infrared, then - with increasing temperature - increasingly in the visible range (figure 4.2-37 shows the black body spectrum at different temperatures; the corresponding spectrum of tungsten differs very little from this). That is, as the temperature increases the optical efficiency (i.e. the ratio of radiated energy falling in the visible range to the total energy emitted) of the source increases.

36 *The luminous efficacy of a source can be defined as the ratio of the lighting power to the electric power used to obtain it.*

37 *All kinds of lamps, to a greater or lesser extent, are subject to a process of gradual decay of the emitted flux prior to failure .*

FIGURE 4.2-37 **BLACK BODY SPECTRUM AT DIFFERENT TEMPERATURES**



The incandescent lamp exploits this principle; it comprises, apart from the filament, a transparent or translucent glass container that protects it, the filament supports and the screw base. The container is filled with an inert gas, typically a mixture of nitrogen and argon, which reduces the oxidation of tungsten, which must be avoided for two reasons: firstly, the erosion of the filament results in its cracking (this influences the life of the lamp); secondly vapours tend to be deposited on the inner wall, reducing its transparency (which translates into a reduction in the luminous efficacy). For this reason, the temperature is kept far below melting point, and this has a negative effect on the optical efficiency of the lamp, and thus on the luminous efficacy. Their operation range lies between 2700 and 3000 K and, since their spectrum is practically coincident with the black body spectrum, their colour temperature coincides with their operation temperature.

The life expectancy of the lamp is 750-1000 hours, with luminous flux at the end of the useful life at 87% of the initial one. Most of the emission of incandescent lamps (up to 95%) is in the infrared region and their luminous efficacy is 8-13 lm/W.

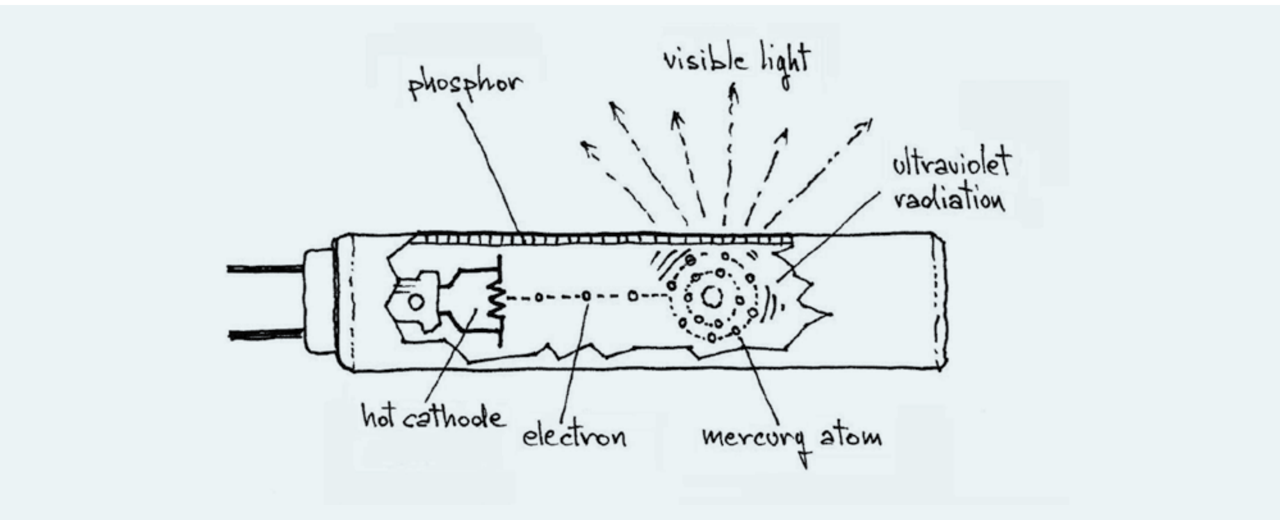
Tungsten halogen lamps

Tungsten halogen lamps are improved incandescent lamps available in tubular (double ended) and single ended (two-pin) form. Besides the inert gases ,the bulb also contains halogen (such as iodine or bromine), whose function is to combine - in cooler areas of the lamp - with the evaporated tungsten, to form a gaseous compound; this compound dissociates in contact with the hot filament, and this gives rise to the re-deposition of most of the sublimed tungsten. In this way, it significantly slows down both the process of erosion of the filament as well as the deposition on the inside the bulb, and therefore, it is possible to increase the temperature up to 3000 K, resulting in improved luminous efficacy and higher colour temperature (light is more "white"). The life expectancy is 3000-5000 hours, with the final luminous flux equal to 94% of the initial one.

Fluorescent lamps

A fluorescent lamp (Fig. 4.2-38) consists of a tubular glass container with two electrodes soldered at each end. It contains mercury vapour at low pressure, in addition to a small amount of inert gas to facilitate starting. The inner surface of the tube is covered with a layer of fluorescent material (phosphorus). The operation principle is as follows: once a potential difference is created, electrons move towards the anode and the ions toward the cathode; the electrons along the tube acquire speed and collide with atoms that they encounter along their path. Some are so fast as to be able to pull out some electrons from atoms, and expand the flow of the free ones, which act as "bullets", while others have only sufficient energy to move

FIGURE 4.2-38 **LINEAR FLUORESCENT LAMP**



the electrons of the atoms from a lower energy level to a higher one. When the electron returns to its stable energy level, it emits a photon of energy equal to the difference between the energy level at which it was pushed and the stable one. These photons constitute the radiant emission of the lamp.

The process described, with mercury atoms in the gas filling of the tube, causes radiation which falls mainly in the ultraviolet region. The inner phosphor coating ensures the transformation of ultraviolet radiation into visible radiation, balancing the outgoing radiation so as to ensure a good colour rendering; the mixture determines the type of light obtained. The spectrum obtained is of the type shown in figure 4.2-39, where the spectrum of the incandescent lamp is also shown, for purposes of comparison.

Fluorescent lamps have a luminous efficacy reaching 100 lm/W.

Fluorescent lamps are usually categorized according to their appearance, tonality, or colour and according to the balance between luminous efficacy and colour rendering. Table 4.2-3 shows the correlated colour temperature[38] (CCT) range and CCT class of most common fluorescent tubes on the market. A "warm" lamp integrates well with incandescent bulbs, a "white" or "intermediate" lamp fits quite well with both incandescent bulbs and with daylight, while "cool" or "daylight" lamps integrate well only with natural light.

Florescent lamps are available in wide variety of sizes, colours, wattages, and shapes. The linear tubular fluorescent lamps are produced in numerous lengths and powers (Fig. 4.2-40). Among the fluorescent lamps are the compact fluorescent type (Fig. 4.2-41), which are replacing the old incandescent ones and have a luminous efficacy about five times higher and a duration from five to eight times longer. At the end of their life, the luminous flux is equal to 85% of the initial one.

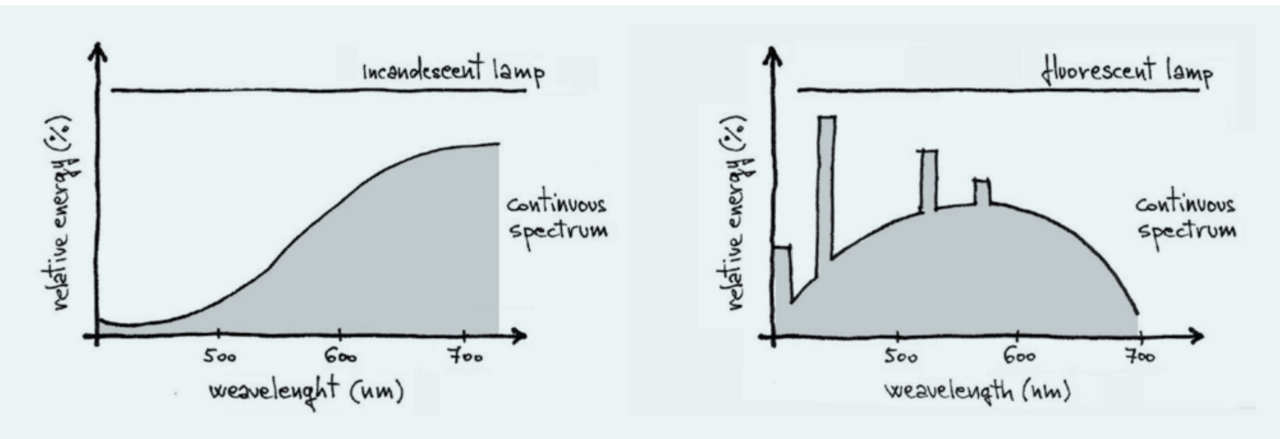
TABLE 4.2-3 **COLOUR TEMPERATURE AND CLASS**

Correlated colour temperature (CCT) [K]	CCT Class
<3300	Warm
3300-5300	Intermediate
>5300	Cold

Metal halide lamps

Metal halide lamps are high intensity discharge lamps, which are very efficient light sources that are more like incandescent than fluorescent lamps in size and shape. Like all discharge lamps they need a blast to work. The light is emitted from a small arc tube located inside a protective outer bulb. The relatively small size of this arc tube permits some optical control similar to that possible with a point source. When increased colour rendering is desired, metal halides are added to the mercury in the arc tube. The white light emitted by metal halide lamps is moderately cool, but there is enough energy in each part of the spectrum to provide very good colour rendering. Metal halide lamps are some of the best sources of light because they combine many desirable characteristics in one lamp: high efficacy (68-120 lm/W), long life (10000-20000 hours), very good colour rendering, and small size for optical control. However, they are not generally suitable for interior lighting because their minimum power is rather high.

FIGURE 4.2-39 **LIGHT SPECTRUM AND EMITTED ENERGY OF INCANDESCENT AND FLUORESCENT LAMPS**



38 *The correlated colour temperature is the absolute temperature of a black body whose chromaticity most nearly resembles that of the light source.*

FIGURE 4.2-40 **COMMON SHAPES OF FLUORESCENT**

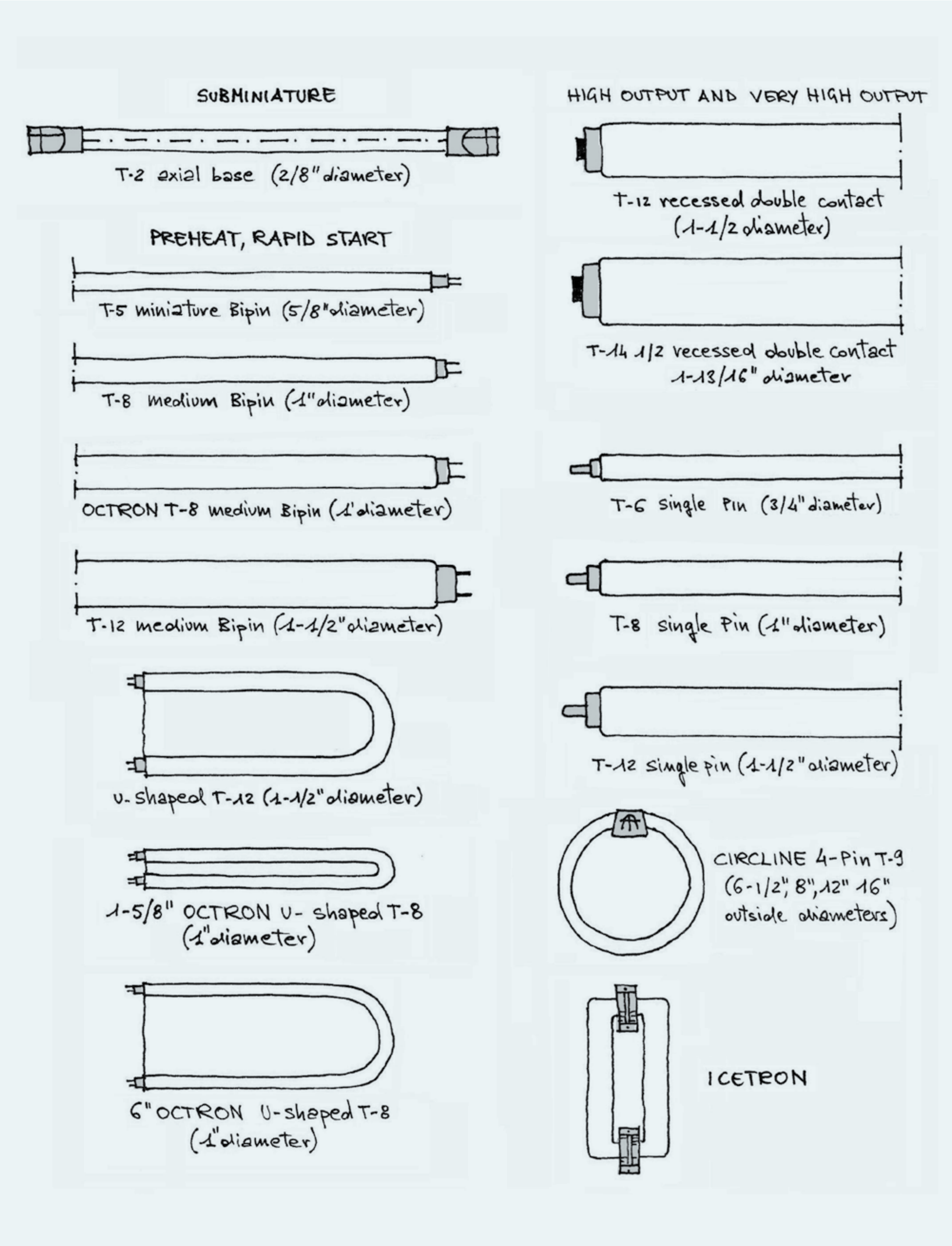


FIGURE 4.2-41 **COMPACT FLUORESCENT LAMPS (CFL)**

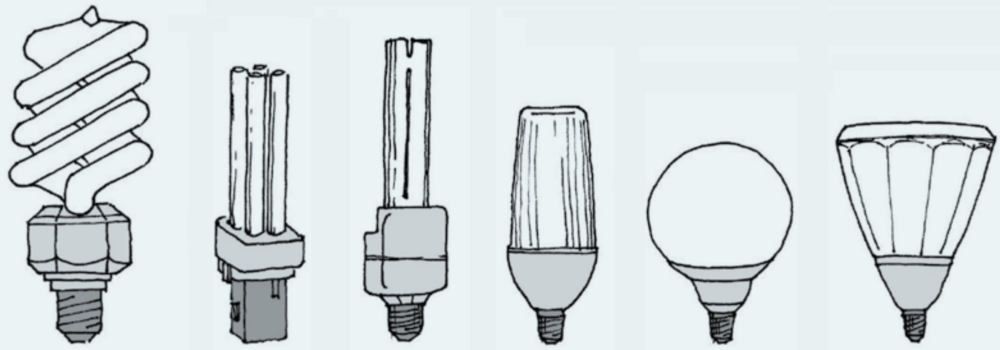


TABLE 4.2-4 **LAMP PERFORMANCE AND OPERATING CHARACTERISTICS***

Lamp type	Luminous efficacy [lm/W]	Colour rendering index [CRI]	Colour temperature [K]	Colour appearance	Life [Hours]
Normal Incandescent	8-13	97+	2500-2800	Excellent	750-1000
Halogen	10-36	97+	2800-3200	Excellent	3000-5000
Fluorescent (Linear)	70-100	50-90+	2700-7500	Excellent	15000-46000
Fluorescent (compact) Screw based CFL	35-65	Low 80s	2700-6500	Excellent	6000-8000
Fluorescent (compact) Pin based CFL	50-80	Low 80s	2700-5000	Excellent	10000-16000
Metal Halide	68-120	60-90	2700-10000	Fair	10000-20000
LED	>50	20-95+	1100-9000+	Poor to very good	20000-50000

* *The Lighting Handbook, Tenth edition-Reference and Application, Illuminating Engineering Society, 2011*

Light emitting diode (LED)

A new and promising development is the light emitting diode (LED) as a light source. LEDs produce pure coloured light, and to generate white light, light from different coloured LED's must be mixed or phosphorus (as in fluorescent lamps) must be used to convert coloured light to white light. Unlike all of the other light sources, LED produces very little heat in the form of infrared radiation; however, LEDs produce a large amount of sensible heat for which a heat sink is needed. LEDs are usually mounted on metal blocks that conduct the heat away from diodes into the air behind the lamps. At present, the luminous efficacy of LEDs emitting white warm light is above 50 lm/W, higher when the light is cool white. LEDs use only 10-20% of the electricity used by incandescent lamps to produce the same quantity of light and their life expectancy is 100 times greater.

The performance and operating characteristics of different types of lamps are summarised in Table 4.2-4.

4.2.4.2 **LUMINAIRES**

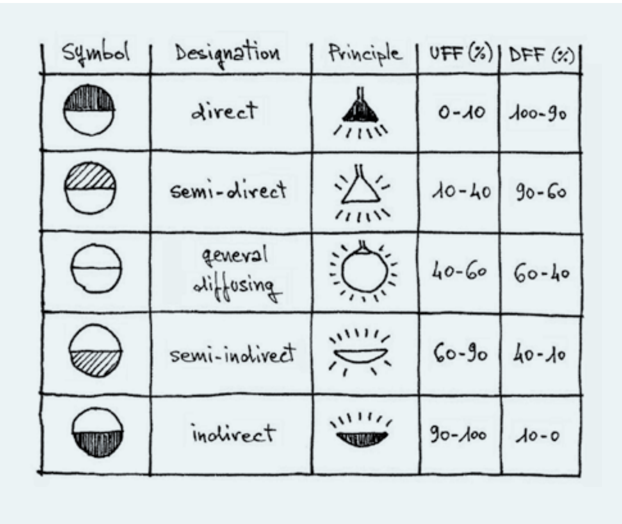
A luminaire is the container of one or more luminous sources, including what is required to fix, protect and connect them to the electric mains. The purpose of luminaires is to modify, in relation to specific requirements, the characteristics of flux and the luminance of the lamps they contain. Control of the luminous flux distribution is obtained by exploiting the optical properties of some materials (Table 4.2-5).

TABLE 4.2-5 **TRANSMISSION COEFFICIENTS OF SOME MATERIALS**

Material	Transmission coefficient [%]
Clear glass	80-90
Frosted glass	70-75
Opal glass	20-60
Clear acrylic plastic	80-90
Opal acrylic plastic	20-60
Alabaster	20-50
Marble	5-30

Luminaires are divided into five groups, in relation to the distribution of the luminous flux in the space above and below the horizontal plane passing through the centre of the unit (Fig. 4.2-42).

FIGURE 4.2-42 **LUMINAIRE TYPES AND THEIR FLUX FRACTIONS**



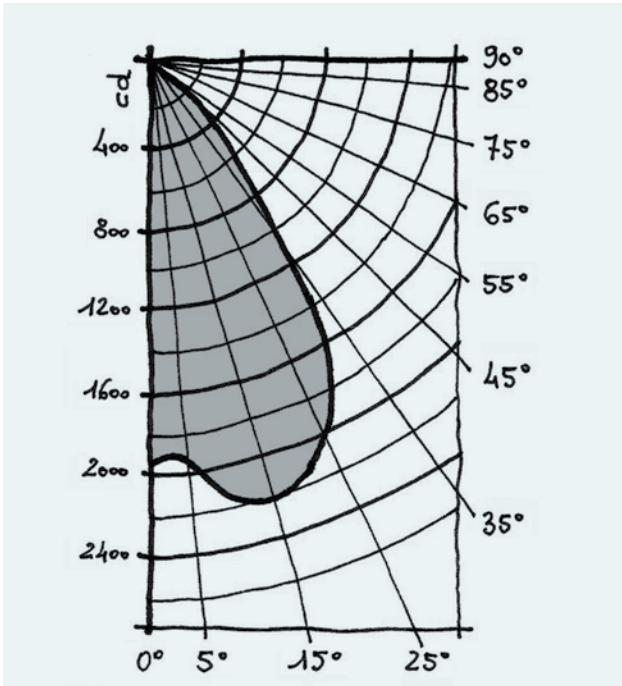
The efficiency of a luminaire is expressed by the light output ratio (LOR) between the flux emitted by the luminaire and that emitted by the lamp, and is usually expressed as a percentage. This may be divided into upward and downward parts (divided by the horizontal plane across the centre of the lamp).

Alternatively, the output of the luminaire can be taken as the basis (the 100%) and the flux fractions (FF) can be defined as UFF upward and DFF downward, defining the flux fraction ratio between UFF and DFF.

Photometric curves

A more precise definition of a lamp/luminaire combination (or a lamp acting as a luminaire) is given by the *polar curves* (or polar intensity diagrams), by plotting the light intensity in a series of directions within one vertical plane through the luminaire. It is a two-dimensional representation and therefore shows data for one plane only. If the distribution of the unit is symmetrical (e.g. luminaires with an incandescent lamp), the curve in one plane is sufficient for all calculations and a semi-circular polar diagram is used on which the source intensity (cd) viewed from different directions (view angles) is plotted (Fig. 4.2-43). If the distribution of the unit is asymmetrical, the greater the departure from symmetry, the more planes are needed for accurate calculations (Fig. 4.2-44), such as with fluorescent luminaires, where at least two planes are required (Fig. 4.2-45).

FIGURE 4.2-43 **PHOTOMETRIC CURVE OF A SPOT-LIGHT**



4.2.4.3 **LIGHTING CONTROL SYSTEMS**

The further one moves from a window, the more difficult it becomes to maintain the daylight illumination levels required for some tasks. When those tasks are localized, like desk work, daylight can be supplemented with artificial lighting located near the task and under the control of the user. This is an effective combination because daylight can still be used in large sections of the building that are distant from the windows, but where illumination level requirements may be lower. For instance, in an office, ambient daylight can be supplied at 100-200 lux over the whole office, while detailed reading at a desk may require 300 lux.

FIGURE 4.2-44 **PHOTOMETRIC CURVES OF AN ASYMMETRICAL LIGHTING SOURCE**

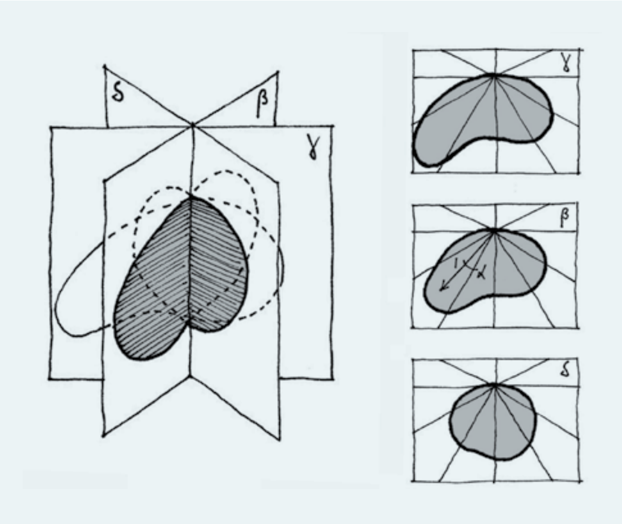
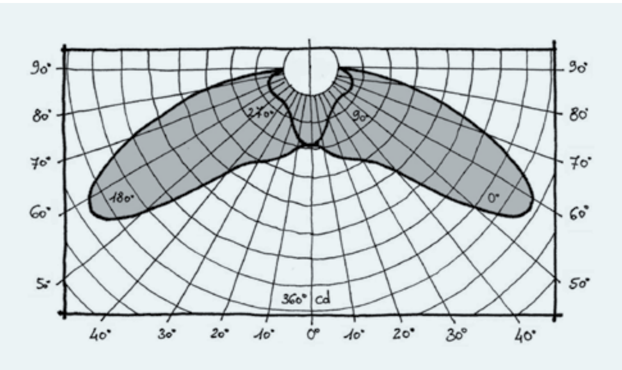


FIGURE 4.2-45 **PHOTOMETRIC CURVES OF A LUMINAIRE WITH FLUORESCENT TUBES. THE ANGLES 0°, 90°, 180° AND 270° INDICATE THE POSITION OF THE PLANES ON WHICH THE CURVE IS PLOTTED (SEE FIG. 4.2-44)**

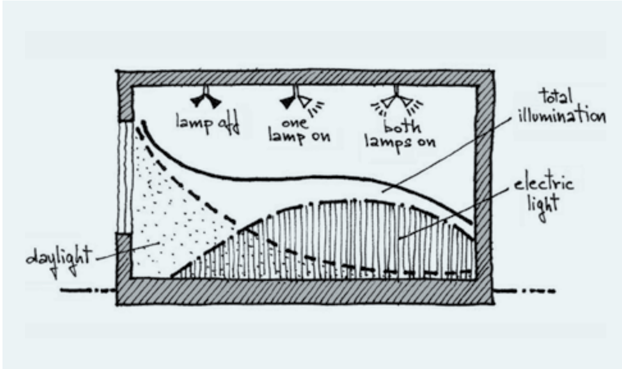


Properly designed artificial lighting control can yield functional, aesthetic, psychological, economic and environmental benefits. Lighting control allows for the flexible use of spaces, as well as the creation of an interesting and varying lighting environment. Lighting control is also is one of the best ways to save large amounts of energy simply by allowing unneeded lights to be turned off. Lighting control generally requires the use of automatic devices, such as occupancy sensors, photo-sensors, timers, and remote switching equipment.

Occupancy sensors respond to people entering and leaving the room. They are based on either infrared or ultrasonic technology or combination of both as hybrid technology.

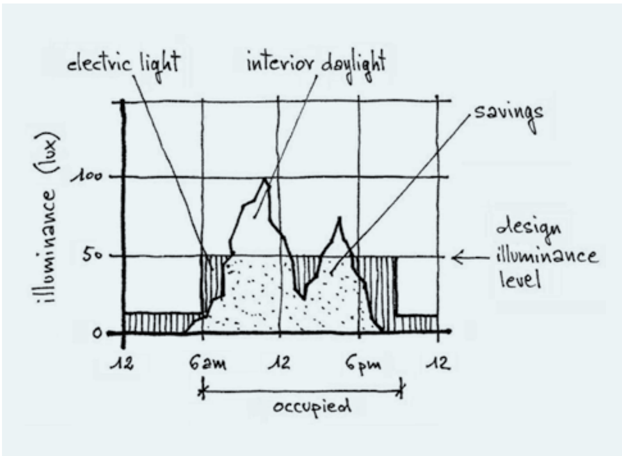
People can also adjust their light levels to suit their tasks and their proximity to the window, sometimes using daylight only and sometimes using a combination of daylight and artificial light (Fig. 4.2-46).

FIGURE 4.2-46 **MAINTAINING DESIGN ILLUMINANCE WITH ELECTRIC LIGHT SWITCHING IN LAYERED ZONES**



Artificial lighting can be controlled by a photosensitive cell so that it is automatically switched on or off when daylighting reaches a certain level or continuously dimmed so that electric lighting supplies just the supplemental light necessary to meet the illumination requirements. The use of automated daylight control can save 30-50% of the electric lighting energy in office buildings, often during a building's peak load times (Fig. 4.2-47).

FIGURE 4.2-47 **POTENTIAL ENERGY SAVINGS FROM DAYLIGHTING**



Most timers are centrally located to turn lights on and off at a pre-set cycles. These are excellent whenever there is a regular schedule of activities.

Remote control switching enables people or a computer at a central location to control the lights. This central control of lights is a part of the energy management system.

Dimming is another powerful tool for energy savings. When daylighting is used, switching and dimming are especially important.

4.2.4.4 DESIGN OF LIGHTING SYSTEMS

The objective of a lighting system design is the identification of the type, the number and power of the luminaires, as well as their location, in order to obtain the optimum visual comfort in relation to the tasks that must take place in the illuminated area. To do this there are numerous methods - from simple empirical rules to complex computer simulation models - which provide more or less accurate results and are used at different stages of the design process.

The final design of lighting systems today is performed with the aid of the computer; a reasonably reliable estimate can be made, however, with fairly simple manual methods such as the total flux method, which allows the designer to quickly calculate the total flux necessary to ensure a certain level of illumination on the work plan[39] of a parallel piped room[40] with the luminaries arranged in a uniform manner.

The system design requires that, once the activities to be performed in the room have been defined, the designer must take initial decisions, which are as follows:

1. The illumination level required on the work plan depends on the activities to be performed in a room and may vary from country to country or as a tradition or as a standard, and also in relation to the optimization of the ratio between the cost of energy and labour. It should be noted, in fact, that the quality of illumination has a direct impact on the productivity of those who perform a task. Table 4.2-6 shows the values of illumination recommended in relation to the activities[41]. It should be noted, however, that recent investigations showed that 300 lux, instead of 500 lux, is the most appropriate value for office buildings.
2. The type of illumination (direct, semi-direct, diffuse, etc.)indicated by the technical, economic and aesthetic parameters, and the choice of the type of illumination goes hand in hand with the choice of the type of luminaries, which is also conditioned by glare control;
3. The type of light source, according to economic (cost, duration) and technical parameters(quality of light).
4. The illumination of the working plane depends both on the direct flux from lighting fixtures, and on indirect, -diffuse- flux from walls and ceiling, which depends on the colours and geometry of the room.

39 The work plane is the plane on which a certain level of illumination should be maintained, in an office it will be the height of the tables, in a butcher's shop it will be the height of the counter, in a corridor it is the floor, etc.

40 For other shapes the method does not apply or should be used with caution.

41 EN 15251 Standard

Total flux or utilization factor method

If E_m is the required illumination level for the work plan of area S of the space to be illuminated, the useful direct and indirect flux that must reach on the surface is expressed as:

$$\varphi_u = E_m \cdot S \qquad (4.2\text{-}1)$$

The utilization factor (or coefficient) is defined by the ratio between the useful flux and the total flux emitted by the lamps:

$$u = \frac{\phi_u}{\phi_t} \qquad (4.2\text{-}2)$$

The difference $\phi_t - \phi_u$ represents the flux absorbed by the luminaires, walls and ceiling. The utilization factor depends both on the type of use, and on the colour (reflectivity) of the walls and the ceiling,: the geometric shape of the room also has great importance.

To characterize the room geometrically from the point of view of the influence on the utilization factor, a pure number, the room index *i* is used:

$$i = \frac{a \times b}{h(a+b)} \qquad (4.2\text{-}3)$$

Where a and b are the room dimensions and h is the height, i.e. the distance between the luminaire and the work plan. For indirect and semi-direct illumination, the useful height means the distance between the ceiling and the work plan (Fig. 4.2-48). The utilization factor varies very little for room index values higher than 5; therefore, a value of 5 can be adopted even if the calculations give a higher value.

Table 4.2-7 at the end of this section shows the values of utilization factor as a function of the reflection coefficient of the walls and ceiling and the room index for the most common types of luminaries.

To calculate the total flux emitted by the lamp, once the luminaries are selected, the reflection coefficients of the walls and ceiling are defined, and the room index is calculated, and then the utilization factor is identified, the following expression is used:

$$\varphi_t = \frac{E_m \times S}{u} \times d \qquad (4.2\text{-}4)$$

where *d* is the depreciation factor, which takes into account the following:

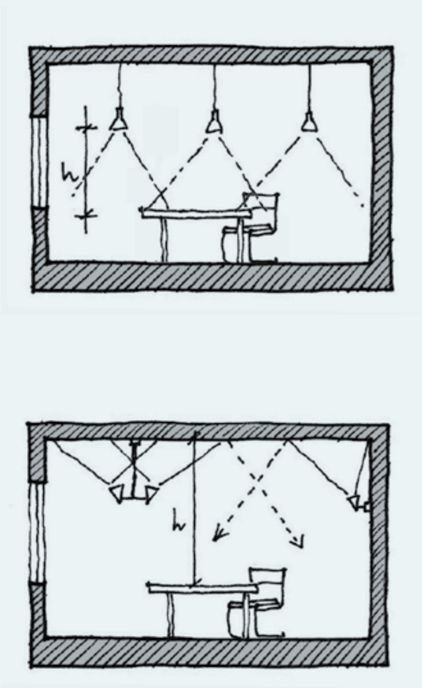
a) over the course of the life of the lamp, the emitted flux is progressively reduced;

b) the optical properties (transparency and reflectance) of the luminaries degrade over time;

TABLE 4.2-6 **RECOMMENDED ILLUMINATION LEVEL (EN 12464-1 STANDARD)**

Type of building	Space	Maintained illuminance, at working area [lux]
Office buildings	Single offices	500
	Open plan offices	500
	Conference rooms	500
Educational buildings	Classrooms	300
	Classrooms for adult education	500
	Lecture hall	500
Hospitals	General ward lighting	100
	Simple examination	300
	Examination and treatment	1000
Hotels and restaurants	Restaurant, dining room	-
Sport facilities	Sport halls	300
Wholesale and retail premises	Sales area	300
	Till area	500
Circulation areas	Corridor	100
	Stairs	150

FIGURE 4.2-48 **USEFUL HEIGHT IN INDIRECT AND SEMI-DIRECT ILLUMINATION**



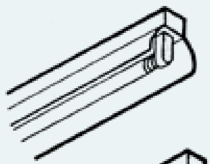
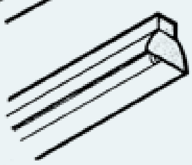
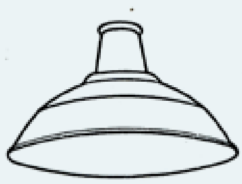
c) the reflection coefficient of the walls decreases with time due to both the natural degradation of the paint and the accumulation of dust.

Evaluation of the depreciation factor is, therefore, quite complex, and should be performed only if it is possible to make reasonable predictions about the frequency of maintenance. In general, in a first approximation, the following values can be used, when other conditions are same:

d = 1.3 for direct illumination;
d = 1.5 for semi-direct illumination;
d = 1.7 for indirect illumination.

The illumination produced by a luminaire on the working plane is never uniform, unless it is indirect lighting; uniformity increases, however, with the increase of the distance between the work plan and the luminaire and with the increase in the number of devices. One can, therefore, identify an optimal ratio between the spacing *D* between the luminaires and the useful height h: $D/h<1.5$ and considering $D' \leq D/2$, the distance between the extreme luminaires and the wall in case of direct illumination. In the case of linear luminaires, such as those with tubular fluorescent lamps, the minimum spacing between the two contiguous extremes of the lamps in line, should be equal to at least half of the length of the luminaire.

TABLE 4.2-7*: **UTILISATION FACTOR OF TYPICAL LUMINAIRES****

Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR* %	*Ceiling* / *Walls* / *Room Index*	*Reflectance %* 70 / 50	70 / 30	70 / 10	50 / 50	50 / 30	50 / 10	30 / 50	30 / 30	30 / 10
(M) Reflectorized colour-corrected mercury lamp MBFR (80–90)		85	0·6	0·4	0·34	0·3	0·39	0·33	0·29	0·37	0·32	0·29
			0·8	0·53	0·46	0·41	0·51	0·45	0·4	0·49	0·43	0·4
			1	0·62	0·55	0·49	0·58	0·52	0·48	0·56	0·51	0·46
			1·25	0·68	0·6	0·55	0·64	0·58	0·53	0·61	0·56	0·51
			1·5	0·72	0·65	0·59	0·68	0·62	0·57	0·65	0·59	0·54
			2	0·81	0·73	0·67	0·75	0·69	0·64	0·69	0·65	0·61
			2·5	0·85	0·78	0·72	0·79	0·73	0·69	0·73	0·68	0·65
			3	0·9	0·83	0·78	0·83	0·78	0·75	0·77	0·73	0·7
			4	0·94	0·89	0·84	0·87	0·83	0·8	0·8	0·77	0·75
			5	0·97	0·92	0·89	0·9	0·87	0·84	0·83	0·79	0·77
(F) Open-end enamel trough (75–85)		75	0·6	0·36	0·31	0·28	0·35	0·31	0.28	0·35	0·31	0·28
			0·8	0·45	0·4	0·37	0·44	0·4	0·37	0·44	0·4	0·37
			1	0·49	0·45	0·4	0·49	0·44	0·4	0·48	0·43	0·4
			1·25	0·55	0·49	0·46	0·53	0·49	0·45	0·52	0·48	0·45
			1·5	0·58	0·54	0·49	0·57	0·53	0·49	0·55	0·52	0·49
			2	0·64	0·59	0·55	0·61	0·58	0·55	0·6	0·56	0·54
			2·5	0·68	0·63	0·6	0·65	0·62	0·59	0·64	0·61	0·58
			3	0·7	0·65	0·62	0·67	0·64	0·61	0·65	0·63	0·61
(F) Closed-end enamel trough (65–83)			4	0·73	0·7	0·67	0·7	0·67	0·65	0·67	0·66	0·64
			5	0·75	0·72	0·69	0·73	0·7	0·67	0·7	0·68	0·67
(T) Standard dispersive industrial reflector (77)												
(M) Aluminium industrial reflector (72–76)		70	0·6	0·39	0·36	0·33	0·39	0·36	0·33	0·39	0·35	0·33
			0·8	0·48	0·43	0·4	0·46	0·43	0·4	0·46	0·43	0·4
(T) High-bay reflector, aluminium (72) or enamel (66)			1	0·52	0·49	0·45	0·52	0·48	0·45	0·52	0·48	0·45
			1·25	0·56	0·53	0·5	0·56	0·53	0·49	0·56	0·52	0·49
			1·5	0·6	0·57	0·54	0·59	0·57	0·53	0·59	0·55	0·53
			2	0·65	0·62	0·59	0·63	0·6	0·58	0·63	0·59	0·57
			2·5	0·67	0·64	0·62	0·65	0·62	0·61	0·65	0·62	0·6
			3	0·69	0·66	0·64	0·67	0·64	0·63	0·67	0·64	0·62
			4	0·71	0·68	0·67	0·69	0·67	0·65	0·69	0·66	0·64
			5	0·72	0·7	0·69	0·71	0·69	0·67	0·71	0·67	0·66

* *In the first column of the table, (F) denotes a luminaire for fluorescent lamp(s) (M) denotes a luminaire for colour-corrected discharge lamp (T) denotes a luminaire for incandescent (tungsten filament) lamp.*

** *Source of Tables: Electricity Council, Interior Lighting Design, London, 1973*

TABLE 4.2-7 **UTILISATION FACTOR OF TYPICAL LUMINAIRES (CONTINUED)**

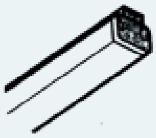
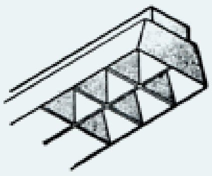
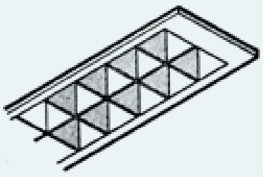
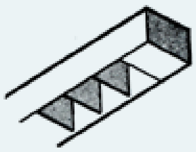
Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR* %	*Ceiling*	*Reflectance %* 70			50			30		
			Walls	*50*	*30*	*10*	*50*	*30*	*10*	*50*	*30*	*10*
			Room Index									
(F) Enclosed plastic diffuser (45–55)		50	0·6	0·27	0·21	0·18	0·24	0·2	0·18	0·22	0·19	0·17
			0·8	0·34	0·29	0·26	0·32	0·28	0·25	0·29	0·26	0·24
			1	0·4	0·35	0·31	0·37	0·33	0·3	0·33	0·3	0·28
			1·25	0·44	0·39	0·35	0·4	0·36	0·33	0·36	0·33	0·31
			1·5	0·47	0·42	0·38	0·43	0·39	0·36	0·38	0·35	0·33
			2	0·52	0·47	0·44	0·47	0·44	0·41	0·41	0·39	0·37
			2·5	0·55	0·51	0·48	0·5	0·47	0·44	0·44	0·42	0·4
			3	0·58	0·54	0·51	0·52	0·49	0·47	0·47	0·45	0·43
			4	0·61	0·57	0·54	0·55	0·52	0·5	0·49	0·47	0·45
			5	0·63	0·59	0·57	0·57	0·55	0·53	0·51	0·49	0·47
(F) Plastic trough, louvered (45–55)		50	0·6	0·26	0·22	0·19	0·25	0·21	0·19	0·24	0·2	0·18
			0·8	0·34	0·29	0·26	0·32	0·28	0·25	0·31	0·27	0·24
			1	0·39	0·34	0·3	0·36	0·32	0·29	0·34	0·31	0·28
			1·25	0·43	0·38	0·34	0·39	0·36	0·33	0·37	0·34	0·31
			1·5	0·46	0·41	0·37	0·42	0·39	0·36	0·39	0·36	0·33
			2	0·5	0·46	0·43	0·43	0·42	0·4	0·43	0·39	0·37
			2·5	0·53	0·49	0·46	0·49	0·46	0·43	0·45	0·42	0·4
			3	0·55	0·51	0·49	0·51	0·48	0·46	0·47	0·45	0·43
			4	0·58	0·54	0·52	0·53	0·51	0·49	0·48	0·47	0·45
			5	0·6	0·57	0·55	0·55	0·53	0·51	0·5	0·48	0·47
(F) Recessed louvered trough with optically designed reflecting surfaces (50)		50	0·6	0·28	0·25	0·23	0·28	0·25	0·23	0·28	0·25	0·23
			0·8	0·34	0·31	0·28	0·33	0·3	0·28	0·33	0·3	0·28
			1	0·37	0·35	0·32	0·37	0·34	0·32	0·37	0·34	0·32
			1·25	0·4	0·38	0·35	0·4	0·37	0·35	0·4	0·37	0·35
			1·5	0·43	0·41	0·38	0·42	0·4	0·38	0·42	0·39	0·38
			2	0·46	0·44	0·42	0·45	0·43	0·41	0·44	0·42	0·41
			2·5	0·48	0·46	0·44	0·47	0·45	0·43	0·46	0·44	0·43
			3	0·49	0·47	0·46	0·48	0·46	0·45	0·47	0·45	0·44
			4	0·5	0·49	0·48	0·49	0·48	0·47	0·48	0·47	0·46
			5	0·51	0·5	0·49	0·5	0·49	0·48	0·49	0·48	0·47
(F) Suspended louvered metal trough, upward and downward light, optically designed reflecting surfaces (47–54)		50	0·6	0·35	0·32	0·29	0·33	0·31	0·28	0·33	0·3	0·28
			0·8	0·41	0·38	0·35	0·39	0·36	0·34	0·38	0·35	0·33
			1	0·46	0·42	0·4	0·44	0·41	0·39	0·42	0·39	0·37
			1·25	0·49	0·46	0·43	0·47	0·44	0·42	0·45	0·42	0·4
			1·5	0·52	0·49	0·46	0·49	0·47	0·44	0·47	0·44	0·42
			2	0·56	0·53	0·51	0·52	0·5	0·48	0·49	0·47	0·45
			2·5	0·58	0·55	0·53	0·54	0·52	0·5	0·51	0·49	0·47
			3	0·59	0·57	0·55	0·55	0·53	0·52	0·52	0·5	0·49
			4	0·61	0·59	0·57	0·57	0·55	0·54	0·53	0·51	0·5
			5	0·63	0·6	0·59	0·58	0·57	0·55	0·54	0·52	0·51

TABLE 4.2-7 **UTILISATION FACTOR OF TYPICAL LUMINAIRES (CONTINUED)**

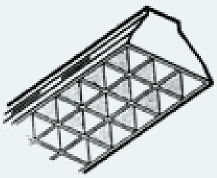
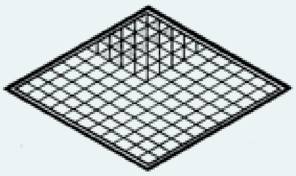
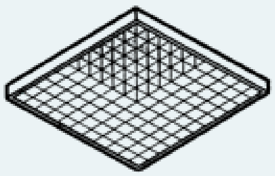
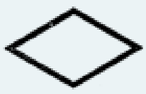
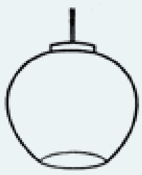
Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR*	*Reflectance %* Ceiling	70			50			30		
			Walls	*50*	*30*	*10*	*50*	*30*	*10*	*50*	*30*	*10*
		%	*Room Index*									
(F) Enamel slotted trough, louvered (45–55)		50	0·6	0·27	0·24	0·22	0·26	0·24	0·22	0.26	0·23	0·22
			0·8	0·32	0·3	0·27	0·32	0·29	0·27	0·31	0·29	0·27
			1	0·35	0·32	0·3	0·35	0·32	0·3	0·34	0·31	0·3
			1·25	0·38	0·35	0·32	0·38	0·35	0·33	0·38	0·34	0·33
			1·5	0·41	0·38	0·36	0·4	0·38	0·35	0·4	0·37	0·35
			2	0·45	0·42	0·4	0·43	0·41	0·39	0·43	0·4	0·39
			2·5	0·47	0·44	0·42	0·45	0·43	0·41	0·45	0·42	0·41
			3	0·48	0·45	0·44	0·46	0·45	0·43	0·46	0·44	0·42
			4	0·49	0·47	0·46	0·48	0·47	0·45	0·47	0·45	0·44
(F) Louvered recessed (module) luminaire (40–50)			5	0·5	0·49	0·48	0·49	0·48	0·47	0·48	0·47	0·46
(F) Shallow ceiling-mounted louver panel (40–50)												
(F) Recessed (modular) diffuser (43–54)		50	0·6	0·21	0·18	0·16	0·21	0·18	0·16	0·2	0·18	0·16
			0·8	0·28	0·24	0·22	0·27	0·24	0·22	0·26	0·24	0·22
			1	0·32	0·29	0·26	0·31	0·28	0·26	0·3	0·28	0·26
			1·25	0·35	0·32	0·29	0·34	0·31	0·29	0·32	0·3	0·28
			1·5	0·37	0·34	0·31	0·36	0·33	0·31	0·34	0·32	0·3
			2	0·41	0·37	0·35	0·39	0·37	0·34	0·38	0·36	0·34
(F) Shallow ceiling-mounted diffusing panel (40–55)			2·5	0·43	0·4	0·38	0·42	0·39	0·37	0·4	0·38	0·37
			3	0·45	0·42	0·4	0·44	0·41	0·4	0·42	0·4	0·39
			4	0·47	0·44	0·43	0·46	0·44	0·42	0·44	0·42	0·41
			5	0·49	0·46	0·45	0·47	0·46	0·44	0·46	0·44	0·43
(T) Near-spherical diffuser, open beneath (50)		50	0·6	0·28	0·22	0·18	0·25	0·2	0·17	0·22	0·18	0·16
			0·8	0·39	0·3	0·26	0·33	0·28	0·23	0·27	0·25	0·22
			1	0·43	0·36	0·32	0·38	0·34	0·29	0·31	0·29	0·26
			1·25	0·48	0·41	0·37	0·42	0·38	0·33	0·34	0·32	0·29
			1·5	0·52	0·46	0·41	0·46	0·41	0·37	0·37	0·35	0·32
			2	0·58	0·52	0·47	0·5	0·46	0·43	0·42	0·39	0·36
			2·5	0·62	0·56	0·52	0·54	0·5	0·47	0·45	0·42	0·4
			3	0·65	0·6	0·56	0·57	0·53	0·5	0·48	0·45	0·43
			4	0·68	0·64	0·61	0·6	0·56	0·54	0·51	0·48	0·46
			5	0·71	0·68	0·65	0·62	0·59	0·57	0·53	0·5	0·48

TABLE 4.2-7 **UTILISATION FACTOR OF TYPICAL LUMINAIRES (CONTINUED)**

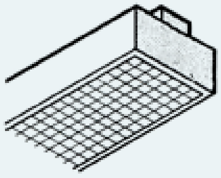
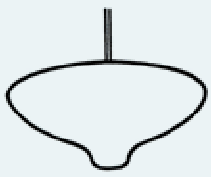
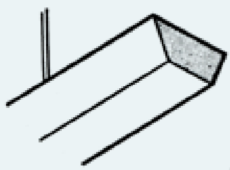
Description of Ceiling	*Typical Outline*	*Basic DLOR %*	*Room Index*	*Reflectance %* Ceiling 70 / Walls 50	70 / 30	70 / 10	50 / 50	50 / 30	50 / 10	30 / 50	30 / 30	30 / 10
(F) Suspended opaque-sided luminaire, upward and downward light, diffuser, or louver beneath (45–50)		45	0·6	0·28	0·24	0·2	0·26	0·22	0·19	0·24	0·2	0·19
			0·8	0·36	0·3	0·28	0·33	0·29	0·26	0·31	0·27	0·24
			1	0·41	0·36	0·32	0·37	0·33	0·3	0·34	0·3	0·27
			1·25	0·45	0·41	0·36	0·41	0·37	0·34	0·37	0·33	0·3
			1·5	0·49	0·45	0·4	0·44	0·4	0·37	0·39	0·35	0·33
			2	0·55	0·5	0·46	0·48	0·45	0·42	0·42	0·39	0·37
			2·5	0·58	0·53	0·5	0·51	0·48	0·45	0·45	0·42	0·4
			3	0·6	0·56	0·53	0·53	0·5	0·48	0·47	0·44	0·42
			4	0·63	0·59	0·57	0·55	0·53	0·51	0·48	0·46	0·44
			5	0·65	0·62	0·6	0·57	0·55	0·53	0·5	0·48	0·46
(T) Opal sphere (45) and other enclosed diffusing luminaires of near-spherical shape		45	0·6	0·23	0·18	0·14	0·2	0·16	0·12	0·17	0·14	0·11
			0·8	0·3	0·24	0·2	0·27	0·22	0·18	0·22	0·19	0·16
			1	0·36	0·29	0·25	0·31	0·26	0·22	0·26	0·23	0·19
			1·25	0·41	0·34	0·29	0·35	0·3	0·26	0·29	0·26	0·22
			1·5	0·45	0·39	0·33	0·39	0·34	0·3	0·31	0·28	0·25
			2	0·5	0·45	0·4	0·43	0·38	0·34	0·34	0·32	0·29
			2·5	0·54	0·49	0·44	0·46	0·42	0·38	0·37	0·35	0·32
			3	0·57	0·52	0·48	0·49	0·45	0·42	0·4	0·38	0·34
			4	0·6	0·56	0·52	0·52	0·48	0·46	0·43	0·41	0·37
			5	0·63	0·6	0·56	0·54	0·51	0·49	0·45	0·43	0·4
(T) Diffuser with open top louvered beneath (30)		30	0·6	0·28	0·23	0·19	0·24	0·2	0·19	0·2	0·18	0·16
			0·8	0·35	0·3	0·26	0·3	0·26	0·23	0·25	0·23	0·2
			1	0·4	0·34	0·31	0·34	0·3	0·27	0·27	0·25	0·23
			1·25	0·45	0·39	0·36	0·38	0·33	0·31	0·3	0·28	0·26
			1·5	0·49	0·44	0·4	0·41	0·36	0·34	0·32	0·3	0·28
			2	0·54	0·5	0·46	0·45	0·41	0·39	0·34	0·33	0·31
			2·5	0·57	0·53	0·5	0·47	0·44	0·42	0·36	0·35	0·33
			3	0·6	0·56	0·53	0·49	0·46	0·45	0·38	0·37	0·35
			4	0·63	0·59	0·57	0·51	0·49	0·48	0·4	0·39	0·37
			5	0·65	0·62	0·6	0·53	0·51	0·5	0·41	0·4	0·38
(T or F) Totally indirect luminaire. Based on Upward Light Output Ratio 75% (Upper and lower walls the same colour)	 		0·6	0·1	0·07	0·04	0·07	0·05	0·03			
			0·8	0·13	0·11	0·08	0·11	0·09	0·07			
			1	0·16	0·15	0·12	0·15	0·12	0·1			
			1·25	0·2	0·19	0·16	0·18	0·15	0·13			
			1·5	0·24	0·23	0·2	0·2	0·18	0·16			
			2	0·28	0·27	0·23	0·22	0·2	0·18			
			2·5	0·32	0·31	0·26	0·24	0·22	0·2			
			3	0·36	0·35	0·29	0·25	0·23	0·21			
			4	0·4	0·38	0·31	0·26	0·24	0·22			
			5	0·43	0·4	0·33	0·27	0·25	0·23			

TABLE 4.2-7 **UTILISATION FACTOR OF TYPICAL LUMINAIRES (CONTINUED)**

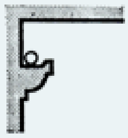
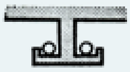
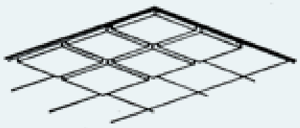
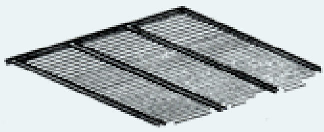
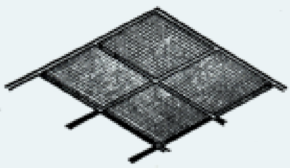
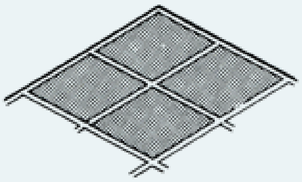
Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR* %	*Ceiling* / *Walls* / *Room Index*	*Reflectance %* 70 / 50	70 / 30	70 / 10	50 / 50	50 / 30	50 / 10	30 / 50	30 / 30	30 / 10
(T or F) As above, but with upper walls the same colour as the ceiling			0·6	0·11	0·08	0·05	0·08	0·06	0·04			
			0·8	0·16	0·13	0·1	0·11	0·09	0·07			
			1	0·21	0·17	0·14	0·13	0·11	0·09			
			1·25	0·25	0·21	0·18	0·15	0·13	0·11			
			1·5	0·29	0·25	0·22	0·17	0·15	0·13			
			2	0·33	0·3	0·27	0·2	0·18	0·16			
			2·5	0·37	0·34	0·32	0·23	0·21	0·19			
			3	0·4	0·38	0·36	0·26	0·24	0·22			
			4	0·43	0·42	0·4	0·28	0·27	0·25			
			5	0·45	0·44	0·42	0·3	0·29	0·27			
(T or F) Indirect cornices, recessed coves and coffers giving all their light above the horizontal. Based on an Upward Light Output Ratio of 40% but details of construction may vary this figure considerably	 		0·6	0·07	0·05	0·04	0·04	0·03				
			0·8	0·09	0·07	0·06	0·06	0·05				
			1	0·11	0·09	0·08	0·08	0·07				
			1·25	0·13	0·11	0·09	0·09	0·08				
			1·5	0·14	0·12	0·1	0·1	0·09				
			2	0·16	0·14	0·12	0·11	0·1				
			2·5	0·17	0·15	0·14	0·12	0·11				
			3	0·18	0·16	0·15	0·12	0·11				
			4	0·19	0·18	0·16	0·13	0·12				
			5	0·2	0·19	0·17	0·14	0·13				
(F) Complete luminous ceiling composed of translucent corrugated strip or individual pan-shaped elements. Based on ceiling cavity surfaces being white, and cavity width being three times cavity depth	 		0·6	0·2	0·15	0·12						
			0·8	0·28	0·24	0·2						
			1	0·34	0·31	0·27						
			1·25	0·37	0·34	0·31						
			1·5	0·4	0·36	0·34						
			2	0·45	0·42	0·39						
			2·5	0·47	0·44	0·42						
			3	0·49	0·46	0·44						
			4	0·52	0·49	0·47						
			5	0·54	0·51	0·49						
(F) Complete louvered ceiling composed of half-inch translucent plastic cells. Based on ceiling cavity surfaces being white, and cavity width being three times cavity depth			0·6	0·31	0·28	0·24						
			0·8	0·34	0·31	0·27						
			1	0·37	0·34	0·3						
			1·25	0·39	0·36	0·33						
			1·5	0·41	0·38	0·36						
			2	0·44	0·42	0·39						
			2·5	0·46	0·44	0·41						
			3	0·48	0·46	0·43						
			4	0·5	0·48	0·45						
			5	0·51	0·49	0·47						

TABLE 4.2-7 **UTILISATION FACTOR OF TYPICAL LUMINAIRES (CONTINUED)**

Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR %*	*Ceiling*	*Reflectance % 70*			*50*			*30*		
			Walls	*50*	*30*	*10*	*50*	*30*	*10*	*50*	*30*	*10*
			Room Index									
(F) Complete luminous ceiling composed of injection moulded flat prismatic panels.* Based on ceiling cavity surfaces being white, and cavity width being three times cavity depth			0·6	0·37	0·33	0·28						
			0·8	0·47	0·42	0·37						
			1	0·52	0·47	0·43						
			1·25	0·56	0·53	0·48						
			1·5	0·59	0·55	0·51						
			2	0·64	0·59	0·54						
			2·5	0·66	0·62	0·56						
			3	0·68	0·63	0·6						
			4	0·71	0·67	0·63						
			5	0·72	0·7	0·67						
(F) Complete louvered ceiling composed of small metalized plastic parabolic cells. Based on ceiling cavity surfaces being white, and cavity width being three times cavity depth			0·6	0·23	0·21	0·18						
			0·8	0·26	0·23	0·2						
			1	0·28	0·26	0·23						
			1·25	0·29	0·27	0·25						
			1·5	0·31	0·29	0·27						
			2	0·33	0·32	0·29						
			2·5	0·35	0·33	0·31						
			3	0·36	0·35	0·33						
			4	0·38	0·36	0·34						
			5	0·39	0·37	0·35						

* **Note:** Due to the wide variation in design and arrangement of prisms in optical controllers, the Utilization Factors shown for prismatic materials can only provide a general guide. Reference should be made to the manufacturers concerned for authoritative information.

Determining the number and power of luminaires, using the lumen method of calculation

With the use of a simple nomogram[42], as shown in figure 4.2-49, the number and power of luminaries required in a lighting system design can be calculated. The procedure is as follows[43]:

1. Establish the Room Index (can be calculated by the expression defined in previous section);
2. With this Room Index, look up the Utilization Factor for the type of luminaire to be used (Table 4.2-7). Mark the UF on Scale 8;
3. Mark the room length on Scale 1 and room width on Scale 2. Draw a line through these points to cut Scale 3;
4. From this point on Scale 3 draw a line through the required illuminance on Scale 4 to cut Scale 5;
5. From this point on Scale 5 draw a line through the mark on Scale 8 to cut Scale 9. This gives the total light flux to be provided by all the lamps;
6. A line drawn from the point on Scale 9 through an appropriate point (number of luminaires) on Scale 10 will cut Scale 11 at the number of lamp lumens required per luminaire. Alternatively, if the lumen output of lamps per luminaire is known, a line between the point on Scale 9 and the appropriate point on Scale 11 will cut Scale 10 at the number of luminaires required;
7. The last two columns on the right give an approximate indication of suitable lamp combinations per luminaire to give the light output required.

4.2.4.8 TIPS FOR ARTIFICIAL LIGHTING

In order to minimise energy consumption, the integration of daylighting and artificial lighting should be considered from the early stages of the building design process. Lighting strategy, fixture selection, and control methods are all affected by the goal of daylight integration.

Daylighting can provide the required ambient lighting for most operating hours. User-controllable task lights should be provided to ensure that task illumination requirements are met at all locations when supplemental lighting is necessary.

Users near windows will often use daylight as their primary task source. In general, ambient illumination levels should be significantly less than task levels (but not less than 1/3 of task levels).

Indirect lighting, often most appreciated by architects because of the visual atmosphere it produces, should be used very carefully: it is very inefficient from the point of view of energy consumption. It is better to use luminaires providing semi-direct illumination with UFF < 20%: this is a good compromise between energy efficiency and visual pleasantness.

Lamps

- Use fluorescent lamps and dimming ballasts. Fluorescent lighting is appropriate for both dimming and switching applications, because it can be efficiently dimmed over a wide range without changes in colour and can be turned on and off virtually instantaneously. Most dimming fluorescent ballasts dim to 10-20% light output, but "architectural" dimmers dim to 1% (these dimmers come at a cost premium).
- Consider the possibility of using LED sources, especially for task lighting. Even though they are more expensive, they are dimmable and have a very long life-span.
- If daylight and artificial light are used at the same time (i.e. daylighting is insufficient all the time and must be complemented with artificial lighting), try to match the cool colour temperature of daylight. For best colour temperature pairing with daylight, specify the use of fluorescent lamps with a colour temperature of 4000 K. If, however, daylighting is sufficient most of the time, and artificial lighting is needed only at night, choose fluorescent lamps with colour temperature 2700-3000 K.
- Avoid high-intensity discharge lamps. Most HID sources (metal halide, high pressure sodium and mercury vapour) are not appropriate for dimming applications because they undergo colour shifts as they dim and have a more limited dimming range.
- Choose energy-efficient hardware. No matter what the lighting strategy, always choose the most cost-effective lighting technologies and the most effective controls available within the design budget.

Lighting control

- Choose dimming hardware if daylighting, lumen maintenance, or tuning are the selected control strategies. With the cost of dimming ballasts still high but falling, dimming control is at least twice as expensive as switching control but it is the best for implementing these strategies.

42 *Electricity Council, Interior Lighting Design, London, 1973*

43 *Note: When using this nomogram in conjunction with the tables of Utilization Factors first enter, on Scale 8, the UF obtained from the tables. If the Downward Light Output Ratio of the luminaire to be used is the same as the Basic DLOR given in these tables ignore Scales 6 and 7.*
If the DLOR of the luminaire to be used differs significantly from that listed in the tables, enter the figures given in the table on Scale 7. Draw a line from this point on Scale 7 through the UF (from the tables) on Scale 8 and produce to cut Scale 6. The intersection on Scale 6 then gives the utilance of the luminaire. From the utilance on Scale 6 draw a line through the actual downward light output ratio of the luminaire to be used on Scale 7. The intersection of this line with Scale 8 gives the corrected Utilization Factor which is then used to complete the calculation.

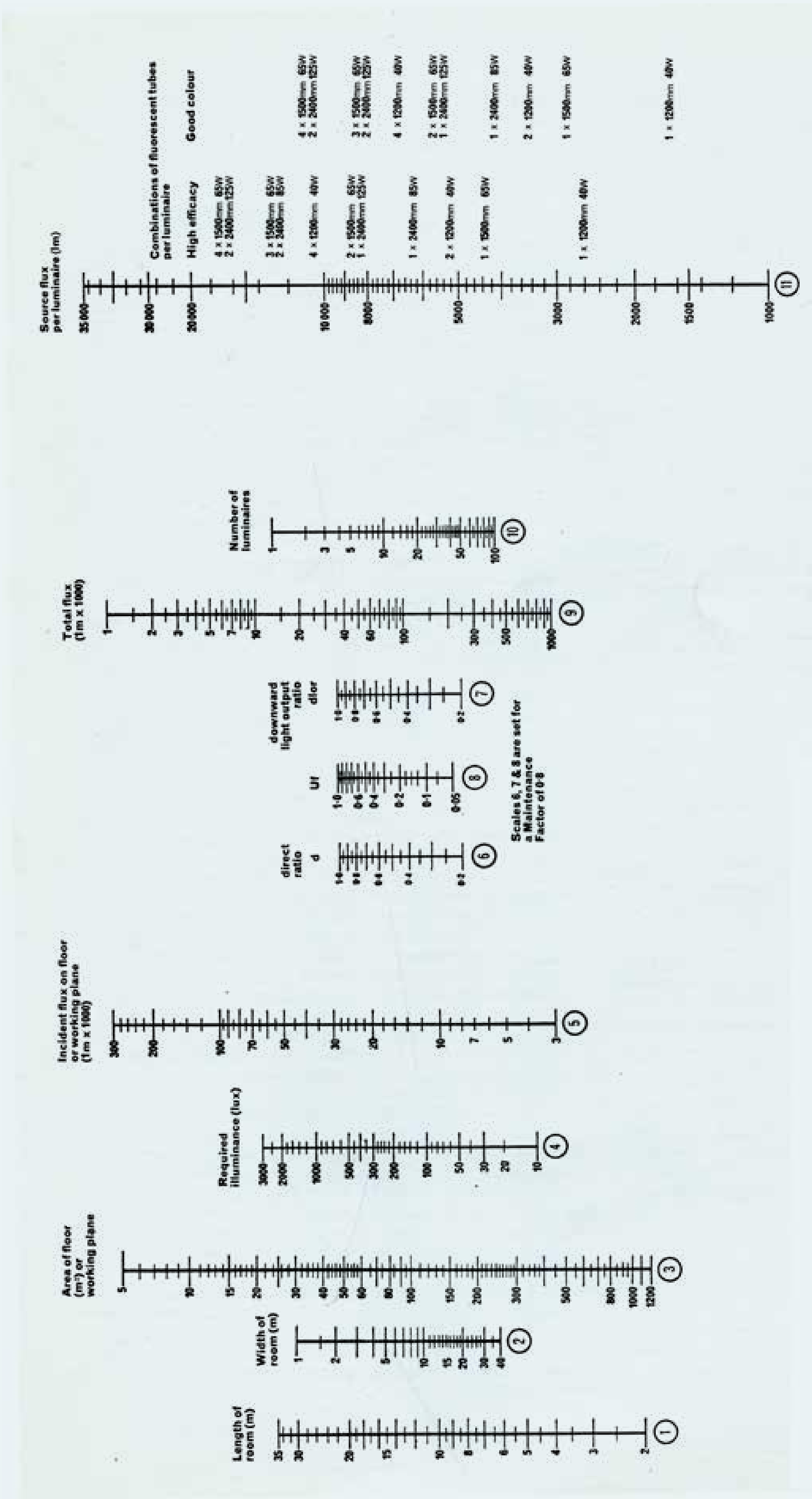


FIGURE 4.2-49 **NOMOGRAM FOR DETERMINING NUMBER AND POWER OF LUMINAIRES**

- For all other strategies, choose switching hardware since switching technologies are inexpensive, have a short payback period, and typically do not require special expertise to install.
- Use programmable time controls for a more sophisticated form of scheduling control than simple time clocks.
- Use occupancy sensors. These are easily installed in wall boxes in lieu of manual switches.

Visual Comfort

- Keep ambient lighting low for computer screens. If computers are present, ambient lighting should not exceed 300 lux. A rule of thumb for spaces with video display terminals (VDTs) is to provide as little light as possible on computer screens, 150-300 lux for surround lighting.
- Keep lamp reflectance out of computer screens. Limit the potential for reflected glare from ceiling lights in computer screens.
- Avoid brightness glare from exposed lamps in the field of view. Obstruct direct views of light sources to avoid glare. Direct/indirect lighting is one method of doing this.
- Use lighting strategies to balance window glare if anticipated. Keep luminance of the interior environment high to balance window brightness if there are no architectural modifiers such as deep reveals, shading devices or elements to filter daylight. A light wall or ceiling wash towards the back of the space (farthest area from window) is generally effective. A small increase in energy use for this purpose is acceptable.

Integration Issues

- Location of the windows directly influences lighting control strategies and placement of photocell sensors.
- Quality of the perimeter spaces depends on blending and balance between daylight (a strongly directional light from the side providing high illumination and cool colour) and the very different nature of electric lighting.
- Interior surfaces, and especially the ceiling, must be light coloured.
- Coordinate workstations with window placement and fixture locations, especially for glare-sensitive workspaces (e.g., computers). Align view direction of VDT parallel to the window wall.
- Locations of partitions and other tall furniture should not interfere with penetration of daylight. This may require re-orienting partitions or using translucent panels rather than opaque.
- Lighting designer should supply a reasonable estimation of lighting power reduction due to daylight controls for the purpose of cooling load calculations. Expect the perimeter zones to have less than peak electric lighting loads at peak cooling periods (e.g., summer noon).
- Incorporating a daylighting strategy does not have a negative effect on lighting design. In fact, lighting quality is typically higher in a carefully daylit space.
- Direct/indirect systems using pendant fixtures are typically a 50% cost premium over direct lighting fixtures.
- Many efficient lighting technologies have short paybacks and often qualify for utility rebates or incentives, due to the very large percentage of building energy use consumed by lighting. Costs of some newer technologies (e.g., dimmable electronic ballasts) are falling rapidly with time. Be sure to use current cost estimates in your analysis.

4.2.5 HVAC DESIGN, COMMISSIONING, OPERATION AND MAINTENANCE GUIDELINES

One of the primary tasks for an architect is to create a built environment that is able to improve human well-being and productivity, at the same time maintaining an adequate level of operational efficiency and an effective use of natural resources.

The HVAC system is one of the most important elements in designing a "sustainable" building. First of all it is necessary to define the objectives and criteria of the design process itself because good results cannot be achieved without clear goals. A conventional design approach is, by itself, not sufficient to achieve good performance because a building should be conceived as a system, capable of providing different types of services with the minimum impact. In fact, the incorrect design of a building from the architectural point of view (envelope, orientation, lay-out of the internal space, etc.) can result, for example, in an oversized HVAC system which can be energy intensive to operate and costly and difficult to maintain.

Subsequently, in the commissioning process, the objectives, criteria and basis of design have to be documented and verified, giving a clear direction for the project during the construction phase, and a benchmark for performance comparison and evaluation in the measurement and testing phase.

Finally, operation and maintenance (O&M) play a key role in maintaining a high energy performance and an adequate level of service for the building during its lifetime, thus helping to achieve the expected results on a long-term basis.

The greenhouse effect is a process by which thermal radiation is absorbed by atmospheric greenhouse gases, and is re-radiated in all directions, causing an increase in the air temperature. The refrigerants which are present in HVAC systems are in most cases greenhouse gases and therefore their impact must be taken into account.

The index that accounts for the greenhouse effect is called GWP (Global Warming Potential) and is expressed in kg equivalent of carbon dioxide (CO_{2eq}) per kg of substance. In practice, the emission of 1 kg of refrigerant with a GWP equal to 100 causes the same environmental impact as 100 kg of carbon dioxide in the atmosphere. Another very important parameter is the atmospheric lifetime of the substance, defined as the time (expressed in years) taken for the substance to halve its amount.

TABLE 4.2-8 **GWP AND LIFETIME OF DIFFERENT REFRIGERANTS**

Tipology	Substance	Lifetime [y]	GWP 100 years [kgCO_2/kg]
CFC (chlorofluorocarbon)	R11	45	4600
	R12	100	10600
HCFC (hydrochlorofluorocarbon)	R123	1.4	120
	R22	11.8	1900
HCF (hydrofluorocarbons)	R32	5.6	880
	R134A	13.6	1600
	R404A	13-54*	4500
	R407C	5-32*	2000
	R410A	5-32*	2300
Natural refrigerants	R717 (ammonia)	-	< 1
	R290 (propane)	-	3
	R744 (C02)	500	1
Other refrigerants	Methane	15	21
	Nitrogen oxides	120	310

**Mixture: value of lifetime depending on the specific composition*

Refrigerants have a high potential impact on the greenhouse effect. It is therefore important to consider this potential impact in the design of HVAC systems and select an appropriate substance, depending on the specifications of the project. Although the most harmful refrigerants are being progressively phased out, their impact today is not negligible. The TEWI (Total Equivalent Warming Index) index is used to determine the greenhouse effect produced during the lifetime of an HVAC system. It is the sum of two factors: the DGW (Direct Global Warming), which indicates the greenhouse effect produced by the dispersion in the atmosphere of the refrigerants (related to the GWP and the mass of the refrigerant) and the IGW (Indirect Global warming), which indicates the greenhouse effect due to the energy consumption of the plant. Therefore, both the effects must be taken into account in the assessment of the energy and environmental sustainability of HVAC systems.

4.2.5.1 DESIGN PRINCIPLES

The selection and design of HVAC systems is related to comfort expectation and type of end-use; this is the reason why similar types of HVAC systems are used in similar building types. However, this standardization, which represents the state of the art design of technical systems, is seriously called into question by the demand for energy efficiency and the need to lower the impact of the built environment.

In general, it is possible to assert that central HVAC systems can be far more efficient than local ones in medium to large scale buildings, while in small scale ones this difference can become negligible. Due to O&M considerations, equipment components are, in general, grouped and organized as much as possible to make intervention easier if there is a disruption in the system, without compromising the functionality of the whole building. Further, by grouping the components in an appropriate way, aesthetic and acoustic issues can be easily solved from the architectural point of view.

Further, central systems offer the possibility of exploiting economies of scale. Larger capacity heating and cooling technologies have higher efficiencies and lower specific costs (cost per unit of power installed), thus reducing the overall investment and O&M costs. If a building is operated in a constant way over time with similar comfort requirements and end-uses, a centralized system is usually the best choice. However, in this case there can also be some drawbacks; for example, an efficient centralized energy management scheme must be correctly tuned for multi-zone operation. Of course, the analysis of performance and operational strategies for optimization are less intuitive than for small, local systems.

In general, appropriate sizing of HVAC components is key to obtaining energy-efficient systems. Oversized systems obviously have higher installation costs, and also typically operate in a less efficient way at part-load conditions and have a shorter life because of frequent ON/OFF cycles. For these reasons, in the detailed design phase, when building architecture and envelope configuration are precisely defined, accurate calculations of cooling loads must be performed without introducing excessive safety margins.

More generally, some useful indications with respect to high-efficiency HVAC design are reported below:

- use multiple equipment components so that each one operates close to full load in every working condition (modulation of power), or use components that reduce power requirements as the load decreases. For example, select multiple chillers of different sizes instead of one large chiller, select a multi-compressor chiller instead of a single compressor chiller, select a multi-stage compressor instead of a single-stage compressor or select variable-speed motors instead of constant-speed motors;
- use VAV-type or VRF-type AC systems if possible, as long as they are typically the most energy efficient solutions, and avoid terminal reheating systems unless the reheating energy comes from waste energy (hot water from solar or CHP technologies);
- when sizing packaged systems, make sure that latent cooling capacity is also adequate in low cooling-load conditions;
- design zone air flow must meet both temperature and humidity requirements in different boundary conditions; the zone cooling and dehumidification needs at both design and off-design conditions must be considered particularly when determining the design air flow and supply temperature.
- provide technologies and controls to continuously adjust the ventilation rate for spaces with varying occupancy to prevent unnecessary cooling of large quantities of outside air (for example CO_2 sensors);
- provide automatic time-controlled or load-controlled auxiliary electric appliances, such as fans or pumps, and automatic temperature setback in order to minimize wasted energy;
- select fans and pumps taking into consideration their type, efficiency and noise level;
- pre-arrange an energy monitoring system and, if suitable, a building automation system to ease analysis and control;
- avoid downsizing air ducts and pipes as it will increase pressure drop, thereby requiring fans, pumps and motors to be oversized;
- select heat pump water heating systems in spaces such as restaurants, commercial buildings and hotels in which it is possible to take advantage of the space cooling opportunity provided by the system and avoid long DHW circuits, and also in contexts where there is limited DHW demand (household context).

4.2.5.2 SUMMARY OF HVAC SYSTEMS FEATURES

In the following tables, the most important features of the different HVAC system types are summarized, and the presence or the absence of some characteristics or the degree of quality of their performance with respect to the different indicators are described.

Yes = the function can be fulfilled by the system/device;

No = the function cannot be fulfilled by the system/device;

Yes*= the function is not always present in all commercial products.

Low/medium/high = level of performance or ability to control a parameter that can be achieved by the system/device.

In the following table the energy conversion systems are described, along with the fuel and energy sources used, the building services guaranteed and the main pros and cons.

TABLE 4.2-9 **BUILDING SERVICES, THERMAL COMFORT, INTERNAL AIR QUALITY AND ACOUSTIC INDICATORS FOR THE DIFFERENT TYPES OF HVAC SYSTEMS**

Type of HVAC systems	Element	Building services		Thermal comfort parameters control capability		Internal air quality	Acoustic comfort
		Heating	Cooling	Temperature	Humidity	Control of air quality	
All-water systems	Fan-coil units	Yes	Yes	Medium	Low	No	Medium
All-air systems	Single-duct systems	Yes	Yes	Medium	Low	Yes	Medium
	Multi-zone systems	Yes	Yes	Medium	Medium	Yes	Medium
	Dual-duct systems	Yes	Yes	Medium	High	Yes	Medium
Direct refrigerant systems	Window air conditioner	Yes*	Yes	Low	No	No	Low
	Split systems	Yes*	Yes	Low-Medium	Low	No	Medium
	Packaged rooftop air-conditioner	Yes*	Yes	Low-Medium	Low-Medium	Yes	Medium
Combined systems	Fan-coil units + air system	Yes	Yes	Medium-High	Medium-High	Yes	Medium
	Chilled beams + air system	Yes	Yes	Medium-High	Medium-High	Yes	Medium
	Induction Unit + air system	Yes	Yes	Medium-High	Medium-High	Yes	Medium
	Radiant ceiling+ air system	Yes	Yes	High	Medium-High	Yes	Medium-High

TABLE 4.2-10 **ENERGY SAVING, COST SAVING AND CONSTRUCTION INDICATORS FOR THE DIFFERENT TYPES OF HVAC SYSTEMS**

Type of HVAC systems	Element	Energy saving	Cost saving			Construction	
		Efficiency	Investment	O&M	Easy installation	Aesthetics	Compactness
All-water systems	Fan-coil units	Medium	Medium	Medium	Medium	Low-Medium	Medium
All-air system	Single-duct systems	Low-Medium	Medium-High	Medium	Medium	Medium-High	Low-Medium
	Multi-zone systems	Medium-High	Low-Medium	Medium	Low-Medium	Medium-High	Low
	Dual-duct systems	Medium-High	Low-Medium	Medium-High	Low-Medium	Medium-High	Low
Direct refrigerant systems	Window air conditioner	Low	Medium-High	Low	High	Low	Medium
	Split systems	Medium-High	Medium	Medium	Medium-High	Low	Medium-High
	Packaged rooftop air-conditioner	Medium	Medium	Medium	Medium	Low-Medium	Medium
Combined systems	Fan-coil units + air system	Medium	Medium	Medium	Medium	Low-Medium	Medium
	Chilled beams + air system	Medium	Medium	Medium-High	Low-Medium	Medium	Medium
	Induction Unit + air system	Medium	Medium	Medium-High	Low-Medium	Medium-High	Medium
	Radiant ceiling+ air system	High	Low-Medium	High	Low	High	High

TABLE 4.2-11 **ENERGY CONVERSION TECHNOLOGIES**

Type of energy conversion system	Element	Building services				Energy sources	Pros and cons	
		Heating	Cooling	DHW	Other	Fuel / Source	Pros	Cons
Vapor compression cycle	Compression refrigerating machine	No	Yes	Yes*	-	Electricity	• High energy efficiency if used with geothermal sources • Economical installation • Low O&M costs • Possibility to get free DWH with machines equipped with desuperheater	• High electrical power demand • The efficiency is low with a great temperature difference between condenser and evaporator • Noisy and bulky if air cooled condensers are used
	Reversible compression heat pump	Yes	Yes	Yes*	-	Electricity	• High energy efficiency if used with geothermal sources • Economical installation • Low O&M costs • High flexibility • Possibility to get free DWH in cooling mode with machines equipped with desuperheater	• High electrical power demand • The efficiency is low with a great temperature difference between condenser and evaporator • Noisy and bulky if air cooled condensers are used
Absorption cycle	Absorption refrigerating machine	No	Yes	Yes	-	Fossil or bio-fuels / Heat	• Possibility to use low-quality heat sources or waste-heat	• High installation costs • High technical complexity • The efficiency is dependent to the temperature of the heat source
	Reversible absorption heat pump	Yes	Yes	Yes	-	Fossil or bio-fuels / Heat	• Possibility to use low-quality heat sources or waste-heat	• High installation costs • High technical complexity • The efficiency is dependent to the temperature of the heat source
Trigeneration	Combined heating, cooling and power system (CCHP)	Yes	Yes	Yes	Electricity generation	Fossil or bio-fuels	• High energy efficiency • High flexibility • Good solution for off-grid users	• High installation costs • High technical complexity • High O&M costs • An optimal balance between thermal energy and electricity needs is required
Decentralized heating devices	Fireplace heating system	Yes	No	Yes*	-	Biomass	• Good energy efficiency • Low running costs	• Local environmental pollution (fine particles)
	Wood stove	Yes	No	No	Cooking	Biomass	• Low installation and running costs • Compact solution	• Low-medium efficiency • Low thermal comfort • Local environmental pollution (fine particles)

4.3 HYBRID VENTILATION

Today's buildings should be designed to interact with the outdoor environment. When building design is integrated with the design of building services it may be possible to use the outdoor environment to create a comfortable indoor environment, with minimal energy use for ventilation, space heating or cooling.

Natural ventilation may replace air conditioning entirely or may coexist with mechanical systems in a hybrid mode. For buildings that require air conditioning in some areas, the best solution is to divide the building into separate zones for natural ventilation and mechanical ventilation and cooling. The next best solution is a changeover system in which windows are shut when the air conditioning is on. Changeover controls should be used to automatically shut off the air conditioning if windows are open.

Hybrid Ventilation is a two-mode system, which is controlled to minimise energy consumption while maintaining acceptable indoor air quality and thermal comfort. The two modes refer to natural and mechanical driving forces.

Hybrid ventilation systems provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or in different seasons.

A hybrid system, unlike a conventional system, has an intelligent control system that can switch automatically between natural and mechanical modes in order to minimise energy consumption.

Three key approaches to hybrid ventilation can be implemented.

1. Natural and mechanical ventilation

This approach is based on two fully autonomous systems. The control strategy either switches between systems or runs both in parallel but for different tasks. An example is a system that uses natural ventilation in mild seasons/hours and mechanical ventilation in hot seasons/times. This approach is also used by a system providing mechanical ventilation in occupied hours and natural ventilation for night cooling.

2. Fan-assisted natural ventilation

This approach uses natural ventilation combined with an extract or supply fan. During periods of peak demand or when the natural driving forces are reduced, pressure differences can be enhanced by fan assistance.

3. Stack and wind-assisted mechanical ventilation

In this approach a mechanical ventilation system optimises the use of natural driving forces. It is used in systems with small pressure losses where natural driving forces can contribute significantly to the pressures needed.

Unlike mechanical ventilation systems, which can be easily retrofitted into buildings, natural ventilation systems need early integration into the building design. Natural ventilation requires operable windows, doors and other openings in the building façade. Natural ventilation can also be achieved by a simple ducted system with intakes and exhausts at different heights.

Hybrid ventilation is tailored to each building whereas mechanical ventilation systems can be purchased 'off-the-shelf'. The success of hybrid systems therefore depends on integrating design from the earliest stages of building design; the designer may need to spend more time in the early stages of a hybrid system than for designing conventional mechanical ventilation systems.

The challenge for designing a hybrid ventilation system is to find a solution that uses the natural mode as much as possible and uses the mechanical mode when the natural mode is inadequate or less energy efficient. The balance between time spent in each mode will depend on the type of hybrid system and control strategy, the local climate and running and maintenance costs. There will also be a strong dependence on the price and availability of energy and the dimensions of the natural components of the system.

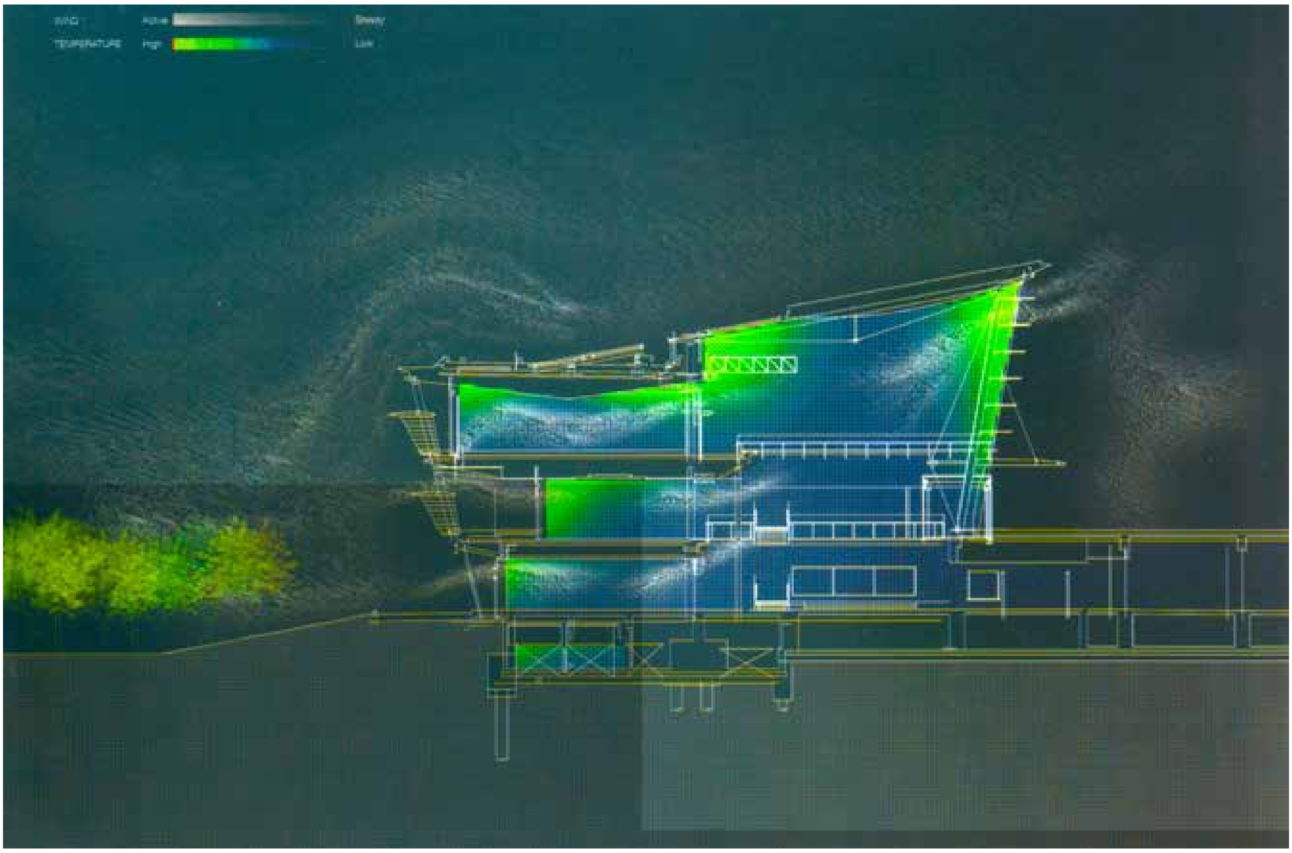
In hybrid systems there is a strong interaction between the ventilation system and the control strategy. It is essential in the integrated design approach, as many of the hybrid ventilation components are an integral part of the building. Close cooperation between the HVAC engineer and the architect will be needed.

Individual control of windows should be maintained, as far as possible, even if it is at the expense of guaranteed indoor thermal comfort or air quality at a specific level. Research suggests that users are more tolerant of variations in the indoor thermal climate if they are in control of it. Automatic control is needed to support user control to achieve a comfortable indoor environment and to control ventilation (and energy use) during unoccupied periods. Automatic control is particularly important for rooms with many occupants (such as meeting rooms, open plan offices) and for pre-conditioning rooms for occupation.

As a minimum the control strategy should include a hot season/hours control strategy, where maximum room temperature is the main concern. A control strategy for mild season/hours, where there may be an occasional demand for cooling, is also needed.

Designing a building provided with a hybrid ventilation system is a very challenging task, and the first approximation methods for estimating natural ventilation provided in chapter 3 may prove to be unable to predict airflows, and different tools must be used.

FIGURE 4.3-1 **CFD ANALYSIS OF AIRFLOW AROUND AND THROUGH A BUILDING**



Source: *Sustainable Architecture in Japan – The continuing challenge 1900-2010 & beyond, Nikken Sekkei, 2010*

Until a few years ago, the only tool available for a reasonably accurate prediction of natural ventilation in complex buildings was the wind tunnel. Today this is not the case, because simulation models are available that allow the designer to calculate and predict precisely the airflow outside and inside the buildings: they are the CFD models, (Computerised Fluid Dynamics) (Fig. 4.3-1).

In order to run a CFD session it is necessary to know the boundary conditions of the space to be evaluated, i.e. walls, surface temperature of windows, air temperature, heat load, wind velocity, etc. Only a dynamic computer simulation of the energy behaviour of the building can provide this information. Simulation is also necessary for optimising the building components. This means that hybrid ventilation design cannot be carried out without sophisticated design tools and appropriate expertise.

4.4 EXISTING BUILDINGS

For existing buildings in EAC climates that are equipped with HVAC systems, a substantial part of the electrical energy consumption is related to summer air conditioning. This consumption can be reduced by: reducing the energy demands of the building, i.e., improving the performance of the envelope by reducing the heat gains; reducing the energy consumption of the air conditioning system by eliminating energy waste and redesigning the system in a more appropriate way.

4.4.1 ENVELOPE IMPROVEMENT

Before any detailed analysis of the envelope is undertaken, it is necessary to have an objective indicator of the consumption. This indicator is given by the energy consumption index Ro defined as:

$$Ro = \frac{Annual\ electricity\ consumption\ [kWh/year]}{used\ floor\ area\ of\ the\ building\ [m^2]} \qquad (4.3\text{-}1)$$

High Ro values are the first sign of excessive energy consumption.

Table 4.4-1 gives some indicative values of Ro as per the Ivorian energy quality code[44].

Evaluation of heat gains of the envelope derives from a detailed analysis of consumption.

44 J. Ndoutoum (ed.), Efficacite energetique de la climatisation en region tropicale, IFDD and Ministère de la Région Wallonne, 2002 - http://www.ifdd.francophonie.org/ressources/ressources-pub-desc.php?id=152

TABLE 4.4-1 **APPROXIMATE Ro VALUES OF AIR CONDITIONED BUILDINGS IN HUMID TROPICAL CLIMATE**

Activity	Electricity consumption indicator Ro [kWh/m² y] Poor building
Office buildings	>275
Small office buildings	>250
Hotels	>300
Hospitals	>400
Shopping centres	>300
Residential	>200

Retrofit strategies to improve the energy and environmental performance of the building envelope are based on passive design (e.g. improvement of thermal quality of opaque envelope, control of solar radiation, etc.): this topic is treated in Chapter 4.

Table 4.4-2 shows some suggested thermal transmittance values (U-value) for building structures after renovation.

TABLE 4.4-2 **RECOMMENDED U-VALUE FOR BUILDING COMPONENTS AFTER RENOVATION**

Structure type	U-values [W/m²K]
External walls (North and South)	1.00-1.50
External walls (West and East)	0.85-1.00
Roofs	0.85-1.00
Basements	1.00-1.50
Windows (average glass and frame)	5.00-6.00

The objective of a HVAC system is to maintain in the indoor spaces the operating conditions specified in the design, such as the air temperature, relative humidity and air purity.

To ensure a healthy environment in the internal spaces it is necessary to maintain suitable IAQ (Indoor Air Quality). Correct ventilation of internal spaces is therefore necessary. However, it contributes significantly to increased energy consumption, since part of the inside air must be continuously replaced with external fresh air, which must be cooled and dehumidified. Besides the improvement of HVAC system performances, primary energy consumption can be further reduced with the use of renewable energy sources (e.g. solar thermal, solar PV, biomass, etc., see Chapter 6).

4.4.1.1 **PITCHED AND FLAT ROOFS**

Measures to reduce heat gains through the roof depend on the type of roof: flat, pitched or domed.

For the thermal insulation of a single leaf pitched roof two retrofit measures can be considered (Tables 4.4-3 and 4.4-4):

- from outside: removal of the tiles and replacement of the existing roof with a new, better insulated one: this is particularly suitable if renovation works on the roof are planned for maintenance reasons;
- from inside: application of one or more insulating panels (in this case it is essential to check that the existing roof is waterproof and that its maintenance status is good).

TABLE 4.4-3 **PITCHED ROOFING THERMAL PERFORMANCE IMPROVEMENT STRATEGIES**

Measure	Description, tips and warnings
External insulation with under-tile insulation	Insulation of the roof from the outside reduces heat gain/loss by transmission and improves indoor thermal comfort. The application of insulating material should be coupled, whenever possible, with the use of a reflective layer (see Chapter 3). The action requires remedial work from the outside and the removal of the roof tiles or roof coverings, which are normally replaced. It is, therefore, a retrofit action that is justified if the building is subject to major renovation. When working from the outside it is necessary to consider the costs of the scaffolding and of the measures needed to ensure the safety of workers. Before programming the remedial work it is necessary to check whether the roof structure is really able to withstand the additional load.
External insulation with ventilated roof	Same comments as above.
Insulation of the roof from the inside	This is appropriate if the space below the pitched roof is normally used/occupied, otherwise it is more appropriate to insulate the attic floor. The internal insulation of a pitched roof significantly increases the thermal performance of the roof with lower costs than external insulation. In this case, in fact, the installation is simpler and more economical and requires no scaffolding. Also in this case, the combined use of a reflective aluminium sheet should be considered. When working from the inside, selective remedial action can be programmed, even within individual areas or parts of the building. Before programming the remedial work it is necessary to verify that the roof structure is really able to withstand the additional load.
Insulation of the attic floor	If the attic is not used at all, the most cost-effective solution is to simply place low density insulation in rolls (e.g. mineral wool or glass fibre), directly on the floor. Obviously the greater the thickness, the better the thermal insulation. If the attic is used occasionally, and the occupants need to walk on the floor or place objects on it, the use of high-density insulation is advisable. In some cases a surface finish (flooring), suitable for walking on may be required.

If the spaces under the roof are not used, action will have to be taken to improve the energy performance of the attic, by putting a layer of insulation on its floor. Any improvement in the energy performance of the building envelope requires a check of the HVAC sizing and control system as the original energy balance has changed.

TABLE 4.4-4 **STRATEGIES FOR IMPROVING THE THERMAL PERFORMANCE OF FLAT ROOFS**

Measure	Description, tips and warnings
Painting external flat roofs with light coloured finish	Roofs painted with finishes with a low solar absorption coefficient make a significant contribution to the reduction of solar gains Light colours normally reflect solar radiation better, however, one should not influenced by the normal perception of light and dark. Since the human eye can see only the "visible" component of radiation, evaluation of the most appropriate material must be made on the basis of the solar absorption coefficients provided by manufacturers and obtained through experimental tests (different materials or pigments could have the same colour but a different solar absorption coefficient).
External insulation with the "warm roof" system	With this type of action the roof insulation is placed above the roof deck but below the weather proofing. This choice is convenient as it permits insulation of flat roofs with a simple installation technique. The choice of a reflective external coating can help to significantly reduce the effects of solar radiation with a reduction of the heat load.
Internal insulation with insulating panels	This technique is used when it is difficult or impossible to operate from outside. It involves the installation of a layer of thermally insulating material and can be carried out in two ways: • using self-supporting insulation panels fixed directly to the slab with coupling systems; • installing a support structure to which the self-supporting insulating panels are fixed (technique of the false ceiling). In some cases facilities equipment, e.g. lighting appliances, wiring, pipes and HVAC terminals, is fitted in the original ceiling. These must be removed and re-installed: the related additional costs must be considered. The application of a layer of insulating material reduces the height of the rooms or spaces below. The cavity may be used for the passage of new pipes and electrical cables.

4.4.1.2 EXTERNAL WALLS

The energy performance of external walls can be improved by (Table 4.4-5):

- painting external walls with a light-coloured finish;
- decreasing the U-value through the application of a layer of insulating material;
- shading the walls.

The above strategies may also be adopted together.

External insulation is preferable to internal insulation because better comfort conditions are created. It should be avoided in hot-arid and savannah climates. Improvement of the thermal resistance is particularly necessary during the day, when the effects of the higher external air temperature are added to the effect of solar radiation on the outer surfaces of the walls. Since solar radiation has the greatest effect on the temperature of external walls, insulation is most appropriate on east and west-facing walls, whereas south and north-facing walls can be easily shaded.

TABLE 4.4-5 **STRATEGIES TO IMPROVE THE THERMAL PERFORMANCE OF EXTERNAL WALLS**

Measure	Description, tips and warnings
Painting external walls with light-coloured finish	For this measure the description is the same as for the flat roofs (see Table 4.4-4).
External insulation with ETICS	The External Thermal Insulation Composite System (ETICS) is an optimal solution for the energy retrofit of the external walls of existing buildings. ETICS is a system applied from the outside of the wall, usually including (from inner to outer side) levelling, an adhesive, a levelling mortar, an insulation panel, an alkali-resistant reinforcement grid, a primer and a finishing coat, as well as sealants and accessory materials for the installation. The operation is carried out relatively quickly and entirely from the outside, with very limited disruption for users. It is also possible to apply external insulation using local materials (for example natural insulation materials, external finishing with sheets of wood, etc.).
Thermal insulation with ventilated façade	The use of this system (see Chapter 3) as a retrofit on existing buildings requires careful design, not only in terms of energy efficiency but also because of the static requirements; specialised and experienced firms are also required for installation. A maintenance programme should be scheduled.
Shading the walls with natural solutions (green façades)	The use of vegetation for sun protection of façades or windows is a natural solution that can contribute to an increase in the sustainability of the building. The objective is to provide an independent green structure that could be installed adjacent to the walls to be protected or positioned at a certain distance from them. The installation of a vegetation system for shading purposes requires a careful design of the system, a thorough understanding of the climatic conditions and the choice of the most suitable type of vegetation, compatible with the climate and orientation.

4.4.1.3 FENESTRATION

When renovating existing buildings, it may be cost effective to install external sunscreens to reduce the effects of solar radiation on windows facing east or west. Internal blinds, even if they are opaque, have solar factors that are too high; these types of devices are not effective in preventing overheating due to solar radiation and are normally used for protection from glare. There are several solutions for effective solar control, as shown in Table 4.4-6.

TABLE 4.4-6 **STRATEGIES TO IMPROVE THE THERMAL PERFORMANCE OF FENESTRATION**

Measure	Description, tips and warnings
Installation of external solar shading systems	The main effects of the external solar shading systems are: • control of the incoming solar radiation; • control of the incoming solar radiation in a high upland climate and contribution to the management of solar gains in order to improve thermal comfort; • control of natural lighting, avoiding glare effects. The design of external shading devices must take into account several factors, namely: • the orientation of the façade; • the shadows of other buildings; • the technical and architectural features of the façade; • any architectural constraints. • Issues that must be addressed on designing these systems do not only relate to energy (see Chapter 3); an energy simulation is however recommended) but should also include structural aspects (how to fix the systems to the façade).
Application of solar control films	The application of a solar control film can reduce the effects of solar radiation incident on the transparent building envelope, improving thermal and visual comfort and reducing the effects of glare. The practical effects of this measure, which is cost-effective if the condition of the windows is good, are that it reduces the solar loads and the costs of energy for cooling. Some solar control films are designed for outdoor installation (in this case it may be necessary to provide scaffolding) while others can be installed from inside. Installation is simple and takes little time, however to get good results and durability, specialised installers are strongly recommended. Maintenance (mainly cleaning) must be carried out using procedures and products compatible with the characteristics of the films applied. The colours of the control films (normally blue, green or brown), may modify the appearance of the building and change the visual atmosphere indoors (see Chapter 5).
Shading with vegetation	The use of vegetation for sun protection of façades or windows is a natural solution that can contribute to an increase in the sustainability of the building. The objective is to provide an independent green structure that could be installed adjacent to the walls to be protected or positioned at a certain distance from them. The drawback may be a strong reduction of the amount of natural lighting available indoors, with the consequent need for artificial lighting.

4.4.2 HVAC SYSTEM IMPROVEMENT

Retrofit measures carried out on mechanical systems on the basis of a careful analysis of the existing plant and components (through field surveys and monitoring) have the objective of reducing the primary energy consumption by increasing the system's efficiency without compromising the required level of indoor comfort.

4.4.2.1 REDUCING INTERNAL LOADS FOR LIGHTING

Internal loads must be removed from the HVAC system. For this reason it is useful to carry out an energy audit in order to plan possible strategies.

The electricity consumption of lighting systems represents a significant proportion of the total consumption of electricity of a building; this consumption, however, also affects the energy consumption for climate control. An energy retrofit on lighting systems, therefore, allows two objectives to be achieved: a reduction in operating costs for lighting and a reduction in operating costs for air conditioning.

The reasons for which lighting costs are normally high can be summarized as follows:

- spaces are lit even when not needed;
- areas are lit in the wrong way;
- natural lighting is not exploited properly;inefficient lighting equipment is used;
- poor maintenance of the lighting fixtures.

Table 4.4-7 shows a list of possible retrofit actions for lighting systems and the approximate energy savings that can be obtained.

TABLE 4.4-7 **LIST OF POSSIBLE RETROFIT ACTIONS FOR LIGHTING SYSTEMS AND THE APPROXIMATE ENERGY SAVINGS***

Audit finding	Corresponding retrofit measures	Approximate Energy Saving
Lighting level in corridor area above 200 lux.	Disconnect power supply in some luminaires and lower the illumination to a suitable level, say 100 lux.	15 to 30% for corridor lighting
Lighting along window areas turned "ON" during the day time, providing a lux level well over 300 lux	Maintain the lighting at 300 lux by turning off corresponding perimeter lighting or - if both interior lighting and perimeter lighting share the same control switch - re-wire to facilitate independent control switches for each of the 2 zones. Alternatively replace the lighting ballasts at the perimeter with dimmable electronic type and lights controlled by means of photo sensors. Remove some of the lamps of the luminaire, or replace them with lower power lamps if possible	20 to 30% for lighting at perimeters
T12/T10 fluorescent tube used in lighting (e.g. exit sign)	Replace with T8 fluorescent tube (not feasible for quick start type)	10%
T8 fluorescent lighting (fixture & tube) used	Replace with T5 fluorescent lighting	30-40%
Manual ON/OFF control for lighting	Add occupancy sensor control	>20%
Electromagnetic ballast used in lighting with T8 fluorescent tube	Replace with electronic ballast	20 to 40%
Incandescent lamps are being used	Change to compact fluorescent lamps or retrofit with fluorescent tube lighting	80%; more if spaces are air conditioned: the extra is cooling energy to offset the higher heat dissipation of the incandescent lamps

**Guidelines on energy audit, Energy Efficiency Office, The Government of the Hong Kong, 2007 - http://www.emsd.gov.hk/emsd/e_download/pee/Guidelines_on_Energy_Audit_2007.pdf*

It should also be considered that the colour of the inner walls of a room has a great influence on the visual comfort of the users. In fact the surface finish influences the uniformity of the distribution of natural light. This measure is cost-effective, easy to apply and has significant advantages. Visual comfort is improved not only in the periods in which the lighting is natural but also when artificial lighting is switched on.

The energy savings derive from a reduced use of artificial lighting. The benefits from the improvement of visual comfort, although difficult to quantify, are significant.

4.4.2.2 IMPROVING PERFORMANCE OF COOLING GENERATION SYSTEMS

It can be cost-effective to replace an existing chiller with a new and more efficient one. In recent years, significant improvements in the overall efficiency of mechanical chillers have been achieved by the introduction of two-compressor, variable-speed centrifugal, and scroll compressor chillers.

As far as the problem of refrigerant gases is concerned (usually CFC, chlorofluorocarbon), it is worth emphasizing that the choice of chillers that use environmentally compatible refrigerants should be carefully considered, even if it is not compulsory, since it is a choice which improves the sustainability of the building (see paragraph 4.2.2).

If the existing chiller is relatively new (less than 10 years old), it may not be cost-effective to replace it entirely with a new non-CFC one. The conversion of the chiller to operate with non-CFCs may be the most economical option. However, the non-CFC refrigerants (e.g. R-134a and R-717) may reduce the cooling capacity of the chiller owing to their inherent properties. Fortunately, this loss in energy efficiency can be limited by upgrading some components of the cooling system, including the impellers, orifice plates and gaskets, even the compressors themselves.

When the cooling capacity of chillers in existing buildings is examined, it is usually found to be oversized. This is another problem that may justify the replacement of the old cooling system. Indeed, several existing chillers may well have a capacity that is significantly higher than the peak cooling load and operate exclusively under part load conditions, with reduced efficiency and hence increased operating and maintenance costs.

If retrofit measures to improve the energy performance of the building envelope (increasing thermal insulation, implementing sun protection strategies, etc.) are planned, the capacity of the cooling system can be significantly reduced. A precise calculation of the actual cooling demand of the system is important also because when it is reduced the size of the other components of the plant (e.g. pipes, pumps, terminals, cooling tower, etc.) can also be reduced.

In Table 4.4-8 possible actions for improving the energy performance of HVAC systems are summarised.

TABLE 4.4-8 **HVAC SYSTEM IMPROVEMENT**

Measure	Description, tips and warnings
Replacement of compression chillers	This measure involves a complete check of existing chillers and the replacement of those using any refrigerant fluid containing chlorofluorocarbons (CFCs) and chlorofluorohydrocarbons (HCFCs), substances responsible for the impoverishment of the atmospheric ozone layer and for global warming. A new chiller will also have a higher energy efficiency, leading to a reduction in electricity consumption. Before choosing the model of chiller to replace the old one, it is advisable to carry out analytical calculations (dynamic computer simulation recommended) of the cooling demand of the building in order to define the cooling capacity of the new chiller according to the actual needs. The heat produced by the condenser of the new chiller could be used for thermal applications compatible with the values of the operating temperatures (for example DHW heating or pre-heating). The cooling capacity of the new chiller can be significantly reduced if a cold thermal storage system is installed: this permits a reduction in peak cooling power and the use of the chiller in the hours in which the cost of electricity is lowest.
Thermal insulation of pipes and air ducts	The heat losses along the distribution loops (pipes and air ducts) can be significantly reduced through effective insulation of piping and/or ducts. • The distribution circuits should be checked in order to verify the quality of the thermal insulation. • Any poorly insulated pipe sections must be restored through improved thermal insulation. • For these pipes the existing insulation, in many cases, must be removed and replaced by new insulation. It is not easy to check the quality of the thermal insulation of pipes for those sections that are not visible (e.g. inside walls structures, inside the ground or inside non-accessible spaces): in this case an infrared audit can assist the inspection phase.
Installation of high efficiency pumps	The energy performance of distribution circuits can be improved by replacing the existing pumps with devices that consume less electricity. Controlling the speed of an electric motor by means of a VFD (Variable Frequency Drive) or frequency inverter is the most effective way to adjust the energy performance of pumps that must operate at variable speeds. The replacement of the electric pumps and of circulators installed in existing hydronic circuits with high efficiency devices is a cost-effective measure since the electrical energy consumed can be reduced by up to 80%.

Measure	Description, tips and warnings
Installation of VFD/inverter-controlled fans	Frequently in HVAC air systems fans run at full speed when the airflow needed is not the peak one. This results in greater consumption of electricity. The installation of a VFD/inverter systems allows the speed of the motors, and hence of the fans, to be adjusted, helping to reduce electricity consumption. In order to save electricity the strategies are as follows: • control the electric motor with a VFD/inverter instead of a simple contactor; • remove the existing limitation device (for example the main airflow regulating damper); • install a device which detects the pressure.
Installation of ceiling fans	If ceiling fans are installed, internal air temperature can be raised to 28 °C, instead of 26 °C, maintaining the same comfort conditions (see Appendix 2).

4.4.2.3 IMPROVEMENT OF AIR HANDLING AND VENTILATION PERFORMANCE

In air-conditioning systems or in ventilation systems, air is treated before being introduced into the conditioned spaces. Types of HVAC systems can vary greatly depending on the needs of users.

Table 4.4-9 shows how energy consumption due to the Air Handling Units (AHU) can be reduced.

TABLE 4.4-9 **AIR HANDLING UNITS IMPROVEMENT**

Measure	Description, tips and warnings
Replacement of AHUs	This measure includes an accurate check on the AHU in order to pinpoint all the inefficiencies. When replacing an AHU with a new one, a detailed analytical calculation is necessary in order to define the appropriate technical specifications.
Installation of heat recovery systems	A heat recovery system captures the exhaust air and reuses some of the energy to pre-cool the replacement air before it is supplied to the air-conditioned spaces (see paragraph 4.2.1). The installation of heat recovery systems in existing buildings can be cost-effective if complete renovation of the HVAC system is planned.
Evaporative pre-cooling the exhaust air	Before passing through the heat recovery system the exhaust air can be pre-cooled. The system is described in paragraph 4.2.1.

4.4.2.4 IMPROVEMENT IN THE PERFORMANCE OF CONTROL SYSTEMS

It is important for the auditor to assess, through measurements and monitoring, the existing indoor air temperature controls in order to evaluate the potential for reducing energy use and/or improving indoor thermal comfort without any substantial investment.

The manually controlled air temperature set-point, does not guarantee performance, since the set-point values can be modified by the users. Only a properly chosen, properly installed and properly adjusted and maintained control system, can guarantee energy performance and thermal comfort over time.

Possible strategies for improving control systems are shown in Table 4.4-10.

TABLE 4.4-10 **CONTROL SYSTEMS IMPROVEMENT STRATEGIES**

Measure	Description, tips and warnings
Installation of zone control systems	Control of the thermal energy output of the HVAC system is one of the most cost-effective measures for the reduction of energy consumption and the improvement of the thermal comfort of the occupants.
Installation of energy metering	For an end-user, awareness of individual energy consumption (and having to pay for the energy actually consumed) is a strong incentive to be more energy conscious.
Installation of timers	Devices or plant sections powered-up during periods when their services are not required cause a considerable waste of electricity. Reliance on manual switching-off is the simplest solution, but there is no guarantee against forgetfulness or laziness. The installation of timers that enable or disable power automatically, provides far better energy management. The practical solutions may be different depending on technologies; digital timers, now available at low cost, are the devices providing the greatest flexibility. Programming is usually simple and scheduling can be hourly, daily, weekly or monthly.
Installation of a BAS (Building Automation System)	The action consists of the installation of a building automation system in order to reduce energy consumption by optimising the use of facilities and improving comfort for occupants. Functional integration is the core innovation introduced by building automation: the different areas (e.g. security, safety, HVAC, lighting, communication, etc.), previously considered independent, interact, communicate and create synergies. A building automation system is an example of a distributed control system. The control system is a computerised, intelligent network of electronic devices designed to monitor and control the mechanical, electronic, and lighting systems in a building. Even before defining the structure of the system it is essential to carry out an accurate, in-depth analysis of the real needs of the user, finding the best way to meet them. A building automation system is a perfect tool to support the implementation of an energy management system model.

4.4.2.5 VISUAL AND ACOUSTIC IMPACT OF EXTERIOR HVAC EQUIPMENT

There are several types of HVAC systems on the market, In retrofitting existing buildings the most popular solution is to install Split Systems (see paragraph 4.2.1). Outdoor condenser/compressor units can be large, cube-like devices that may be noisy and difficult to screen.

To lessen the visual impact of these units it is important to consider an appropriate location. Rear yards that are not visible from a public way are the preferred location, side yards are an alternative location, but will often require a screen. Front yards and walls (and other above-ground locations) are the least preferred options. Rooftop mechanical equipment that is not visible from a public way is often an acceptable option.

Screening the visibility of ground-level HVAC equipment that is visible from a public way is an important part of the installation. The size of a unit, combined with the additional height created by the concrete pad it sits on, will often create the need for fencing, latticework, plantings, or similar screening options. If fencing is the preferred approach, it is important to consider how the fence will relate to the architecture and materials of the house and existing landscaping features. Plants must also be chosen carefully, as the goal is to provide consistent year-round screening. One need to consider, in addition, is that some plants may not thrive if they are situated too close to a source of heat or exhaust air. Rooftop mechanical equipment can usually be screened, but sometimes the screen may be more intrusive than the mechanical unit itself.

Screening of the equipment should not detract from its performance. For this reason all screening options should be discussed with the installation contractor, as condenser unit require ample clearance to provide adequate air flow so that the coils will be cooled efficiently. Units mounted too close to a wall or surrounded by shrubs, or multiple units located too close together may not receive enough cool air to function properly. The result can be a shorter compressor life and/or less efficient cooling operation.

Another factor for a home owner to consider is the noise impact of an exterior condenser unit. Although technology has improved and newer units are quieter than the old ones used to be, their placement relative to abutting houses still has the potential to create conflict with one's neighbours. When multiple condensers units are installed together, the noise levels will also increase. Screening can act as a sound attenuation strategy to help reduce noise while also reducing the visual impact of an exterior condenser units.

Municipalities or territorial administrations in many cases have building codes or ordinances that define the pre-requisites that must be met in order to avoid the visual and noise impacts of exterior HVAC equipment

4.4.3 IMPROVEMENT OF DHW SYSTEMS

A set of retrofit measures can be implemented in order to reduce the use of energy for DHW systems in existing buildings:

- check that water temperature is not higher than necessary;
- check the possibility of turning off all the pumps at night or at times when the plant is not in use;
- replace the heat generator with a more efficient one (for example condensing boiler or heat pump);
- check the thermal insulation of the distribution pipes;
- check if there is any process heat at a low temperature that can be used for this purpose (e.g. chillers' condenser water circuit);
- check if it is possible to install a solar thermal system.

4.4.4 OPERATION AND MAINTENANCE IMPROVEMENT

Poor management and/or lack of maintenance cause most waste of energy and resources. Actions leading to improved management are among the most cost-effective since they do not require significant investments (sometimes zero). On the other hand, proper maintenance of the system not only maintains the high performance of the individual components but also prevents unexpected breakdowns.

An initial list of measures that can be applied is as follows (Table 4.4-11):

- correct setting of control devices (e.g. reduction of the hours of operation, appropriately matching needs, or precise setting of the temperature of occupied spaces);
- disabling components which are consuming energy unnecessarily;
- implementing control procedures and consumption monitoring;
- implementing maintenance procedures;
- implementing information strategies and incentives amongst users.

TABLE 4.4-11 **OPERATION AND MAINTENANCE IMPROVEMENT STRATEGIES**

Measure	Description, tips and warning
Reduction of operation times for HVAC systems	The objective of this measure is to remove energy waste by re-scheduling, where possible, the times of activation of the HVAC system according to the actual hours of use of the spaces, thus avoiding any unnecessary air-conditioning. The new schedule of the activation times of the HVAC system should be agreed with the client. This measure entails no extra cost if a building management system is available.
Control of indoor environmental conditions	This measure consists of programming monitoring campaigns to verify the indoor environmental conditions at least twice a year. The effect of this measure is not only the reduction of possible energy waste but also the upkeep of the best indoor environmental conditions in terms of the occupants' thermal comfort. The scheduling of the monitoring campaigns should be discussed and agreed with the client. Regular monitoring of the environmental conditions of the indoor spaces (e.g. air temperature, relative humidity, CO_2 concentration) permits the detection of potential problems and the implementation of action to restore the optimum situation.
Cleaning and replacement of filters	Cleaning or replacing filters in HVAC systems (air handling units, fan coil units and other HVAC emitting units) is often a neglected maintenance activity. Not only are dirty filters not capable of retaining impurities but they also greatly increase pressure losses, thus supply and extraction fans greatly increase their consumption of electricity. For this reason a scheduling of the cleaning and sometimes replacement of filters should be seriously considered.
Cleaning of coils	Cleaning of coils on Air Handling Units or on fan-coil units is often a neglected maintenance activity. In dirty coils the heat exchange efficiency decreases considerably and the chiller operates at a higher power. Dirtying of the coils is usually due to dirty filters (see measure described above).

Measure	Description, tips and warning
Control of DHW temperature	Domestic hot water is often distributed to the user at a temperature that is higher than necessary: this situation then requires the user to mix that hot water with cold water in order to obtain the right temperature. The reduction of the temperature of DHW through a simple adjustment of the thermostat or of the control system brings a significant reduction in thermal losses along the distribution circuit and thus saves energy.
Providing an instruction manual to users	End-users rarely have enough technical and practical knowledge to understand how to use the equipment of the building facilities properly. This is sometimes one of the root causes of energy wastage. This lack of knowledge can be overcome by a simple user manual containing the necessary information. The manual should be clear, concise and easy to read. In writing the manual it is important to take full account of the fact that the intended readers will not be experts.
Scheduling of energy accounting procedures	The scheduling of energy accounting procedures is one of the measures that allows control of the energy management of the facilities. Energy accounting can be performed periodically by checking the energy consumption of the various users. Internal benchmark indicators are useful for this measure.

4.4.5 EVALUATION OF ENERGY SAVING POTENTIAL

Energy retrofit measures require investments depending on the type of action. Once a list of possible retrofit actions has been defined, each with energy saving potential and estimated cost, they can be ranked in relation to their payback time, from the shortest to the longest. This ranked list is essential information for taking decisions. Actions to improve operation and maintenance often do not require physical investments but only the dissemination of good practice and investments in labour, and for this reason they are the most cost-effective. Proper planning of the system's operation and maintenance is in all cases necessary to maintain the high energy performance of the building and its facilities.

Among the physical actions, those involving the physical equipment are the most cost-effective because inefficiencies are widespread and the obsolescence of components and systems requires continuous technological and functional renewal. Retrofit actions on the envelope of the building are generally repaid over a longer time and they should be scheduled to coincide with the scheduled maintenance of the building.

For the evaluation of the energy saving potential it is also necessary to consider the interactions that can occur between multiple actions. In other words, the overall energy saving is not derived from the sum of the energy savings of individual actions but from the overall result that is achieved.

The best way to assess the potential for energy saving is to use computer models, preferably dynamic simulation models (the energy performance assessment for air conditioning can indeed be complex).

For a preliminary overview of the energy saving potential it is possible to refer to the data in Table 4.4-12. The figures are for reference only. Actual energy savings will depend on different conditions and applications.

TABLE 4.4-12 **LIST OF POSSIBLE RETROFIT ACTIONS FOR HVAC SYSTEMS AND THE APPROXIMATE ENERGY SAVINGS***

Audit finding	Corresponding retrofit measures	Approximate Energy Saving
Too cold in summer, e.g. measured room temperature < 25 °C	Set thermostat to desired room temperature of 25.5 °C; or repair/replace the thermostat if it is not working	10 to 30%
Excessive air pressure drop across air filter of Air Handling Unit (AHU) and fan coils	Clear air filter	5 to 20% fan power consumption
Chiller set to provide 6 °C chilled water	Re-set operating temperature to 8 °C	3 to 6% chiller power
No blinds or blinds not closed for windows exposed to strong sunshine	Install or close blinds	5 to 30% cooling energy to offset solar heat gain through window, also depending on the colour of the blinds
Overcooled spots due to improper water balancing	Balance the water supply system, add valve if practicable	15 to 25%
Window exposed to strong sunlight	Apply "anti-ultraviolet film"	>20%
Air flow of VAV AHU controller by inlet guide vanes	Add VVF inverter type variable speed drive	10 to 30% fan power
Secondary chiller water pump driven by constant speed motor	Add VVF inverter type variable speed drive	10 to 30% pump power

** Guidelines on energy audit, Energy Efficiency Office, The Government of the Hong Kong, 2007 - http://www.emsd.gov.hk/emsd/e_download/pee/Guidelines_on_Energy_Audit_2007.pdf*

4.5 SIMULATION TOOLS

Many dynamic simulation tools are available on the market, and are more or less expensive, according to their interface (more or less friendly) and completeness (integration with other relevant tools). There is also a number of dynamic simulation tools, developed by Universities or research laboratories, that can be downloaded for free, and are completely reliable (in fact, DOE2 and EnergyPlus, developed by the Lawrence Berkeley Laboratory, are the engine of most commercial products). In the following, some of these free simulation tools are listed with a brief description.

DOE-2.1E

DOE-2.1E predicts the hourly energy use and energy cost of a building. The inputs required are hourly weather information, geometric dimensions of the building, and a description of its HVAC. Designers can choose the building parameters that improve energy efficiency, while maintaining thermal comfort and cost-effectiveness. DOE-2.1E has one subprogramme for translation of input (BDL Processor), and four simulation subprogrammes (LOADS, SYSTEMS, PLANT and ECONOMICS). LOADS, SYSTEMS, PLANT and ECONOMICS are executed in sequence, with the output of LOADS becoming the input of SYSTEMS, and so on. Each of the simulation subprogrammes also produces printed reports of the results of its calculations.

The Building Description Language (BDL) processor reads input data and calculates response factors for the transient heat flow in walls, and weighting factors for the thermal response of building spaces.

The LOADS simulation subprogramme calculates the sensible and latent components of the hourly heating or cooling load for each constant temperature space, taking into account weather and building use patterns. The SYSTEMS subprogramme calculates the performance of air-side equipment (fans, coils, and ducts); it corrects the constant-temperature loads calculated by the LOADS subprogramme by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and thermostat set points. The output of SYSTEMS is air flow and coil loads. PLANTS calculates the behaviour of boilers, chiller, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. It takes into account the part-load characteristics of the primary equipment, to calculate the fuel and electrical demands of the building. The ECONOMICS subprogramme calculates the cost of energy and so can be used to compare the cost benefits of different building designs, or to calculate savings for retrofits to an existing building.

A number of interfaces have been developed to make the programme easy to use.

eQUEST

eQUEST is an easy to use building energy use analysis tool that provides professional-level results with an affordable level of effort. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module, with an enhanced DOE-2.2-derived building energy use simulation programme.

eQUEST features a building creation wizard that guides the user through the process of creating an effective building energy model. This involves following a series of steps that help one to describe the features of the design that would impact energy use such as architectural design, HVAC equipment, building type and size, floor plan layout, construction material, area usage and occupancy, and lighting system. After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy the building would use.

Within eQUEST, DOE-2.2 performs an hourly simulation of the building design for a one-year period. It calculates heating or cooling loads for each hour of the year, based on factors such as walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. During the simulation, DOE-2.2 tabulates the building's projected use for various end uses.

eQUEST offers several graphical formats for viewing simulation results. It allows one to perform multiple simulations and view alternative results in side-by-side graphics. It offers features like: energy cost estimating, daylighting and lighting system control , and automatic implementation of common energy efficiency measures (by selecting preferred measures from a list).

ENERGYPLUS

EnergyPlus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E. It is primarily a simulation engine; input and output are simple text files. EnergyPlus grew out of a perceived need to provide an integrated (simultaneous load and systems) simulation for accurate temperature and comfort prediction. Loads calculated (by a heat balance engine) at user-specified time step (15-minute default) are passed to the building system simulation module at the same time step. The EnergyPlus building systems simulation module, with a variable time step (down to 1 minute as needed), calculates the heating and cooling system, and plant and electrical system response. This integrated solution provides a more accurate space-temperature prediction, crucial for system and plant sizing, and occupant comfort and health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

EnergyPlus has two basic components: a heat and mass balance simulation module, and a building systems simulation module. The heat balance module manages the surface and air heat balance, and acts as an interface between the heat balance and the building system simulation manager. EnergyPlus inherits three popular windows and daylighting models from DOE-2.1E – fenestration performance based on WINDOW 5 calculations, daylighting using the split-flux inter-reflection module, and antistrophic sky models. In addition, a new daylighting analysis module named 'Delight' has been integrated with EnergyPlus.

OPENSTUDIO

Since EnergyPlus is the only simulation engine that requires a text input data file, some GUI to aid users in compiling this text file is necessary. OpenStudio is the first free plug-in for SketchUp[45] that allows users to build the model geometry and to specify corresponding envelope components by using intuitive SketchUp drawing tools and interfaces. Furthermore, it allows the main characteristics of thermal zones like occupancy, ventilation rates, internal heat gains and set-point temperatures to be set.

BESTenergy is also a SketchUp based tool and was developed starting from the 1.08.395 version of OpenStudio plugin, with respect to which some specific modules were implemented, in order to make the modeling of some specific EnergyPlus objects more affordable and to better manage and design some architectural components. It also supports decisions on strategic aspects of architectural design that can highly improve building energy performance, even in the preliminary phases. For instance, it implements specific interface modules for definition of schedules, evaluations of occupant comfort , opaque and transparent constructions (with the capability to edit and import material libraries), solar shading devices and airflows due to natural ventilation.

Both of them are building envelope focused, so they currently provide only an ideal load conditioning system.

SIMERGY

Simergy is a very suitable software to model plant systems using EnergyPlus objects, by an interface that allows the user to drag and drop blocks and components in a graphical scheme in which characteristics of the single item can be edited, but its capabilities for modeling geometric ad zone properties are quite limited and cumbersome.

45 SketchUp is a free 3D modeling program.

RADIANCE

RADIANCE is the most powerful and reliable software intended to aid lighting designers and architects in predicting light levels and visual appearance of a space prior to construction. The package, available for UNIX-platform, Windows and Mac, includes routines for modelling and translating scene geometry, luminaire data and material properties, all of which are needed as input to the simulation. It can also be used by researchers to evaluate new lighting and daylighting technologies and to study visual comfort.

The main inputs required are the geometry and materials of the design space, including luminaire photometry and surface reflectance characteristics. Unfortunately, it lacks a graphical user interface to model the scene in an easy way. A third-party tool should be used to perform modelling.

It calculates spectral radiance values (illuminance and colour) for interior and exterior spaces considering electric lighting, daylight and inter-reflection.

The major portion of the Radiance package, and the part that is of greatest interest to users, is the lighting simulation engine that calculates light levels and renders images by using a hybrid approach of Monte Carlo and deterministic ray tracing to achieve a reasonably accurate result in a reasonable time. The method employed (well known as "backward ray-tracing technique") starts at a measurement point (usually a viewpoint) and traces rays of light backwards to the sources (i.e. emitters).

Output consists of luminance and illuminance values and appearance to the eye of the lit space (Fig. 4.5-1 and 4.5-2), and they can be plotted in tables or imported in calculation grids by other graphical interfaces. Also, it can provide photograph-quality images and video animations.

FIGURE 4.5-1 **ILLUMINANCE DISTRIBUTION (ISOLUX CURVES), LEFT, AND RENDERING OF THE ROOM AS IT APPEARS TO THE EYE, RIGHT**

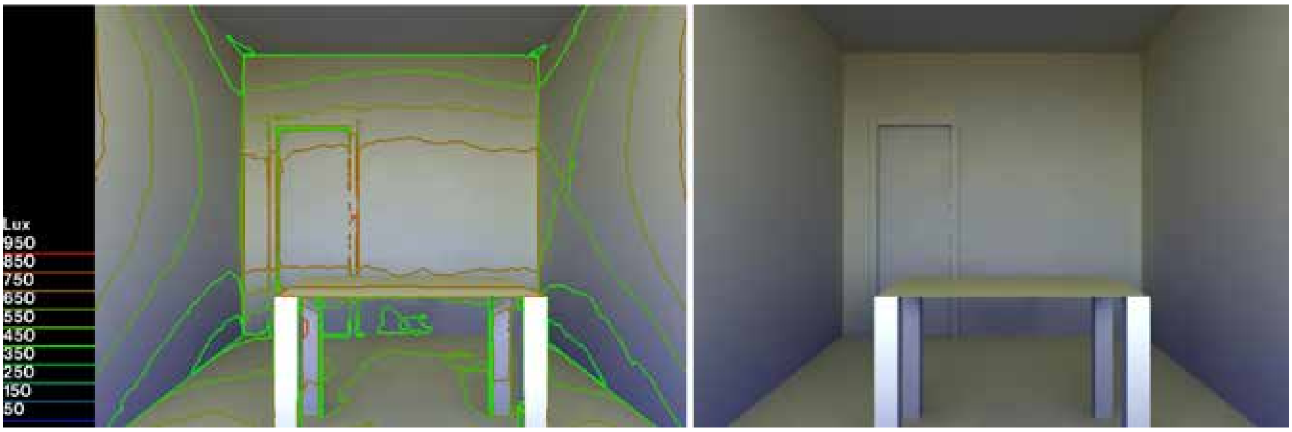
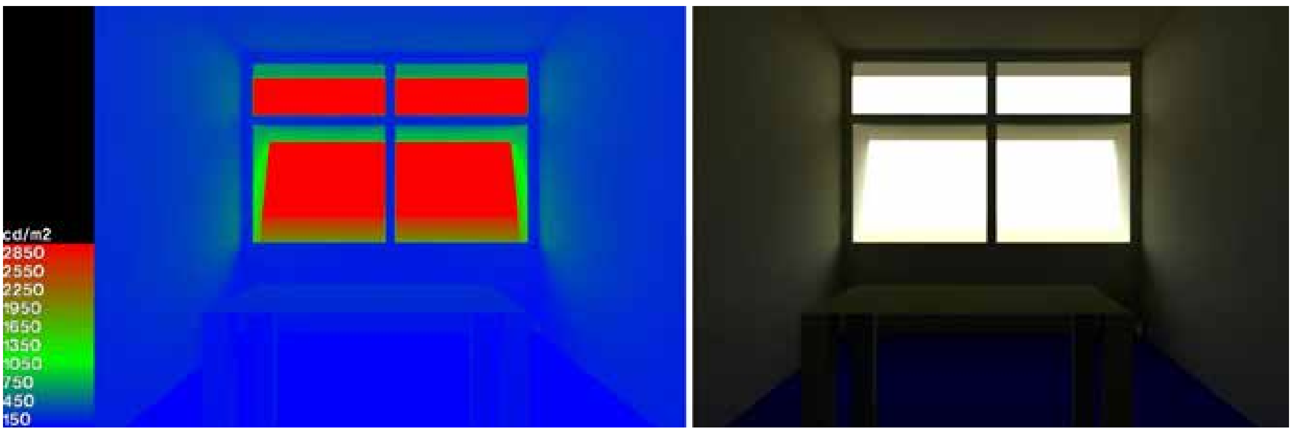


FIGURE 4.5-2 **LUMINANCE DISTRIBUTION IN A WALL WITH A WINDOW (LEFT) AND RENDERING OF THE WALL AS IT APPEARS TO THE EYE (RIGHT)**

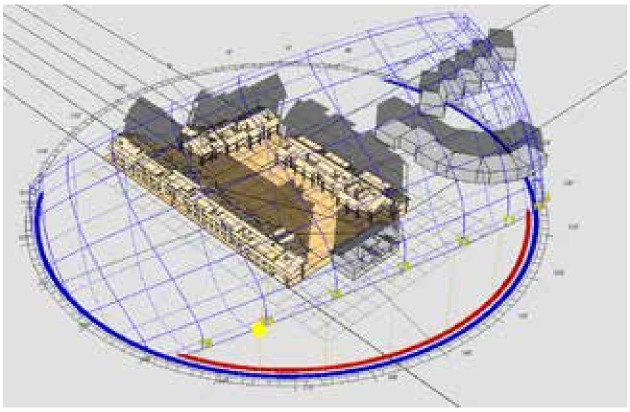


DAYSIM

DAYSIM is a validated RADIANCE-based daylighting analysis software that models the annual amount of daylight in and around buildings. DAYSIM allows users to model dynamic façade systems ranging from standard Venetian blinds to state-of-the-art light redirecting elements, switchable glazing and combinations thereof. Users may further specify complex electric lighting systems and controls including manual light switches, occupancy sensors and photocell controlled dimming. It can work on Windows operating system.

Simulation outputs range from climate-based daylighting metrics such as daylight autonomy and useful daylight illuminance to annual glare and electric lighting energy use. DAYSIM also generates hourly schedules for occupancy, electric lighting loads and shading device status which can be directly coupled with thermal simulation engines such as EnergyPlus, eQuest and TRNSYS.

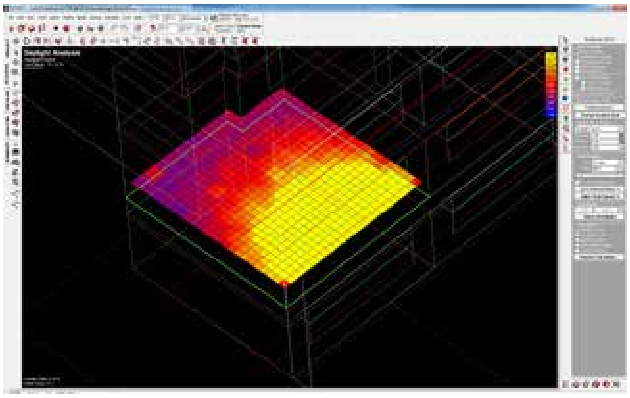
FIGURE 4.5-3 **SHADOWS ANALYSIS WITH ECOTECT**



ECOTECT

Even if it seems to couple an intuitive 3D modelling interface with extensive solar, thermal, lighting, acoustic and cost analysis functions in a comprehensive and simple way, ECOTECT can't provide a reliable numeric simulation of those items. It is very useful for a realistic and expressive shading analysis (Fig. 4.5-3) and for building models to be processed into EnergyPlus (with many limitations) Radiance and Daysim, and it can import and show their output in a calculation grid that makes results easy to understand (Fig. 4.5-4).

FIGURE 4.5-4 **DAYLIGHT ANALYSIS OUTPUT WITH ECOTECT**



4.6 ENERGY PERFORMANCE CERTIFICATES AND GREEN BUILDING RATING SYSTEMS

Energy Performance Certificates (EPC) and Green Building Rating Systems (GBRS) play an important role in achieving energy and resource efficiency, as well as sustainability in the building sector as such. They are the most important set of voluntary or mandatory tools available. More specifically the following functions can be identified:

- EPCs & GBRSs help to define what energy efficient, green and/or sustainable buildings are, thereby providing an objective scale of performance measurement;
- EPCs & GBRSs help to label and identify energy efficient, green and/or sustainable buildings in the context of a real estate market;
- EPCs & GBRSs provide a detailed insight into the energy performance and sustainability features of a building, i.e. which components, principles and practices have what effect on the performance of the building;
- EPCs & GBRSs help to recognise and reward environmental leadership in the property industry and help to improve knowledge about the level of sustainability in each countries buildings stock;
- EPCs & GBRSs help to reduce greenhouse gas emissions of the built environment and therefore significantly contribute to the mitigation of climate change.

Procedures for obtaining EPCs and GBRSs however differ due to the extent and nature of the assessment. Certification under a GBRS can entail long and comparatively expensive procedures. EPCs are obtained rather quickly, in comparison. Here, a visual inspection and energy survey is undertaken, mainly focussing on specific consumers and building features, including loft insulation, domestic boilers, hot water storage tanks, radiators, windows and glazing etc. This standard procedure is fixed by the legislator. It is also highly dependent on local (climatic) conditions.

Buildings that achieve the highest ratings, i.e. platinum, 5 star, exceptional etc. are typically even better performing than required by national building regulations. EPCs, if required as mandatory documentation for a building (for instance for a change of ownership), are effective tools to enforce building energy efficiency regulations.

4.6.1 ENERGY PERFORMANCE CERTIFICATE

The Energy Performance Certificate (EPC) is a document evaluating the energy performance of buildings. EPCs provide information on the energy performance in operation, according to the building design, the HVAC and DHW systems used and the renewable energy production. They may also contain information on carbon dioxide emissions and potential savings in energy consumption. EPCs allow building owners and buyers to gain insight into the value and potential long-term operating costs of a building. Moreover, EPCs help to demonstrate returns on investment for energy efficiency upgrades, based on existing cases.

Generally, the use of EPCs is required and regulated by law. This makes EPCs a regulatory instrument used by governments to enhance energy efficiency and energy performance in buildings.

EPCs set minimum requirements for the energy performance of a building.

Energy Performance Certificates exist in many countries around the world, including the Americas, Europe and Asia. The first example of a Building Energy Efficiency Standard was set up on a voluntary basis in California with Title 24 in 1978.

EPCs have been mandatory in the European Union since 2002 (EU directive 2002/91/EC). An amendment of the legislation took place in 2010 (EU directive 2010/31/EC) which states – inter alia – that, starting from 2018 public buildings and from 2021 also private, all new or substantially renewed buildings must be "nearly zero energy".

In the U.S. there is no federal law similar to that of the EU. The federal states are responsible for setting standards and regulations.

In South Africa EPCs are currently used to evaluate public buildings.

In India the first energy code for commercial buildings was the 2007 ECBC (Energy Conservation Building Code). The code is voluntary until made mandatory by individual state governments.

In Brazil in 2010, the National Program of Energy Efficiency in Buildings launched the Brazilian energy Labelling Schemes for Residential (RTQ-R) and for Commercial buildings (RTQ-C). It is a voluntary standard.

4.6.1.1 METHODOLOGICAL APPROACH AND KEY FEATURES

It is well established that energy efficient buildings are the result of a combination of three factors: building regulations, awareness of the final users[46] and know-how of designers, builders, installers and operators, as shown in figure 4.6-1; incentives accelerate progress towards an energy efficient building stock.

All the energy certification methods follow a common scheme (Fig. 4.6-2); first energy consumption limits are set for each climatic zone of the country, which requires knowledge of climatic data and current building types to determine a benchmark. Then there are two options: to follow either the prescriptive or the performance approach. In the first case, the limits are "embedded" in a set of prescriptions regarding the U values and the thermal inertia of walls and roofs, the U value and the Solar Heat Gain Coefficient of windows, the technical characteristics of the heating or cooling equipment, the characteristics of the DHW system, etc. Compliance with the EPC can be achieved by meeting or exceeding the specific levels described for each individual element of the building systems.

In the second case, the energy performance evaluation for each climatic zone is explicit and the energy consumption of the envelope, of the heating and cooling system and of the DHW system must by evaluated by means of calculations. The result of the evaluation is compared with the energy consumption limit set for the climatic zone: if equal or lower, the building complies with the certification, otherwise the envelope or the mechanical systems have to be changed in order to match the energy consumption limit. Usually, there are different prescriptions and limits for residential and commercial buildings.

46 *In order to achieve and maintain higher levels of efficiency the participation of users is very important. An efficient building with inefficient users may become inefficient where a building inefficient. Similarly, inefficient buildings can significantly increase their efficiency if there is a commitment of its users.*

FIGURE 4.6-1 **THE INGREDIENTS FOR ENERGY EFFICIENT BUILDINGS**

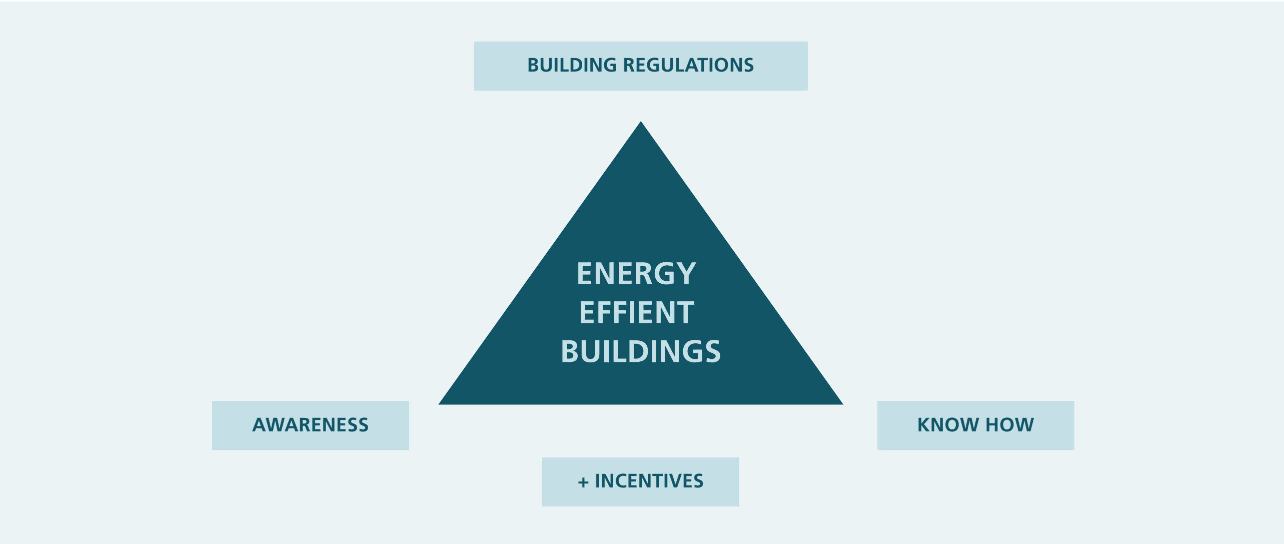
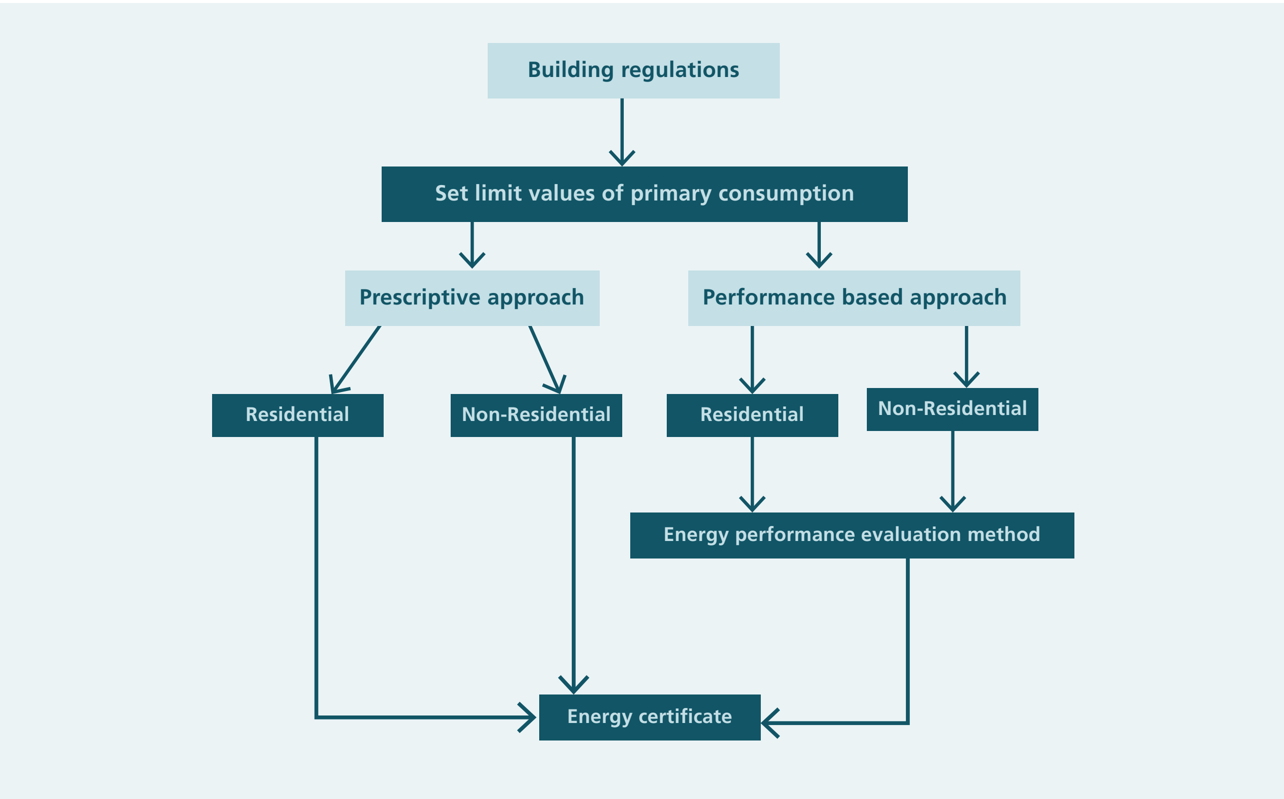


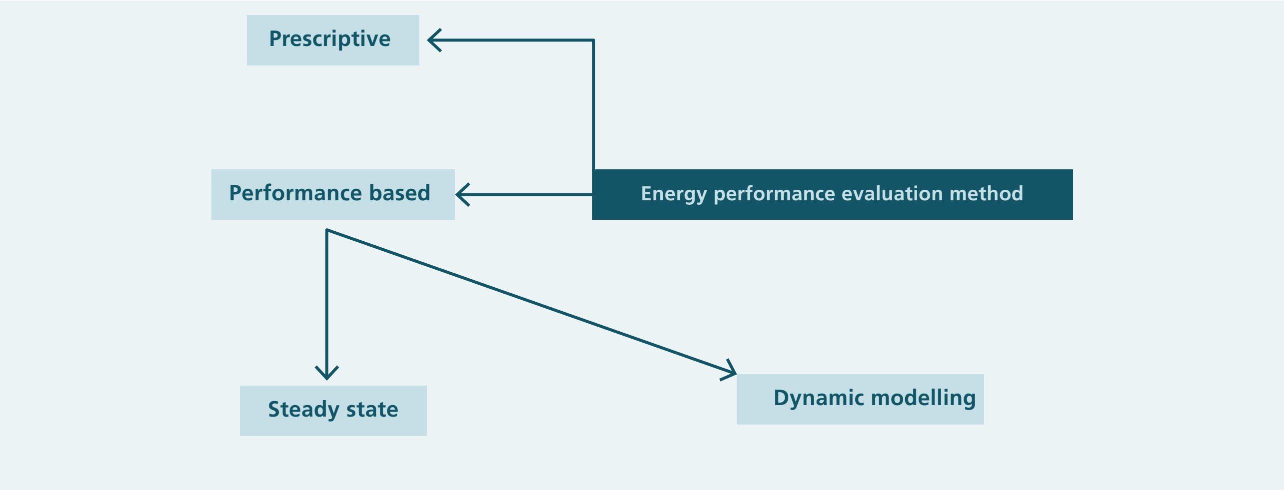
FIGURE 4.6-2 **THE ENERGY CERTIFICATION PROCESS**



The energy performance evaluation method can be carried out either by simple calculations or by means of a dynamic simulation model (Fig. 4.6-3). Computer simulation of energy use can be accomplished with a variety of computer software tools and in many cases may be the best guide for making a building project energy-efficient. However, this approach does require considerable knowledge of building simulation tools and very close communication between members of the design team.

The biggest advantage of using this approach is that it enables the design and construction teams to make comparisons between different design options to identify the most cost-effective and energy-efficient design solution.

FIGURE 4.6-3 **ENERGY PERFORMANCE EVALUATION METHODS**



Whatever the calculation method used, it should take into consideration at least the following aspects[47]:

a) the following actual thermal characteristics of the building including its internal partitions:

   i. thermal capacity;

   ii. insulation;

   iii. passive heating;

   iv. cooling elements; and

   v. thermal bridges;

b) heating installation and hot water supply, including their insulation characteristics;

c) air-conditioning installations;

d) natural and mechanical ventilation which may include air-tightness;

e) built-in lighting installation (mainly in the non-residential sector);

f) the design, positioning and orientation of the building, including outdoor climate;

g) passive solar systems and solar protection;

h) indoor climatic conditions, including the designed indoor climate;

i) internal loads;

and the positive influence of the following aspects shall, where relevant in the calculation, be taken into account:

a) local solar exposure conditions, active solar systems and other heating and electricity systems based on energy from renewable sources;

b) electricity produced by cogeneration;

c) district or block heating and cooling systems;

d) natural lighting.

In the EU, EPCs are required when buildings are built, modified, sold or let, i.e. if there is a change in status with regard to the building structure, use or ownership. In this way EPCs are also a marketing and information instrument. The consumer or customer is entitled by law to be fully informed about the energy performance of a building in question, while the builder, seller or the renting entity is obliged by law to provide this information.

Important key elements of EPCs are:

- EPCs are a mandatory requirement;
- EPCs are standardised and comparable;
- The rating and rating process carried out by accredited assessors.

There are some buildings which are excluded from EPCs. These can be, for instance, temporary buildings that will be used for a limited period of time.

47 EU directive 2010/31/EC, the "Energy Performance in Buildings Directive"

The list of exclusions may also include buildings of religious, historic, monumental or other value that would inhibit alterations designed to improve energy efficiency.

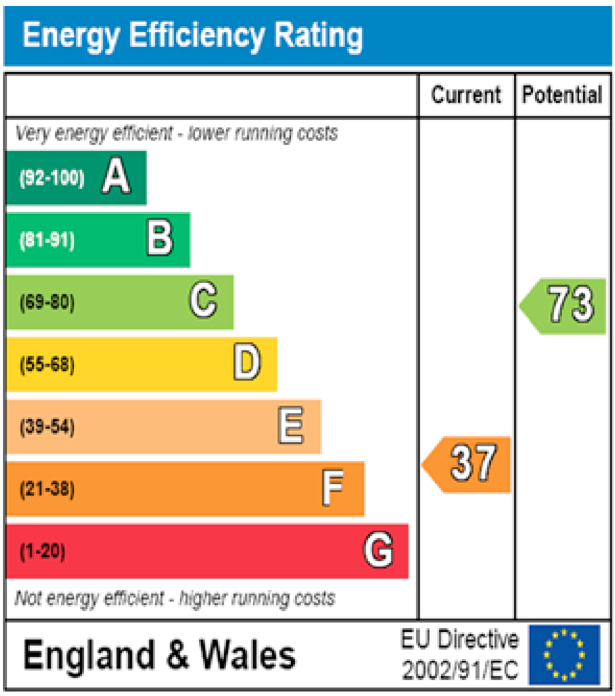
The key information provided by EPCs is the following:

- The energy efficiency rating;
- Estimated energy use (in kWh/m^2 per year) and, in some cases, CO_2 emissions;
- Recommended measures to improve the energy performance;
- Low and zero carbon energy sources.

The individual performance is indicated by a rating from "A" (highest rating, most efficient) to "F" or "G" (lowest rating, least efficient).

An example of an Energy Performance Certificate is shown in figure 4.6-4.

FIGURE 4.6-4 **ENERGY PERFORMANCE CERTIFICATE (EU, ENGLAND AND WALES).**



A rating for a specific building is typically valid for 10 years, unless there are major changes in that building, e.g. construction and alteration. This timeframe also takes into account the pace of technological innovation.

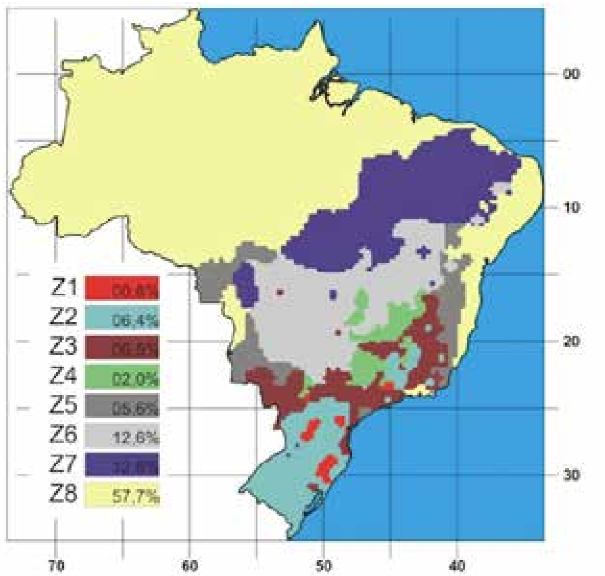
4.6.1.2 EPC IN BRAZIL AND INDIA

Many countries with tropical climates, where the criteria developed in Europe and North America need to be adapted, are adopting energy performance certificates. Significant examples of this are Brazil and India.

BRAZIL[48]

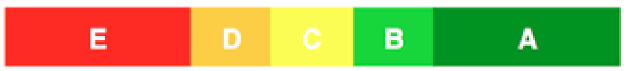
In Brazil 8 Bioclimatic zones were defined (Fig. 4.6-5), according to climatic data.

FIGURE 4.6-5 **CLIMATIC ZONES IN BRAZIL**



There are five possible levels of energy performance of buildings: E is the lowest and A is the highest (Fig. 4.6-6). The EPC does not define the upper limit of level A, since higher efficiency can always be pursued. In this respect, the demand for higher levels of efficiency includes commissioning. Commissioning is planning and executing projects to ensure that they effectively achieve the expected performance, correcting defects or adjusting equipment if necessary to achieve the proposed objectives.

FIGURE. 4.6-6 **LEVELS OF ENERGY EFFICIENCY**



For residential buildings two individual systems are considered when determining the energy efficiency level according to the climate zone and geographic region in which the building is located: the envelope and the DHW system.

48 *Eletrobras/Procel Edifica and Centro Brasileiro de Eficiência Energética em Edificações, Manual para aplicação do RTQ-R, 2013*

The evaluation of the envelope's efficiency can be performed through the prescriptive method or by energy simulation. The evaluation of the DHW system is accomplished through the prescriptive method except for solar heating systems, which can also be evaluated through simulation.

In the prescriptive method the evaluation of the energy efficiency of the envelope is based, for each climatic zone, on the following items:

1. limiting solar absorptance, U-value and heat capacity of walls and roofs;
2. limiting the ratio of the openings area to the floor area of each room for natural ventilation;
3. limiting the ratio of inlet openings area to outlet openings area for cross ventilation;
4. limiting the window area for natural lighting.

The actual values of the above listed parameters for the building being evaluated are introduced into a set of equations (a spreadsheet making all calculations automatically is provided on request), resulting in a numerical value for each item, taking into account – where appropriate – of both winter and summer requirements. These values are then weighted on floor areas to give a final rating value PT of between 0 and 5.

The energy efficiency level of the building is then derived from Table 4.6-1.

TABLE 4.6-1 **BUILDING ENERGY PERFORMANCE LEVEL AS A FUNCTION OF PT**

Resulting final value PT	Building Energy Performance level
PT ≥ 4.5	A
3.5 ≤ PT < 4.5	B
2.5 ≤ PT < 3.5	C
1.5 ≤ PT < 2.5	D
PT < 1.5	E

An example of the final EPC label issued is shown in figure 4.6-7.

FIGURE 4.6-7 **EXAMPLE OF EPC LABEL**

INDIA[49]

The EPC is applicable to buildings or building complexes that have a connected load of 100 kW or higher, i.e.:

Commercial buildings

- Offices
- Retail and wholesale premises
- Hotels
- Hospitals

Public buildings

- Offices
- Hospitals
- Educational buildings

Residential buildings

- High rise residential apartments

49 *Energy Conservation Building Code User Guide, Bureau of Energy Efficiency, 2009*

The provisions of the code (Energy Conservation Building Code) are not applicable to buildings that do not use electricity or fossil fuel and to manufacturing systems and units in a building.

The code specifies few mandatory requirements and provides two alternative methods for buildings to comply with them: the prescriptive method and the whole building performance (WFP) method. In the prescriptive method, the building must comply with all the mandatory measures and prescriptive measures individually.

In the second method of whole building performance, a building complies with the code as long as it meets all the mandatory criteria of the code and when the estimated annual energy use of the proposed design estimated by hourly energy simulation tools is less than that of the standard design.

Prescriptive Method

The Prescriptive Method specifies prescribed minimum energy efficiency parameters for various components and systems of the proposed building. The prescriptive requirements deal with the building envelope, HVAC systems, service hot water and pumping, lighting systems, and electric power respectively. For building envelope, the Indian code provides a Trade-Off option that allows trading off the efficiency of one envelope element with another to achieve the overall efficiency level required by the code. This is a systems-based approach, where the thermal performance of individual envelope components can be reduced if compensated by higher efficiency in other building components (i.e., using higher wall insulation could allow for a less stringent U-factor requirement for windows, or vice versa).

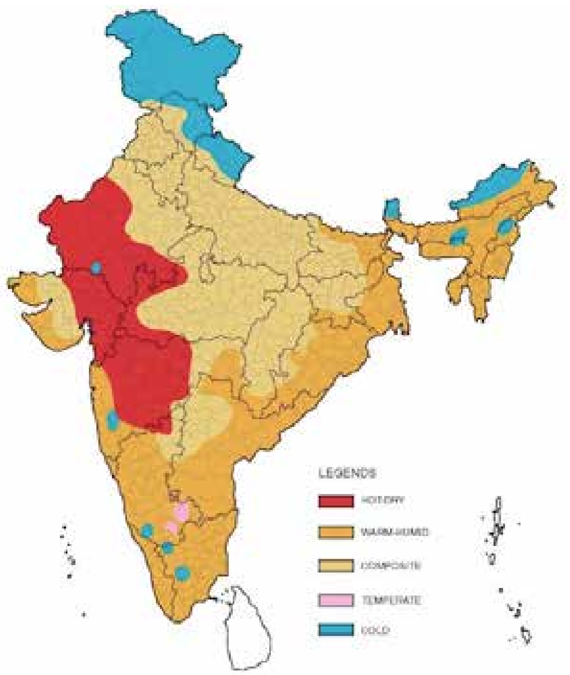
Whole Building Performance (WBP) Method

The Whole Building Performance (WBP) Method is an alternative method to comply with the code. This method is more complex than the Prescriptive Method, but offers considerable design flexibility. It allows for code compliance to be achieved by optimizing the energy usage in various building components and systems (envelope, HVAC, lighting and other building systems) in order to find the most cost-effective solution. WBP method requires an approved computer software program.

The Code also applies to additions in existing buildings.

Different requirements are set for each of the 5 climatic zones into which India is subdivided (Fig. 4.6-8) and for two different building occupancy schedules (24-hour use and daytime use only).

FIGURE. 4.6-8 **CLIMATE ZONES MAP OF INDIA**



The energy uses and functions covered by the Code are:

- Heating
- Cooling
- Ventilation
- Airtightness
- Hot water
- Building parts (lifts, pumps etc.)
- Technical installations
- Lighting
- Appliances
- Design, position & orientation of building
- Passive solar
- Passive cooling
- Natural ventilation
- Solar protection
- Daylighting requirements
- Renewable energy (solar, PV, others)
  The provisions of the Code apply to:
  Building Envelope:
- Opaque construction: U-values

- Fenestration: maximum area weighted U-value and SHGC according to window-to-wall ratios (WWR) visible light transmittance, and air leakage
- Skylights: maximum U-values and SHGC
- Overhang and side-fin
- Envelope sealing details
- Cool roof with slopes of less than 20°: solar reflectance and emittance

HVAC:

- Systems and equipment and controls
- Economizer details
- Variable speed drives
- Piping insulation
- Duct sealing
- Insulation type and location
- HVAC balancing

Service Hot Water and Pumping:

- Solar water heating system details
- Equipment efficiency
- Supplementary water heating systems
- Piping insulation

Lighting:

- Schedules
- Automatic lighting shutoff
- Occupancy sensors and other lighting control details
- Lamp efficacy for exterior lamps

Electrical Power:

- Transformer losses, motor efficiencies, and power factor correction devices
- Metering and monitoring system
- Power distribution systems

For each item limit values are provided and compliance forms have to be submitted to obtain the EPC with the Prescriptive Method. If the WBP approach is adopted, two simulations must be run: one with the actual building's parameters and one with the standard building parameters (i.e. the ones required in the prescriptive approach). The actual building's simulated energy consumption must be lower or equal to that of the simulated standard one to comply.

4.6.2 GREEN BUILDING RATING SYSTEMS

Green Building Rating Systems (GBRSs) are standardised methods or tools for the assessment of the wider environmental performance of buildings; they are voluntary market-based instruments.

GBRSs use a holistic approach that goes beyond the approach underlying Energy Performance Certificates (EPCs), even though some similarities exist. GBRSs incorporate an energy performance evaluation of buildings, but at the same time also take into consideration resource efficiency, and the overall environmental impact of a building as well as its life cycle.

The assessment of energy and resource efficiency is a central objective of GBRSs. Resource efficiency refers to the management and optimisation of material flows within a building, and especially to the minimisation, re-use and re-cycling of solid and liquid wastes. Rainwater harvesting and the use of renewable energies on-site is an example of the utilisation of natural and renewable sources of energy and materials. The optimal rating for a green building should be equivalent to a minimal ecological footprint.

Most GBRSs today follow a Live Cycle Assessment (LCA) approach that means the assessment considers the entire life-cycle of a building from "cradle to grave". It is important for the optimisation of the environmental performance of buildings to consider not just the building as it stands and as it is used, but also its production and its disposal (or demolition). The LCA approach includes therefore the design of the building, the site selection, the construction, the operation and maintenance, renovation, demolition, the selection and optimal use of building materials etc. However, the optimisation of operation and maintenance may be considered the most important feature of GBRS.

GBRS help and provide guidance in improving energy and resource efficiency of buildings as well as their environmental performance. The assessment of a building by means of GBRS can, however, be a significant cost factor. The rating systems are operated by non-profit and non-governmental organisations. The assessment as well as the certification is, however, not free of charge. The improvements and technical interventions necessary for achieving a high rating normally require additional investments as compared to the business-as-usual scenario. Improved efficiency, on the other hand, can and will translate into cost savings for operation and an increased market value of a building (for retail or lending).

GBRSs typically comprise a number of rating schemes that are tailored to the assessment of specific building types, for instance community housing and compounds, education facilities, health care facilities, private or individual homes, industrial buildings, multi-residential buildings, offices, prisons, retail facilities etc. (example: BREEAM, UK). International schemes of GBRSs offer the opportunity for their adoption in different countries and under conditions other than those of the country where the GBRS originates. GBRSs are hence not only building type specific (specific rating schemes), but are also linked to particular conditions in the countries they have been developed for. This includes for instance legal, regulatory, social, cultural and climatic conditions that must all be addressed by a GBRS. Hence, the rating schemes are not necessarily or automatically uniformly applicable around the world, but require careful revision and adaptation for the countries they are newly introduced into.

The main criticism of some GBRS is that many fully glazed buildings recognised as mostly energy wasteful both in embodied energy and in operation, often reach the maximum sustainability rating: this is obtained by using the most expensive envelope components and HVAC systems and by compensating for the inefficient envelope with renewable energy, thus generating energy waste. Studies have shown that no significant difference in energy consumption between non-certified buildings and certified buildings was found[50]. Which is not what one should expect from green buildings.

Another, related, criticism derives from the fact that green building certification is becoming more and more fashionable and is going to have a very strong impact on a building's marketing, stimulating "greenwash" in place of real greening.

4.6.2.1 BREEAM (UK)

BREEAM is the Environmental Assessment Method (EAM) developed and promoted by the Building Research Establishment (BRE) in the United Kingdom. BREEAM was established in 1990 as an assessment tool for the measurement of the environmental performance of existing and of new buildings.

Today's rating schemes of BREEAM cover a wide range of building types (Table 4.6-2). The Rating system, however, is under continuous development and improvement. Hence, amendments of existing schemes, as well as the creation of new schemes, are taking place at regular intervals.

TABLE 4.6-2 **OVERVIEW OF EXISTING RATING SCHEMES UNDER BREEAM**

Name of the Rating Scheme under BREEAM	Application
Communities	Application to community and neighbourhood development (e.g. gated communities and residential compounds)
Courts	Application in courts and similar public buildings
Education	Application to schools, colleges, universities etc.
Health care	Application to hospitals, clinics, retirement homes etc.
Homes	Application to residential buildings, i.e. town houses, bungalows, single family houses etc.
Industrial	Application to industrial buildings, manufacturing halls, workshops etc.
Multi-residential	Application in multi-unit apartment blocks and buildings.
Offices	Application in all types of offices, including private and public buildings.
Prisons	Application to prisons and detention centres.
Retail	Application to shops, malls, department stores etc.
Other	Application to any building that does not fit in one of the other schemes. This scheme is more generic than the above mentioned.
International	Application tool for the use of BREEAM outside the UK.

50 *J.H. Scofield, Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings, Energy and Buildings (2013), http://dx.doi.org/10.1016/j.enbuild.2013.08.032*

Each rating scheme includes a variety of aspects of interest or concern, summarised in rating categories. BREEAM includes eight main rating categories:

- Energy;
- Health and well-being;
- Land use and ecology;
- Management;
- Materials and water;
- Pollution;
- Transport;
- Water.

BREEAM thus considers contemporary sustainability issues, including maintenance and operation policies, reduction of CO_2 emissions, energy and water management, recycling and responsible use of materials and the effects of the building on the urban ecology. Credits are awarded in each of the categories. Weightings are applied to each category and then scores from each category are added together to produce an overall percentage score.

The first step in attaining BREEAM certification is to have a pre-assessment of the building completed by a BREEAM pre-assessment estimator. The pre-assessment estimator will explain the BREEAM process and determine in which scheme the building should be assessed. For buildings that do not fit within one of the normal assessment schemes, a customised version of the scheme, called a bespoke assessment, can be completed.

After the correct scheme has been determined, the next step in the process is to decide what the goals are for the building, including certification level, improved processes, the addition of alternative energy sources and more. The certification level is linked to the credits achieved, as shown in Table 4.6-3.

In the United Kingdom, many new developments, schools and government buildings require a Very Good or Excellent rating.

TABLE 4.6-3 **CERTIFICATION LEVELS AND ASSOCIATED PERCENTAGE**[51]

Certification level / score	Associated percentage (of full credits/points)
Outstanding	85 %
Excellent	70 %
Very good	55 %
Good	45 %
Pass	30 %

51 http://www.breeam.org/

As the rating increases, additional requirements must be met to achieve the certification. The Outstanding level also requires that information about the building be published as a case study written by BRE.

4.6.2.2 HQE (HAUTE QUALITÉ ENVIRONMENTAL, HIGH ENVIRONMENTAL QUALITY), FRANCE

The Environmental Quality of a Building is structured in 14 targets (sets of concerns), which can be grouped into 4 families:

Site and construction

1. Relationship between buildings and their immediate environment
2. Integrated choice of construction methods and materials
3. Low environmental impact of the construction site.

Management

4. Energy management
5. Water management
6. Waste management
7. Maintenance and repair

Comfort

8. Hydrothermal comfort
9. Acoustic comfort
10. Visual comfort
11. Olfactory comfort

Heath

12. Hygiene and cleanliness of the indoor spaces
13. Air quality
14. Water quality

These 14 targets are themselves broken down into sub-targets, representing the major concerns associated with each environmental issue, followed by the basic concerns.

Environmental and health performance of the construction are illustrated through the QEB (Qualité Environnementale du Bâtiment) profile: This profile identifies the level of performance referred to or obtained (depending on the phase in which it is located) for each target and their associated sub-targets. For each target there are three possible judgements: base, performing, very performing.

The award of the certificate is subject to obtaining a minimum profile over the 14 targets, i.e. minimum three targets judged very performing, minimum four targets judged performing and maximum seven targets judged base.

In all cases, the target "Energy Management" must be at the "Performing" or at the "Very performing" level.

Regardless of compliance with the requirements specified for each target QEB, the developer and its partners will ensure the overall consistency and quality of the project, through an iterative and integrated approach. In terms of programming, design and management, HQE operation must be broadly understood and each step must be consistent with the previous one as well as with the original objectives.

The main element that determines overall consistency is the analysis of interactions between target and arbitrations arising.

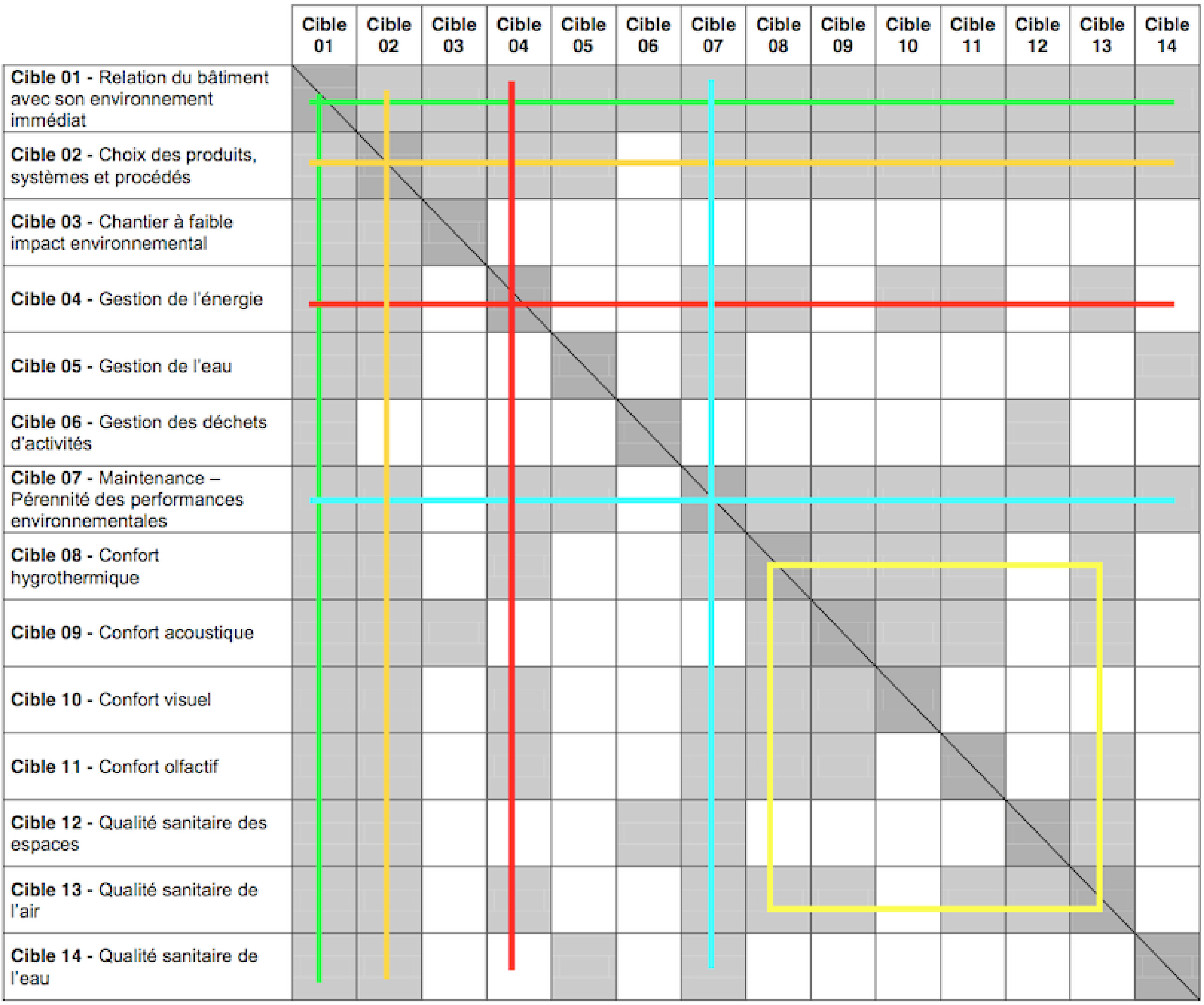
To initiate the process of evaluating the environmental and health performance of the building, it is necessary to partition the QEB into separate concerns in order to assess the project in relation to the issues identified and segregated. However it is important that users perform this QEB assessment bearing in mind that improving the treatment of one target may change the treatment of other targets in a favourable or unfavourable direction as appropriate.

For this purpose a schematic table of interactions is provided (Fig. 4.6-9).

This figure, for example, shows that most cross-cutting targets, such as targets 1, 2 and 7, require an integrated approach. In addition, it shows the need for targets such as indoor air quality and comfort to be treated in a holistic manner,and their interactions properly controlled.

The HQE system is the only one that does not provide a quality ranking. It replaces it with an environmental profile and a design methodology.

FIGURE 4.6-9 **INTERACTIONS TABLE [CIBLE = TARGET].**



Source: *CERTIVEA, Référentiel pour la qualité environnementale des bâtiments – Bâtiments tertiaires, 2012 - http://www.certivea.fr/assets/documentations/9be0d-Guide_Generique_20-01-2012.pdf*

4.6.2.3 **LEED (USA)**

The Leadership in Energy and Environmental Design (LEED) rating system was developed by the U.S. Green Building Council (USGBC) between 1998 and 2000 and drew significantly from the BREEAM system. Like BREEAM, LEED also saw a wider application outside the USA, its country of origin.

The first LEED rating system developed was for new construction. Today, a variety of rating schemes exist under LEED: Commercial Interiors (CI), Core and Shell (CS), Existing Buildings (EB), Health Care (HC), Homes (H), Neighbourhood Development (ND), New Construction (NC), Retail (R) (Shops, Malls etc.) and Schools (S).

LEED is perhaps the most prevalent rating system in the World.

Most of the LEED rating systems focus on the design and construction stages of a building. LEED for Existing Buildings Operations and Maintenance (LEED-EBOM) is for existing buildings and for buildings that were originally certified under new construction and are seeking recertification. Overall, certification processes for both new and existing buildings are nearly the same. The existing buildings certification process also requires an operation period of between three months to two years where performance data, such as energy and water usage, are collected.

Rating schemes available under LEED are highlighted in the Table 4.6-4.

The first step in achieving LEED certification is to register the building with the Green Building Certification Institute (GBCI).

While involving a LEED Accredited Professional in a LEED project is not mandatory, it can help to streamline the certification process and provide valuable information on achieving certification. Moreover, it will allow one additional credit to be achieved.

LEED includes seven different main categories with a variety of issues relevant for sustainable buildings and each category is assigned a weighting (Fig. 4.6-10)

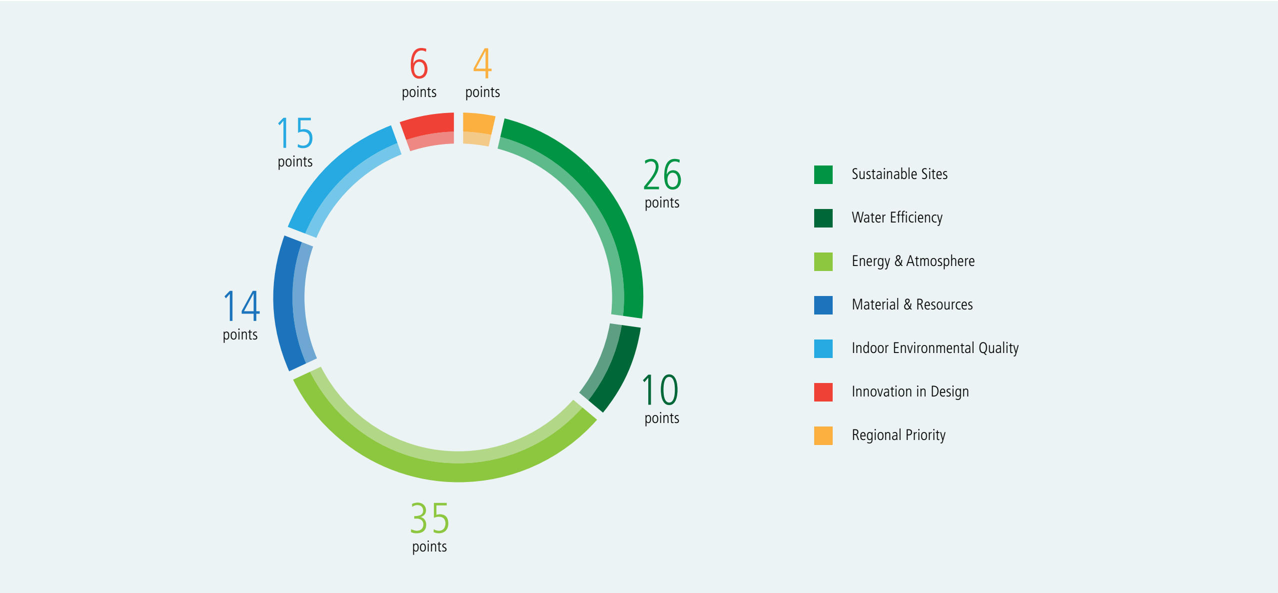
The US GBC provides checklists for each rating scheme that cover the prerequisites and credits. The checklists to be completed prior to the actual rating can be used to identify the possibility of earning each credit as a yes, no or maybe. The prerequisites must be completed in order to submit for certification. The checklist should be used at the beginning of either the design or construction process to determine which credits are feasible for the building and what level of certification is sought.

TABLE 4.6-4 **AVAILABLE RATING SCHEMES UNDER LEED**

Name of the Rating Scheme under LEED	Application
Commercial interiors	Application to shops, malls, department stores etc.
Core & shell	Application to commercial office buildings, medical office buildings, retail centres, warehouses, and laboratory facilities in which the developer controls the design and construction of the entire core and shell base building, such as mechanical, electrical, plumbing, and fire protection systems, but has no control over the design and construction of the tenant fit-out
Existing buildings	Application mainly to the operation and maintenance of existing buildings
Health care	Application to hospitals, clinics, retirement homes etc.
Homes	Application to residential buildings, i.e. town houses, bungalows, single family houses etc.
Neighbourhood development	Application to community and neighbourhood developments (e.g. gated communities and residential compounds)
New construction	Application to new constructions and major renovations of mainly commercial and institutional buildings, including offices, libraries, churches, hotels, but also multi-storey residential.
Retail	Application to shops, malls, department stores etc.
Schools	Application to schools, colleges, universities etc.

Source: *http://www.usgbc.org/leed/rating-systems*

FIGURE 4.6-10 **LEED CERTIFICATION SCORECARD BREAKDOWN**



The certification levels and the associated credit percentages achieved are shown in Table 4.6-5.

TABLE 4.6-5 **CERTIFICATION LEVELS AND ASSOCIATED PERCENTAGE UNDER LEED**

Certification level / score	Associated percentage (of full credits/points)
Platinum	75%
Gold	56%
Silver	47%
Certified	37%

Once a project is registered, the applicant will have access to the USGBC's LEED Online system. This system provides online templates that must be completed for each prerequisite and credit, and is used to upload supporting documentation. As the project progresses it is important to document necessary data. The LEED Online system also has credit interpretation rulings that provide technical answers to the questions officially submitted by other users. It is important to note that achieving some credits requires that the building be occupied for a certain period of time after construction. Once all of the documentation is assembled and the construction is finished, the documentation is submitted to the GBCI for review and certification. The entire LEED process typically takes anywhere from one to five years, depending on the type and requirements of the desired certification.

The number of credits available and the number of credits needed for each rating level varies with each rating scheme. When evaluating the credits, the cost of achieving each credit must be considered.

4.6.2.4 **GRIHA (INDIA)**

GRIHA, an acronym for Green Rating for Integrated Habitat Assessment, is the National Rating System of India. GRIHA has been conceived by The Energy and Resources Institute (TERI), New Delhi and developed jointly with the Ministry of New and Renewable Energy, Government of India (MNRE). It is a green building 'design evaluation system', and is suitable for all kinds of buildings in different climatic zones of the country. It is a five star rating system for green buildings which emphasises passive solar techniques for optimizing indoor visual and thermal comfort.

The rating applies to new building stock – commercial, institutional, and residential – of varied functions.

GRIHA was developed after a thorough study and understanding of the current internationally accepted green building rating systems and the prevailing building practices in India. The green building rating system devised by TERI and the MNRE is a voluntary scheme. The rating system aims to achieve efficient resource utilization, enhanced resource efficiency, and better quality of life in the buildings.

The system has been developed to help 'design and evaluate' new buildings (buildings that are still at the inception stages). A building is assessed on the basis of its predicted performance over its entire life cycle – inception through operation.

The stages of the life cycle that have been identified for evaluation are:

- Pre-construction stage (intra- and inter-site issues like proximity to public transport, type of soil, kind of land, where the property is located, the flora and fauna on the land before construction activity starts, the natural landscape and land features);
- Building planning and construction stage (issues of resource conservation and reduction in resource demand, resource utilization efficiency, resource recovery and reuse, and provisions for occupant health and well being). The prime resources that are considered in this section are land, water, energy, air, and green cover;
- Building operation and maintenance stage (issues of operation and maintenance of building systems and processes, monitoring and recording of energy consumption, and occupant health and wellbeing, and also issues that affect the global and local environment).

On a broader scale, this system, along with the activities and processes that lead up to it, will benefit the community at large with the improvement of the environment by a reduction in greenhouse gas emissions, a reduction in energy consumption and the use of natural resources.

The GRIHA rating system consists of 34 criteria divided into four categories: site selection and site planning; building planning and construction; building operation and maintenance; and innovation. Eight of these 34 criteria are mandatory; four are partly mandatory, while the rest are optional. Each criterion has a number of points assigned to it. It means that a project intending to meet the criterion would qualify for the points. Different levels of certification (one star to five stars) are awarded, based on the number of points earned. The minimum points/ percentage required for certification is 50.

The evaluation process under GRIHA includes nine distinct steps:

1. Registration;
2. Submission of documentation;
3. Preliminary evaluation by ADaRSH (Association for Development and Research of Sustainable Habitats[52]) technical team;
4. Evaluation by panel of experts;
5. Preliminary rating with comments sent to project team,
6. Final submission of documents;
7. Final evaluation by panel of experts;
8. Approval of rating by advisory committee;
9. Award of rating.

After online submission of documents, the preliminary evaluation is carried out by a team of professionals and experts from ADaRSH. Documentation should be complete in all respects for all criteria attempted. The ADaRSH team reviews the mandatory criteria and rejects the project in the event of non-compliance with such criteria, and then evaluates the optional criteria and estimates the total number of achievable points. All compliance documents are checked and vetted.

The evaluation summary report is sent to members of the evaluation committee for GRIHA comprising renowned experts in each sector, landscape architecture, lighting and HVAC design, renewable energy, water and waste management, and building materials. The evaluation committee members examine the points estimated by the technical team. The evaluation committee then independently reviews the documents for the award of points. The evaluation committee may use the evaluation summary report submitted by the technical team as a guiding document. The evaluation committee awards provisional points and also comments on specific criteria, if required. The evaluation report is sent to the project proponent for review and, if desired, for steps be taken to increase the score. The client is given a period of one month to resubmit the document with the necessary modifications /additions. The resubmitted document comprises only the additional documents / information desired in the evaluation report. The resubmitted documents is again put through the vetting process described above. The evaluation committee then awards the final score. The final score is presented to an advisory committee comprising eminent personalities and renowned professionals in the field for approval and award of rating. The rating is valid for a period of five years from the date of commissioning of the building. ADaRSH reserves the right to undertake a random audit of any criteria for which points have been awarded. Great emphasis is placed on the efficient use and conservation of resources, health, bioclimatic comfort and the protection of living organisms.

52 It is an independent platform for the interaction on scientific and administrative issues related to sustainable habitats in the Indian context. It was founded jointly by MNRE and TERI along with experts in the fields related to sustainability of built environment from across the country.

Table 4.6-6 illustrates the point scoring and subsequent rating under GRIHA.

TABLE 4.6-6 **CERTIFICATION LEVELS AND ASSOCIATED PERCENTAGE UNDER GRIHA**

Certification level / score	Associated percentage (of full credits/points)
5 star	91%
4 star	81%
3 star	71%
2 star	61%
1 star	50%

Source: *GRIHA, The little Book of GRIHA rating - http://www.grihaindia.org/static/Griha%20Rating%20Booklet_Dec12.pdf*

Unique to GRIHA is the requirement that, to achieve any certification level, at least 50% of the full credits must be obtained. Also, for the 5 star certification level 91% of credits is required.

Some of the benefits of a green design according to GRIHA to a building owner, a user, and society as a whole are as follows:

- Reduced energy consumption without sacrificing comfort levels;
- Reduced destruction of natural areas, habitats, and biodiversity, and reduced soil loss from erosion etc.;
- Reduced air and water pollution (with direct health benefits);
- Reduced water consumption;
- Limited waste generation with recycling and reuse;
- Reduced pollution loads;
- Increased user productivity;
- Enhanced image and marketability.

4.6.2.5 GREEN BUILDING RATING IN SOUTH-EAST ASIA - GREEN MARK (SINGAPORE), GBI (MALAYSIA), GREENSHIP (INDONESIA)

The South-East Asian states of Singapore, Malaysia and Indonesia have developed their own GBRS. The impulse for developing a new rating system in each of the countries mainly came from the understanding that none of the GBRS available internationally would address the unique climatic conditions as well as the socio-economic dynamics well enough. The understanding of the market and revenue potential of each system perhaps contributed to the independent development, despite the similarity of many climatic and socio-economic/developmental features in the three countries. Developed in 2005, the BCA Greenmark Scheme[53] is an initiative by the Government of Singapore to drive the country's construction towards more environmentally friendly buildings. It was developed to promote sustainability in the built environment as well as to raise environmental awareness during the design and construction period of buildings. Greenmark is one of the few GBRS that is designed for tropical climates and that is a government (and not a private sector) initiative.

The Green Building Index (GBI)[54] was developed in 2009 and is Malaysia's industry recognised rating tool for green buildings. GBI is also designed specifically for tropical climates. However, it also considers the country's current state of socio-economic and urban infrastructure development and its unique dynamics, and is hence different to, for instance, LEED and BREEAM. GBI parameters are within the tropical climatic conditions. Its scoring priorities are very much customized for Malaysia, where priority is given to energy and water efficiency scores.

GREENSHIP[55] is the rating system set to assist in promoting a greener built environment in Indonesia and was developed by the Green Building Council of Indonesia. GREENSHIP uses a rating system that is based on other rating systems around the world, but it incorporates characteristics unique to Indonesia. It promotes sustainability in planning, implementation and operation of buildings.

The Green Mark approach includes a pre-assessment process that is distinct from the assessment process itself, in order to give the project team a better understanding of the Green Marks requirements.

In order to maintain their status, certified buildings need to be re-assessed every three years.

Rating schemes include:

- New buildings;
- Rental;
- Existing buildings;
- Schools;
- Office interior;
- Restaurants;
- Districts and infrastructure.

Benefits of BCA Green Mark include:

- Reduction in water and energy bills;

53 *www.bca.gov.sg*
54 *www.greenbuildingindex.org*
55 *http://www.gbcindonesia.org*

- Reduction of potential environmental impact;
- Improvement of indoor environmental quality for a healthy and productive workplace;
- Provision of clear direction for continual improvement.

Green mark is also designed for requirements to be met in tropical climates.

The Green Building Index (Malaysia) currently features two rating schemes:

1. Non-residential;
2. Residential.

There are 6 main categories within GBI to assess non-residential and residential properties. These are energy efficiency, indoor environment quality, sustainable site planning and management, materials and resources, water efficiency and innovation.

The GBI Non-Residential rating scheme evaluates the sustainable aspects of buildings that are commercial, institutional and industrial in nature. This includes factories, offices, hospitals, universities, colleges, hotels and shopping complexes (all in one scheme).

Of the six criteria that make up the GBI rating, emphasis is placed on energy efficiency and indoor environmental quality as these have the greatest impact in the areas of energy use and well-being of the occupants and users of the building. By improving the efficiency of active (mechanical and electrical) systems as well as incorporating good passive designs together with proper sustainable maintenance regimes, significant reductions in energy consumption can be realised. Subsequently, the carbon footprint will also be reduced and long-term savings will also be realised for the building owners.

The GBI Residential rating scheme evaluates the sustainable aspects of residential buildings. This includes linked houses, apartments, condominiums, townhouses, semi-detached houses and bungalows. This tool places more emphasis on sustainable site planning and management, followed by energy efficiency. This serves to encourage developers and home owners to consider the environmental quality of homes for their inhabitants through better site selection, provision of access to public transport, increased community services and connectivity, as well as improved infrastructure. These measures are intended to reduce the negative impact on the environment and to create a better and safer place for residents and the community as a whole.

The Green Building Index has been specifically created to meet requirements in tropical climates. Table 4.6-7 provides an overview of the certification levels under GBI.

TABLE 4.6-7 **CERTIFICATION LEVELS AND ASSOCIATED PERCENTAGE UNDER GBI**

Certification level / score	Associated percentage (of full credits/points)
Platinum	86%
Gold	76%
Silver	66%
Certified	50%

GREENSHIP was launched by the Green Building Council of Indonesia (GBCI) in 2010. It was developed with the wide participation of stakeholders and under national consensus.

There are three rating schemes: New Buildings, Existing Buildings and Interior Spaces. Additionally, the following rating schemes are currently under development: Neighbourhood, Manufacturing, Natural Ventilation and Power Plant.

There are seven main rating categories in GREENSHIP, including:

- Appropriate site development;
- Energy efficiency and conservation;
- Water conservation;
- Material resources and cycle;
- Indoor air, health and comfort;
- Building environment management.

GREENSHIP, in that respect, has some similarities to GBI Malaysia, discussed above.

There are a total of 45 criteria and 101 points are distributed among them (Existing Buildings).

Criteria include issues like site landscaping, micro climate, electrical sub-metering, water metering, refrigerants, environmental tobacco smoke, thermal comfort, submission of green building data for database, etc.

GREENSHIP makes explicit reference to the Indonesian context, for instance:

- It refers to local regulations through the requirements under “basic green area”;
- It sets the requirement to use only indigenous plants under “site landscaping”;
- It requires rain water harvesting and the collection of condensate water under “alternative water sources”;
- It also sets as rating criteria the collection and submission of data into the green building database of Indonesia.

Table 4.6-8 provides an overview of the certification levels under GREENSHIP.

TABLE 4.6-8 **CERTIFICATION LEVELS AND ASSOCIATED PERCENTAGE UNDER GREENSHIP**

Certification level / score	Associated percentage (of full credits/points)
Platinum	73%
Gold	57%
Silver	46%
Bronze	35%

05 DESIGN AT COMMUNITY SCALE

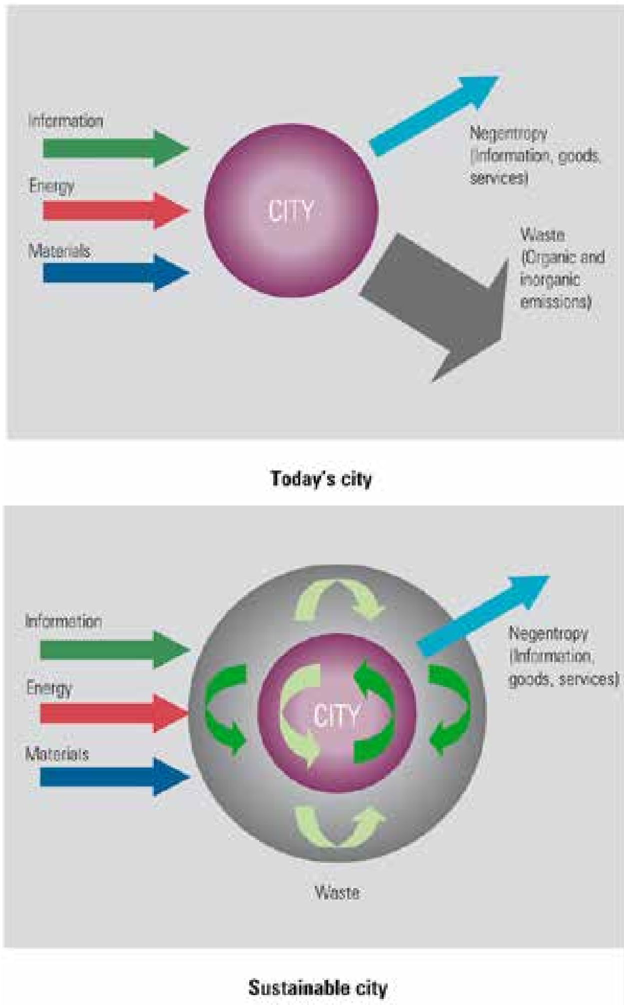
5.1 ENERGY AND THE URBAN METABOLISM

An effective metaphor that is sometimes used is that the city is a living system, and as such is provided with its own metabolism[56]. The inputs of a city – energy, raw materials, goods and information – are metabolised and transformed, by means of technological and biological systems, into wastes and neg-entropy (negative entropy: information, goods, services) i.e. the city's outputs (Fig. 5.1-1)[57].

The direct impact of the life of a city on climate change is primarily due to the production of CO_2 from the combustion of fossil fuels[58], i.e. from the energy system. The energy system of a city can be seen as a thermodynamic system in which high grade energy (exergy) is transformed into low grade energy. This process allows the urban metabolism to run, by means of thermodynamic transformations that take place at all levels, individual devices such as domestic appliances, systems for heating and cooling buildings, cars, etc. Like any thermodynamic system, the urban energy system can be more or less efficient, i.e. can require more or less high grade energy to perform its tasks: the efficiency of the earliest power plants was less than 10%, nowadays it is well above 50%. The present urban thermodynamic system is very inefficient, as inefficient as power plants were two centuries ago, and for this reason we waste a very large amount of the high grade energy, or exergy that is contained in fossil fuels – as well as in solar radiation, in wind, in water heads, in biomass.

An environmentally successful – i.e. sustainable – city should be characterised by a successful economy combined with social equity and minimum waste production (including GHG gases).

FIGURE 5.1-1 **URBAN METABOLISM**



***(Source:** UN-Habitat - State of the World's Cities 2008/2009 - Harmonious Cities, Earthscan, 2008)*

In order to minimise waste two prerequisites must be fulfilled: i) minimisation of inputs of fossil fuels and materials; ii) maximisation of recycling and reuse of energy, water and materials.

56 *L. M. A. Bettencourt, J. Lobo, D. Helbing, C. Kühnert, G. B. West, Growth, innovation, scaling, and the pace of life in cities, Proc. National Academy of Sciences, vol 104, no. 17, 7301-7306*

57 *tF. Butera, Urban Development as a Guided Self-Organisation Process, in C. S. Bertuglia, G. Bianchi, A. Mela (eds.) "The City and its Sciences", Physica-Verlag, Heidelberg, 1998*

58 *There is also an in direct impact, due to the GHG emissions caused by the production that takes place elsewhere – of the materials and goods that enter the city.*

To fulfil these prerequisites, the urban metabolism must be a circular metabolism, not the linear one that has characterised urban development since the beginning of the industrial revolution.

The need for sustainable urban development requires a shift from the linear to a circular metabolism and, in order to guide this transformation, it is necessary to analyse and understand present processes and their final aims, and replace them with new ones.

5.1.1 DESIGNING A LOW ENERGY DEVELOPMENT

To design a renewable built environment means, first of all, maximising its thermodynamic efficiency, i.e. minimising the amount of exergy that is used or, as it is more commonly expressed, the amount of primary energy consumed. Only after this has been done is it conceivable that a settlement will run mainly on renewable energy sources.

Thus, in low energy urban design, the main aim is to minimise primary energy consumption, more than two thirds of which is currently due to the residential, commercial and transport sectors. The fulfilment of this aim involves a combination of several actions i.e.:

- optimise the energy efficiency of the urban structure;
- minimise the energy demand of buildings;
- maximise the efficiency of energy supply;
- maximise the share of renewable energy sources.

This list, however, is not exhaustive, since the entire urban metabolism is based on energy or linked to it; so other actions must be taken into consideration, involving water, waste and mobility, i.e.:

- minimise primary water consumption and exploit the energy potential of sewage water;
- minimise the volume of waste being generated and sent for disposal, and use the energy content of waste;
- minimise transport needs and optimise transport systems;
- minimise the primary energy consumption of the means of transport;
- maximise the use of energy from renewable sources in transport.

The aim is to increase the energy efficiency of the urban structure, of individual buildings, of mobility and of energy supply systems and furthermore to maximise the proportion of energy from clean and renewable sources.

5.1.1.1 OPTIMISE THE ENERGY EFFICIENCY OF THE URBAN STRUCTURE

The manner in which the different functions of a settlement are distributed has a great impact on energy consumption, for several reasons. The first, most obvious, is that if the three main functions, i.e. work, leisure and living, are not closely integrated, the need for transportation is greatly increased.

Another important advantage of compact mixed-use developments is that they allow energy and power to be shared between activities in a more efficient way, taking into account their use at different times, thus smoothing out power peaks.

5.1.1.2 MINIMISE THE ENERGY DEMANDS OF BUILDINGS

Building design has the second greatest impact on long-term energy consumption after urban design and new buildings should therefore have the best possible energy performance.

Envelopes for low energy buildings

In recent years the use of air conditioning has begun to create concern because of its rapid growth all over the world and the consequent increase in energy consumption.

Appropriate building shape and orientation, internal layout, the position of openings and sun shielding can improve ventilation in mid seasons and reduce the need for air conditioning in the hottest periods (see Chapter 3 and 4). Naturally, the implementation of most of these features is possible or made easier if the layout of urban settings has been properly configured.

5.1.1.3 MAXIMISE EFFICIENCY OF ENERGY SUPPLY

Once the demand for energy has been minimized, with appropriate urban and building design, it is time to evaluate the use of the most energy efficient technologies for providing heating and cooling, hot water production, lighting, etc. (see Chapter 4).

5.1.1.4 MAXIMISE THE SHARE OF ENERGY FROM RENEWABLE SOURCES

As energy consumption is minimised with appropriate technological systems, renewable energy can play a significant role in the energy balance of an urban settlement. There are many technologies available and already being used.

Biomass

Wood biomass can be used for supplying CHP power plants directly (as pellets or wood-chips) or after gasification (see paragraph 6.4). These practices are being applied more and more frequently.

There are now many biomass CHP plants all over Europe ranging from the 37 MWe CHP plant in the Swedish town of Växjö (52,000 inhabitants) supplying 35% of the electricity and 95% of the heat needed[59], to the 1.1 MWe CHP plant in the alpine town of Tirano, Italy, supplying heat and electricity to 6,900 inhabitants.

Generally, wood biomass is chipped and burnt in boilers to produce steam supplying one or more turbines coupled with generators. Some CHP systems use, instead, internal combustion engines fuelled with gas produced by a biomass gasification plant.

The Sterling engine is used in smaller (down to 10 kW) biomass fuelled CHP units that are being developed for multifamily housing.

These examples can be adapted to tropical countries, by using the waste heat for the production of hot water cooling, instead of heating, at district scale.

The popularity of biofuels is growing, mainly in cars as a substitute for or as an additive to gasoline or diesel oil; more recently, small internal combustion CHP units running on biofuels are also becoming available.

Solar energy

The most immediate and cost effective use of solar energy is for hot water production.

Solar thermal systems equipped with evacuated tubes are also suitable for solar cooling, either by means of absorption and adsorption chillers or coupled to desiccant cooling systems[60] (see paragraph 6.2).

Solar energy can be used either for DHW production or for cooling, complementing the heat produced with CHP systems, helping to balance the mismatch occurring between the electricity and cooling demand of buildings and electricity and cooling supply systems.

Photovoltaic systems, in a low energy consumption settlement, are best used when integrated in the buildings' envelopes. In the near future, when PV systems will be competitive with fossil fuels for electricity production, they will be the main actors in the energy system of a low energy urban settlement, also providing electricity for cooling, coupled with heat pumps.

Wind energy

Wind power is not available everywhere, but in coastal areas is often significant enough to make the installation of wind turbines cost effective. Hills and ridges are also suitable locations. Offshore wind farms are becoming attractive options, due to technological improvements and the lowering of costs; besides being capable of harvesting higher speed winds, these plants have the advantage of reducing the problem of the visual impact, which often prevents or slows down the development of wind power.

Not only are large wind turbines to be taken into consideration, small wind generators, on either a horizontal or vertical axis, are also an option (see paragraph 6.3). Even if their cost-effectiveness is lower than that of the large ones, from the above mentioned perspective of rising fossil fuel costs, they are a viable option and could make a considerable contribution to the energy balance of the settlement, due to the large number that could be installed on roofs, and integrated into the urban landscape.

Mini hydro power

Mini-hydro potential, including one deriving from the water supply, is still largely unexploited, especially in developing countries; this water often collects in springs or basins up in the mountains and is delivered to the settlement's lower level via forced conduits. The pressure available at the bottom can be exploited by means of water turbines.

Energy storage

The more CHP and renewable energy sources are used in the energy system the more storage technologies become crucial. Thermal storage is relatively easy: it can be a more or less large and well insulated tank containing water, or ice. Phase change materials, capable of storing more heat per unit volume than water, can also be used.

It is not so easy to store electricity. The most common technology in use is the battery. In the last few years, some new types of battery have been developed, with higher storage density. Pumped hydro and compressed air, which are used by energy utilities, are also well established means of storing electricity.

Other technologies, however, are close to coming on the market, such as supercapacitors, superconductive coils and flywheels[61]. Hydrogen is another storage medium; electricity is used to produce it from water (hydrolysis) and then part of this electricity is recovered by using the gas to supply a fuel cell. This system is by far the least efficient for electricity storage[62] (Table 5.1-1).

Small scale advanced batteries, supercapacitors, flywheels, and compressed air will be an intrinsic part of a low energy system, relying heavily on renewables.

59 *Energie-cités, Biomass CHP – Växjö, http://www.energie-cites.org/db/vaxjo_139_en.pdf*

60 *IEA Task 25, Solar Assisted Air Conditioning of Buildings, http://www.iea-shc-task25.org/*

61 *D. U. Sauer, The demand for energy storage in regenerative energy systems, First International Renewable Energy Storage Conference (IRES I), Gelsenkirchen, October, 30th/31st 2006*

62 *U. Bossel, Physics and Economy of Energy Storage, First International Renewable Energy Storage Conference (IRES I), Gelsenkirchen, October, 30th/31st 2006*

TABLE 5.1-1 **ENERGY STORAGE TRANSFER LOSSES [%]**

Super capacitors	10
Lithium-ion batteries	14
Lead-acid batteries	23
Pumped water	28
Compressed air	36
Compressed hydrogen	68
Liquefied hydrogen	75

Wastewater and solid wastes

Recycling wastewater and solid wastes and using them as energy sources, is essential in an energy efficient city.

Solid waste incineration, after selection and pre-treatment, supplying a CHP plant can make a significant contribution to the energy balance of the city.

An alternative to the incineration of wastes is their gasification, producing syngas. Such gas can be used both to supply a CHP unit and can be distributed for use in cooking.

5.1.2 URBAN MOBILITY

Transport is a major factor contributing to energy consumption directly and indirectly. Urban noise, for example, comes mainly from road traffic (80%) and causes higher energy consumption for air conditioning, given that it forces people to keep windows closed, impairing natural ventilation.

In recent years the use of energy for transport has been rising rapidly. Forty years ago, in most developed economies, the proportion of total energy use for transport was between 15% and 20%. Today it is around 35% of world energy consumption and is still rising[63] (according to Exxon forecasts[64], the global demand for liquid fuels for transportation will have risen by 35% by 2030, mainly due to the development of motorised transport in developing countries). The highest CO_2 emissions per capita for passenger transport are in the USA, with 4.4 tons per person: four times higher than in Europe[65].

In EU-25, CO_2 emissions for road transport account for 22%[66] of the total, nearly half of which is due to urban mobility[67]. This share will grow because of the progressive reduction in energy consumption of the building sector, as a consequence of the new, tighter, energy standards.

If the present trend continues, private vehicles will be the biggest cause of CO_2 emissions in urban settlements, as they are already in cities where, because of the mild climate, the energy consumption of buildings is relatively low and where there are no energy intensive industrial activities (Fig. 5.1-2).

Technological improvements in the efficiency of present vehicles can change the picture only marginally; a radical change is needed if we are to tackle the problem of the impact of mobility on global warming.

It is easy to see the path to follow, at least in Europe, if a few data are considered. Today, approximately 75 % of the EU population live in urban areas (this will be 80% in 2020)[68]; on average a European citizen makes 1000 trips per year and half of these are less than 5 km long[69]. For many of these shorter trips walking or cycling could be a viable alternative. Even if public transport is available, the car is by far the dominant urban mode of transport, contributing about 75% of the kilometres travelled in EU conurbations. Cars cause so much congestion that, in some European cities, average traffic speeds at peak times are lower than in the days of the horse-drawn carriage.

Present mobility, based on private cars, whose average efficiency (useful work done/primary energy used) is lower than 15%, usually carrying a single person (i.e. spending energy to push more than one ton to move 70 kilos), is incompatible with energy sustainable urban development. Already a dwelling designed according to the new energy standards produces less CO_2 every year than an average car travelling 12,000 km in the city. The number of circulating vehicles must drastically decrease. A completely different urban form of mobility must be developed, i.e. a new generation of cars used in a new way.

63 S. Potter, Transport Energy and Emissions: Urban Public Transport, http://oro.open.ac.uk/4378/01/PT_Energy_and_Emissions.pdf

64 Exxonmobil, The Outlook for Energy – a View to 2030, http://www.exxonmobil.com/corporate/files/corporate/energy_outlook_2006_notes.pdf

65 J.R. Kenworthy Transport Energy Use and Greenhouse Gases in Urban Passenger Transport Systems: A Study of 84 Global Cities, Third Conference of the Regional Government Network for Sustainable Development, Fremantle, Western Australia, 2003, http://www.sustainability.murdoch.edu.au/

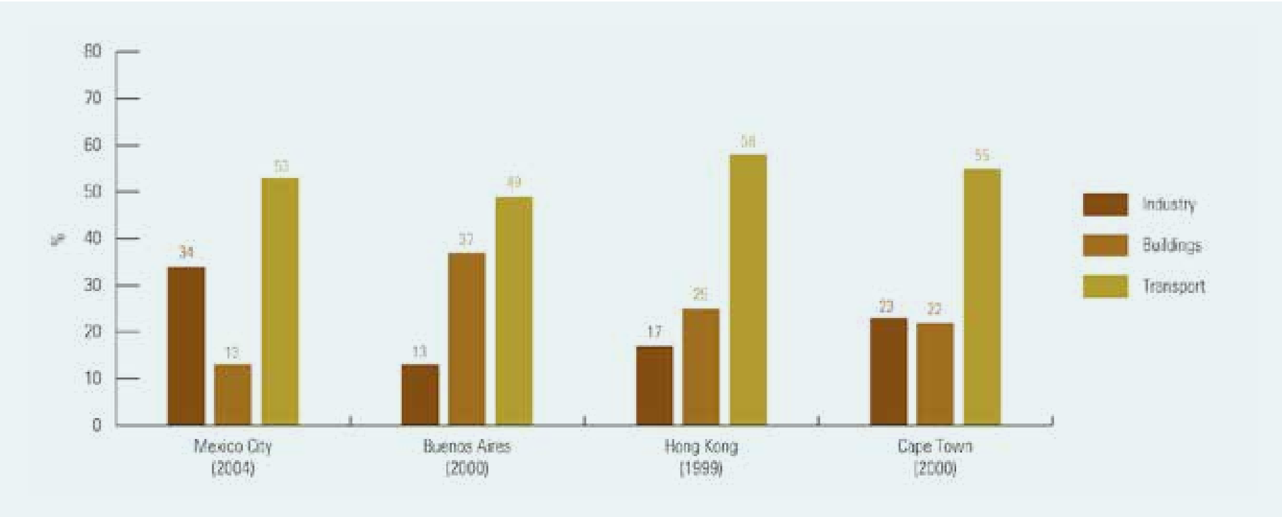
66 European Commission, DG Energy and Transport, Energy and Transport Figures, 2006, http://ec.europa.eu/dgs/energy_transport/figures/pocketbook/doc/2006/2006_energy_en.pdf

67 European Commission, DG Energy and Transport, Clean Urban Transport, 2007, http://ec.europa.eu/transport/clean/index_en.htm

68 R. Uhel (ed.), Urban sprawl in Europe – The ignored challenge, European Environment Agency, Copenhagen, 2006, http://reports.eea.europa.eu/eea_report_2006_10/en/eea_report_10_2006.pdf

69 R. Uhel (ed.), Urban sprawl in Europe – The ignored challenge, European Environment Agency, Copenhagen, 2006, http://reports.eea.europa.eu/eea_report_2006_10/en/eea_report_10_2006.pdf

FIGURE 5.1-2 **ENERGY CONSUMPTION BY SECTOR IN HOT/WARM CLIMATE**



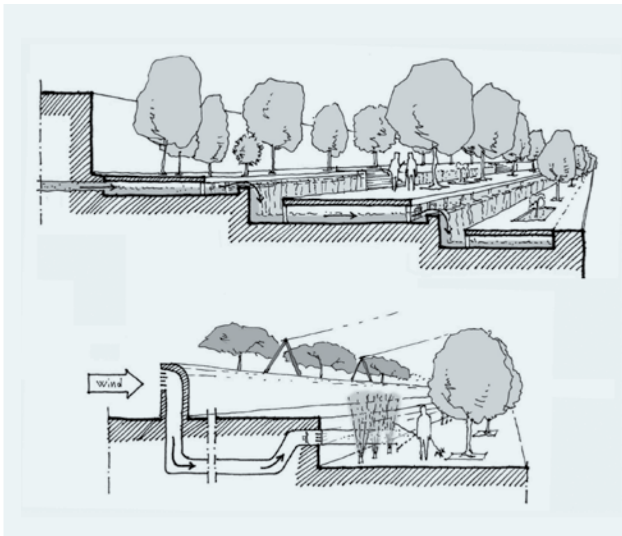
Source: *UN-Habitat - State of the World's Cities 2008/2009 - Harmonious Cities, Earthscan, 2008*

5.1.2.1 **MITIGATED ENVIRONMENT PATHS**

It is important to give planning priority to pedestrians and cyclists. The aim is to maximise the attractiveness and usability of walking and cycling as alternatives to motorised transport. The goal should be a dense, high-quality, supply-oriented infrastructure network for pedestrians and cyclists.

The main problem connected to walking and cycling is comfort, when it is too cold or too hot or when it is raining. There are means, however, for improving the comfort of outdoor spaces, by mitigating environmental conditions. Arcades providing shelter from rain, wind and sun were very common in the past. For cyclists other kinds of sheltered paths could be created.. Green shading can be developed and, in dry hot climates, water can be used in many ways, as demonstrated in the EXPO 92 in Seville (Fig. 5.1-3). This is possible with very limited energy consumption and by using purified water from wastewater treatment plants. In this way, walking and cycling could be enhanced by creating a grid of mitigated environment paths that are cool and shaded. Even if some energy is needed, it will be far less than that used by the cars that are substituted.

FIGURE 5.1-3 **OUTDOOR CLIMATE MITIGATION CIEMAT, MADRID, 1992)**



Adapted from: *S. A. Alvarez et al., Control Climatico en Espacios Abiertos – Projecto EXPO '92, Secretaria General Tecnica del*

5.1.2.2 **INDIVIDUAL MOTORISED TRAVEL**

It is not only public transport that should be promoted. Advanced means of mobility can also be envisaged. Car sharing now takes advantage of GPS technologies and the internet.

An improved car technology, already on the market, is the so-called "plug-in hybrid", a hybrid car with an improved battery. A plug-in hybrid car, with its 35 km range as an electric car, is capable of meeting all the mobility needs of an average citizen. If, moreover, the engine is powered with biofuels, it is easy to reach the objective of a car running only on renewables. Hybrid cars are a transition technology, since low energy urban mobility should be based on electric cars especially designed for the urban context in which they have to work.

With an urban mobility based on a more or less advanced car sharing scheme it is possible to implement a transport system powered only with renewable energy, where batteries are charged by mini wind turbines, where suitable, or dedicated PV systems integrated into buildings.

Before the Soviet collapse, Cuba imported most of its needs. It exported sugar and tobacco to the Soviet Union at agreed premium prices, and received oil in return, some of which was re-exported. This set-up created distorting incentives for large swathes of land to be given over to export crops grown in industrial monocultures, heavily dependent on oil-based inputs. Just before the collapse, in 1989, three times more land was dedicated to sugar than to growing food.

Then oil imports dropped by over half, crippling the economy and slashing foreign-exchange earnings from the re-export trade. The use of chemical pesticides and fertilisers dropped by 80 per cent, sounding a death knell to industrialised farming. The knock-on effect on people's daily lives was dramatic. The availability of basic food staples, such as wheat and other grains, fell by half. The average Cuban's calorie intake fell by over one-third in around five years, leading to an average weight loss of 20 pounds per person.

But in contrast to the situation that many countries find themselves in today, Cuba was in a position to respond. Serious and long-term investment in science, engineering, health and education meant the country had developed human resources, a strong social fabric and the capacity to act. Before the 'oil shock', Cuba was already investigating forms of ecological farming far less dependent on fossil fuels. When the shock came, a system of regional research institutes, training centres and extension services was quickly put in place to support farmers.

Drawing on these strengths, the threat of serious food shortages was overcome within five years. At the heart of the transition after 1990 was a rapid shift to the use of biofertilisers and biopesticides, crop rotation and intercropping, and the use of animal labour and manure. In other words: a largely organic system. The success of small farms and of urban farms and gardens was also an important factor.

Shortages and rising food prices made urban farming into a very profitable activity. It also proved highly productive. Once the state backed the urban farming movement, it grew rapidly. Lots of backyards in Cuban cities became home to food crops and farm animals – grown and reared almost exclusively along organic lines. Half the food consumed in the capital, Havana, is grown in the city's own gardens. Urban gardens provide 60 per cent of the vegetables eaten in Cuba.

Source: *The Green New Deal Group, A Green New Deal, new economic foundation, 2008 - http://dnwssx4l7gl7s.cloudfront.net/nefoundation/default/page/-/files/A_Green_New_Deal_1.pdf*

5.1.3 URBAN GARDENS

Cities rarely produce food, and their supply of agricultural products normally comes from the rural hinterland and from the international market. This implies much energy use for transportation, as well as for cooling and storing of food. Moreover, much of this energy is wasted because of the production losses and food waste.

With the increase in urban population, more food will need to be produced and supplied from the hinterland. A seven- fold increase in food production will be needed to feed the projected population of 9 billion in 2050; this will demand higher usage of energy and land resources in an era where the existing usage already has adverse impacts on the environment and agricultural land is continuously lost through urban sprawl[70].

Urban authorities can act against the reduction of agricultural land by controlling urban density and actively pursuing the reduction of food waste at the consumer and retailer end with policy measures such as awareness campaigns and charges for food waste. Promoting urban agriculture has proved to be another successful tool in addressing food shortages.

70 *UN-Habitat, Sustainable Urban Energy: a sourcebook for Asia, 2012 - http://www.unhabitat.org/downloads/docs/11115_1_594431.pdf*

5.2 WATER AND SANITATION

Water is essential for the environment, food security and sustainable development. All the known civilizations flourished as long as their water sources also flourished and this is true in the present context too. Availability of drinking water and provision of sanitation facilities are the basic minimum requirements for healthy living. Water supply and sanitation, the two most important urban services, have wide ranging impacts on human health, quality of life, environment and productivity.

Water and energy are related. Water is used in the production of energy and energy is used to pump, treat and distribute water. As the population grows, so does the demand for water, and more and more energy is required.

The reliability and regularity of the water supply in low-income countries is a big problem, with poor quality water and a high price when bought from street vendors; on the sanitation front, shared toilets and pit latrines are inadequate and poorly maintained in urban areas[71].

Despite technological advances, the global scenario still remains grim, as not all the inhabitants of the world have access to safe water and adequate sanitation.

71 *UN-Habitat, Sustainable Urban Energy: A Sourcebook for Asia, 2012 - http://www.unhabitat.org/downloads/docs/11115_1_594431.pdf*

In most urban areas, the population is increasing rapidly and supplying adequate water to meet societal needs and ensuring equal access to water are the most urgent and significant challenges facing policy-makers.

As a consequence of rapid population growth, combined with industrialisation, urbanisation, intensification of agriculture and water intensive lifestyles a global water crisis has developed, exacerbated by climate change: water-related natural disasters, such as flooding, drought, and landslides, are more frequent and more severe; rising temperatures, causing increased evaporation and glacial melt, are reducing the reliability and quality of water supplies.

Problems related to falling water tables are widespread and cause serious damage, because they lead to both water shortages and, in coastal areas, to salt intrusion. Both contamination of drinking water and nitrate and heavy metal pollution of rivers, lakes and reservoirs are common problems throughout the world.

Water loss refers to the total amount of water lost through leakage in distribution networks. A conservative estimate for this has been placed at around 35 per cent of the total water supplied. For some low-income countries this loss may be as high as 80 per cent[1].

This problem demands immediate attention and appropriate action to reduce avoidable stress on vital water resources. Numerous cities across the globe have already implemented programmes geared towards the step-by-step reduction of water loss and many water suppliers have developed effective strategies and applied technologies to control leakage and water loss.

5.2.1 WATER SOURCES

Rainwater is a free source of nearly pure water and rainwater harvesting is the collection and storage of rainwater and other activities aimed at harvesting surface and ground water. It also includes prevention of losses through evaporation and seepage and all other hydrological and engineering interventions, aimed at conservation and efficient utilisation of the limited water endowment of physiographic unit such as a watershed. In general, water harvesting is the direct collection of rainwater. The rainwater collected can be stored for direct use or can be recharged into the ground water. Rain is the first form of water that we see in the hydrological cycle, hence is a primary source of water for us.

Rivers, lakes and ground water are all secondary sources of water. At the present time, we depend entirely on such secondary sources of water. In the process, generally, it is forgotten that rain is the ultimate source that feeds all these secondary sources. Water harvesting means making optimum use of rainwater at the place where it falls so as to attain self-sufficiency in water supply, without being dependent on remote water sources.

Groundwater refers to the water available underground in aquifers, and accessed by wells or boreholes.

5.2.2 IMPORTANCE OF WATER CONSERVATION

Increased demand and the depletion of resources make water conservation an essential part of an efficient water management system, along with strategies for efficient reuse of water.

To that end the following three issues have to be considered: rainwater harvesting, water recycling and water conservation. For example rainwater can be stored in the earth or in cisterns for domestic use; grey and black water treated on-site can be reused; technologies for conserving water used for irrigation and domestic use can be implemented. Water efficiency measures also include reduction in losses and in overall water use.

The recommended measures for water reuse and water conservation can be summarized as follows:

- reduce the amount of potable water used for non-potable applications;
- install dual plumbing lines for the use of treated waste water for flushing applications. The treated water, which should meet the local pollution control board standards, can also be used for lawn watering;
- harvest rainwater;
- use rainwater harvested from the roof or from the site for irrigation, to whatever extent possible.

Recycling of water is another important aspect of water conservation. One way of recycling is by using aquatic plants. Raw sewage is recycled using aquatic plants (such as duckweed, water hyacinth, etc.) to produce clean water suitable for re-use in irrigation and industry.

5.2.3 DRAINAGE

Conventional drainage methods usually involve transporting water as quickly as possible to a drainage point, either by storm-water drainage or a sewer. If drainage is planned with more emphasis on sustainability, it is possible to benefit from on-site infiltrations. This system permits the accumulation and flow of water into the drainage points to be slowed down, resulting in a more stable ecosystem as the water level and the water flow speed in the watercourse is more stable, and hence less erosion will take place. The best strategy should be to slow down the drainage and then clean the water by a natural system, before discharging it into a watercourse.

Drainage can be slowed down using swales, soak-ways, holding ponds and by having more pervious surfaces.

Pervious surfaces should be encouraged on site in the form of pavements and parking which allow rainwater to seep through them. Pervious surfaces such as gravel or other open-textured materials are only suitable for pedestrian or light-weight traffic, such as walkways and personal driveways, but they are very easy to implement and inexpensive compared to other methods. A combination of different types of pervious surfaces such as large or small paving blocks should be used.

Large blocks have large holes that are filled with soil, and allow grass to grow in them.

The surface is only suitable for foot traffic or occasional cars but has an aesthetic benefit due to the mostly grassy surface. Small blocks are impervious blocks that fit together in such a way so as to leave small openings in the joints between the blocks, allowing water to flow through. These blocks can take more and heavier traffic than large element blocks.

Well planned roadways, parking lots, or walkways, with compact circulation patterns, could minimize pavement costs, centralize run-off, and improve efficiency of movement. This would help to reduce the ratio of impermeable surfaces to the gross site area.

The net run-off from a site should be restricted to a maximum of 60%. If the site hydrogeology does not allow the run-off factor to be 0.6, measures should be taken to allow the collection of run-off in soak pits or collection pits so that the net run-off from the site is not more than 60%.

TABLE 5.2-1 **RUN-OFF COEFFICIENT FOR VARIOUS SURFACES**

Surface type	Run-off coefficient
Roofs conventional	0.7 – 0.95
Concrete	0.95
Gravel	0.75
Brick paving	0.85
Vegetation	
Slope:	
1-3%	0.2
3-10%	0.25
>10%	0.3
Turf	
Slope:	
0-1%	0.25
1-3%	0.35
3-10%	0.4
>10%	0.45

Source: *UNEP, Eco-housing Guidelines for Tropical Regions, 2006 - http://www.rrcap.ait.asia/ecohouse/2005-08/ecohouse%20 guidelines_261106_for%20review.pdf*

The run-off from construction areas and material storage sites should be collected or diverted so that pollutants do not mix with storm water runoff from undisturbed areas.

Temporary drainage channels, perimeter dykes etc. should be constructed to carry the polluted water directly to municipal drains.

5.2.4 BUILDING DESIGN STRATEGIES FOR REDUCING WATER CONSUMPTION

The design and management of communities and buildings can make an important contribution to water conservation.

The recommended guidelines for efficient management of water can be summarized as follows:

- prepare a water balance for the site;
- fix norms for water quality from various sources as per the specified local standards for different applications;

- use efficient fixtures that distribute water at the desired pressure and avoid wastage and losses;
- ensure regular monitoring of both consumption patterns and quality;
- perform regular checks on plumbing systems to check for leakages, wastages, and system degradation; plant native species and trees with minimal water requirements;
- use mulches and compost for improving moisture retention in soil;
- encourage rainwater harvesting and storage/recharge for capturing good quality water.

5.2.4.1 EFFICIENT TOILETS AND DEVICES FOR OTHER USES

Several devices are available for water conservation in buildings. The following innovations are examples of this:

- ultra low-flow flush toilets (flow rate of 3 litres per flush);
- water-efficient urinals and waterless urinals;
- faucet aerators;
- low-flow shower heads (flow rate of 9.0 litres per minute);
- electronic flush systems;
- sensor taps for urinals;
- efficient water taps;
- auto-control valves;
- pressure-reducing device;
- efficient shower heads.

The potential for water conservation can be easily understood when we take into account the fact that conventional toilets use 13.5 litres of water per flush, while low-flush toilets are available with a flow rate of 6 litres of water per flush and ultra low flush toilets with a flow rate of 3 litres of water per flush (earlier, the problem was that the old bowls of WCs - western commodes - did not flush the contents properly with 6.2 litres of water per flush; however, the design of the bowl has now been modified and it has been elongated to facilitate cleansing at a low flow rate).

Dual flush adapters can be used for standard flushing for solids and a modified smaller flush for liquids. This can result in a saving of 2.2– 4.5 litres per flush[72].

72 Water can also be saved by installing waterless toilets. This is possible by using either a composting or an incinerating mechanism. Composting toilets are based on the principle of biological treatment of the human waste resulting in a valuable product that can be used as a soil conditioner.

It has to be stressed that the benefits of adopting these devices are not only related to water conservation but also to other savings (i.e. energy, chemicals, space etc.) related to waste water treatments.

5.2.5 RAINWATER HARVESTING AND USES

Two physical solutions for sustainable management of freshwater are:

- finding alternative or additional water resources using conventional centralised approaches;
- utilising the limited amount of water resources available in a more efficient way.

To date, much attention has been paid to the first option and only limited attention has been paid to optimising water management systems. Among the various technologies to augment freshwater resources, rainwater harvesting and utilisation is a decentralised, environmentally sound solution, which can avoid many of the environmental problems often caused by conventional large-scale projects using centralised approaches.

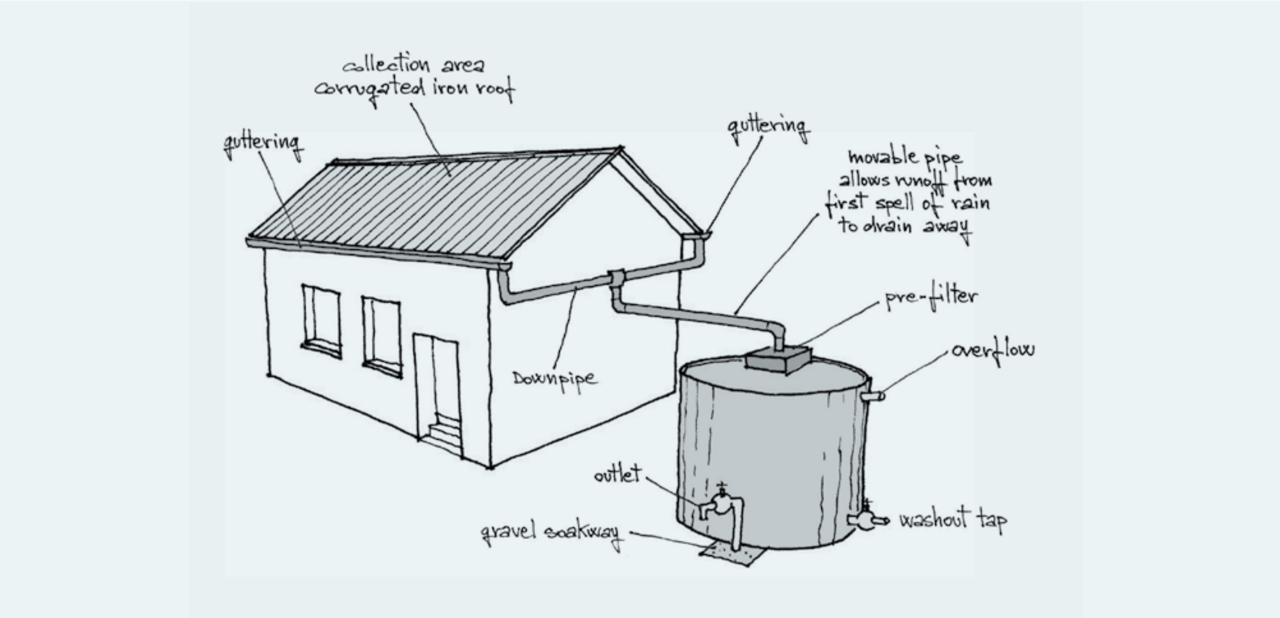
Rainwater harvesting in buildings has been practised for more than 4,000 years and, in its broadest sense, is a technology used for collecting and storing rainwater for human use from roofs, land surfaces or rock catchments using simple techniques such as jars and pots as well as engineered techniques. The application of appropriate rainwater harvesting technology is important for the utilisation of rainwater as a water resource especially where it is the only source of drinking water.

Appropriate precautions should be taken to prevent contamination of stored water. Mesh filters should be provided at the mouths of drain pipes to prevent leaves and debris from entering the system. If stored water is to be used for drinking, a sand filter should also be installed.

Underground masonry/reinforced cement or concrete tanks, or above ground PVC tanks can be used for storage of rainwater. Each tank must have an overflow system connected to the drainage/recharge system (Fig. 5.2-1).

Rainwater collected from roof is free of mineral pollutants like fluoride and calcium salt but is likely to be contaminated by air and surface pollutants. All these contaminant can be largely avoided by flushing off the first 10-20 minutes of rainfall. Water quality improves over time during storage in the tank as impurities settle if the water is not disturbed. Even pathogenic organisms gradually die out due to storage. Additionally, biological contamination can be removed by other means.

FIGURE 5.2-1 **RAINWATER HARVESTING SYSTEM**



5.2.5.1 SIZING THE RAINWATER STORAGE TANK

The amount of rainwater that can be collected monthly can be calculated according to the equation:

$$W_{ry} = A_c \times e \times h_N \times \eta \quad (5.2\text{-}1)$$

where:

W_{ry} = monthly rainwater yield [l/month];

A_c = roof collecting area [m²]. The size of the roof collecting area is the calculated base area of the house (plus the roof overhang), independent of the roof shape and roof slope. The base area is the projection on a horizontal plane of the roof area;

e = yield coefficient. The position, slant, orientation and composition of the collecting area are to be taken into consideration in the determination of the yield coefficient. The values in Table 5.2-2 can be used as a planning basis for the slant and composition of the collecting area;

h_N = monthly precipitation [l/m² month] or [mm/month] (10 mm = 10 l/m²). Values of monthly precipitation can be found in Appendix 4;

η = hydraulic filter efficiency. The manufacturer information with regard to the usable rainwater volume flow is to be taken into consideration for hydraulic-action filter systems that are used in the reservoir supply line. The value of 0.8 can be used in absence of more precise information.

TABLE 5.2-2 **YIELD COEFFICIENTS**

Type of surface	e
Slanted hard roof	0.8
Flat roof, without gravel	0.8
Flat roof, with gravel	0.6
Green roof, intensive	0.3
Green roof, extensive	0.5
Paved surface/compound paved surface	0.5
Asphalt covering	0.8

Source: *DIN 1989-1:2001-10 standard - Rainwater harvesting systems*

The monthly water requirement in the household is defined according to the equation:

$$W_{wr} = [(P_d \times n_p + W_i \times A_w) \times N] + (W_m \times n_m) + (W_c \times n_c) \quad (5.2\text{-}2)$$

where:
W_{wr} = monthly water requirement [l/month];
P_d = daily per person requirements [l/day];
n_p = number of persons;
W_i = irrigation daily requirement [l/m²day];
A_w = watering areas [m²];
N = number of days per month in which water is required;
W_m = washing machine (each wash) [l/wash];
n_m = number of washes per month;
W_c = car wash (each car) [l/wash];
n_c = number of car washes per month.

Values of P_d, W_i , W_m and W_c are given in Table 5.2-3.

The volume of the storage tank can be estimated as:

$$V_n = Minimum\ of\ (W_s\ or\ W_d) \times 1.2 \qquad (5.2\text{-}3)$$

where:

V_n = storage tank volume [l];

W_s = water surplus $\sum_{i=Jan}^{Dec}(W_{ry}-W_{wr})_i$ = excluding months where $(W_{ry} - W_{wr})_i < 0$ [l];

W_d = water deficit $\sum_{i=Jan}^{Dec}(W_{ry}-W_{wr})_i$ = excluding months where $(W_{ry} - W_{wr})_i > 0$ [l].

5.2.6 WATER TREATMENT TECHNOLOGIES

At household level some means of disinfecting water are: boiling, chemical disinfection using chlorine and filtration.

At community level other systems are available for various kinds of community applications. For example, an on-line dosing coagulant system could be used to prevent microbial growth in treated, stored water.

Systems have been developed to treat brackish water, fluorides, arsenic, and iron. These are also available as hand pump attachments. The particles are either adsorbed on a resin or onto a catalytic media. Another option for providing quality water at low cost is to use "package plants". They consist of various components of the treatment process, such as chemical feeders, mixers, flocculators, sedimentation basins, and filters in a compact assembly. As these units are assembled based on standard designs, they are cheaper compared to those that are built on site (see also figure 5.2-3).

Wastewater can be divided into grey-water and black-water. Grey-water consists of the wastewater from washing/bathing, washing of clothes and from the kitchen. The wastewater from the toilet is called black-water. Storm-water also contains solids and pollutants, picked up from the surfaces it flows on. So it too requires treatment. Storm-water collection is important from the point of view of flood control. If wastewater is combined with storm-water, we call it a combined sewage (Fig. 5.2-2).

If the wastewater is discharged to water bodies that are sensitive to nutrients, then nutrients should also be removed. Pathogenic and faecal indicator microorganisms need to be reduced to acceptable levels, to ensure that they will not pose any threat to human health.

Different types of treatment techniques can be adopted depending on land availability and on the quantity, and characteristics of wastewater. These processes produce sludge that has to be further treated, before reuse or disposal. Treatment plants which are used for treating sewage are usually based on the biological process. The process is dependent on natural microorganisms that utilize oxygen and organic contaminants in wastewater to generate CO_2, sludge, and treated water.

FIGURE. 5.2-2 **SOURCES OF HOUSEHOLD WASTEWATER**

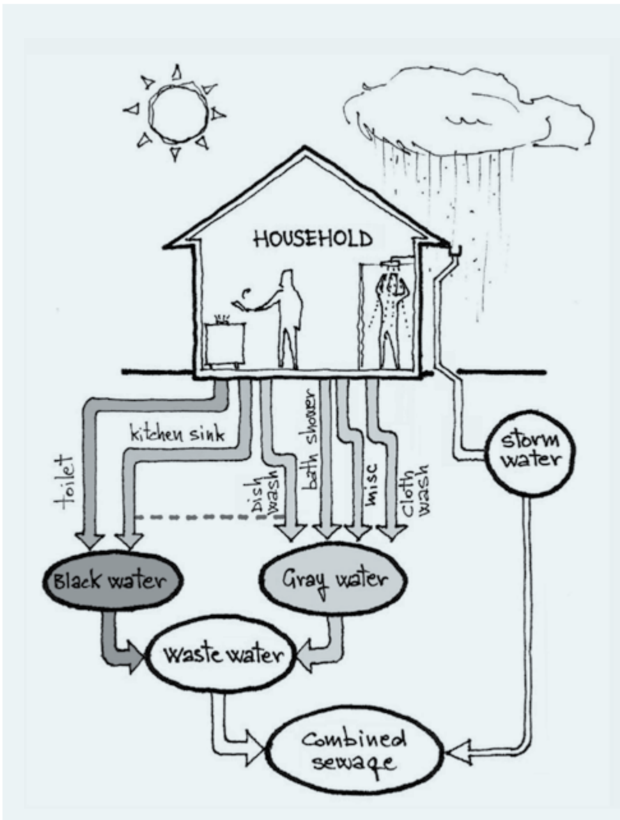


TABLE 5.2-3 **DETERMINATION OF ANNUAL PROCESS WATER REQUIREMENTS FOR PEOPLE AND FOR IRRIGATION**

Average consumption for personal use	Consumption	Unit of measure
Toilets in the household	24	l/day per person
Toilets in office areas	12	l/day per person
Toilets in schools	6	l/day per person
Washing machine:		
Class A (low consumption)	60	l/ wash
Class F (high consumption)	100	l/ wash
Average consumption for private use	**Consumption**	**Unit of measure**
Washing cars (each car)	300	l/wash
Watering the garden	2	l/m^2day
Watering orchard	0.17	l/m^2day
Average consumption for public use	**Consumption**	**Unit of measure**
Watering:		
terraces	2	l/m^2 day
roads with pavement or asphalt pavement	1	l/m^2 day
roads with paved floor	1.5	l/m^2 day
gardens and flower beds	2	l/m^2 day

Sources: *Manuale di progettazione edilizia, Fondamenti, strumenti, norme – Volume 2 Criteri ambientali e impianti, Hoepli (2004); DIN 1989-1:2001-10 standard - Rainwater harvesting systems and http://www.asaspa.it/asasi/risparmiare/dati.html*

5.2.6.1 CONVENTIONAL SYSTEMS

Sewage treatment plants based on the biological process are commonly used for treating wastewater. The treatment can be carried out either in the presence of oxygen (aerobic system) or in its absence (anaerobic system). The aerobic process involves a higher energy input and requires regular maintenance of the mechanical parts. The land requirement is also significant and requires a higher retention time. On the other hand, anaerobic systems do not require higher energy input and space. They are the most widespread treatments for wastewater all over the world. At the end of the process we have a flow of clean water and a flow of sludge (Fig. 5.2-3).

Common off-site treatment systems are: activated sludge treatment, trickling filtration, constructed wetlands. simple anaerobic systems, up-flow Anaerobic Sludge Blanket (UASB), lagoons or ponds, DEWATS (Decentralised Wastewater Treatment Systems). Depending on climate and other local conditions, there are several variations and improvements of these systems.

Small size systems

Depending on climate and other local conditions, there are several variations of small size systems:

- purification and infiltration ponds;
- rainwater harvesting systems;
- man-made systems for waste water treatment;
- pit latrines and pour flush latrines;
- composting toilets;
- septic tanks and Imhoff tanks.

5.2.6.2 SLUDGE TO ENERGY

A sustainable water cycle management system includes the phases sketched in figure 5.2-3, where it is possible to look at the final product of the waste water treatment: the sludge.

FIGURE 5.2-3 **DRINKING WATER TREATMENTS (UP) AND WASTE WATER TREATMENTS (DOWN) AS PARTS OF THE WATER MANAGEMENT SYSTEM**

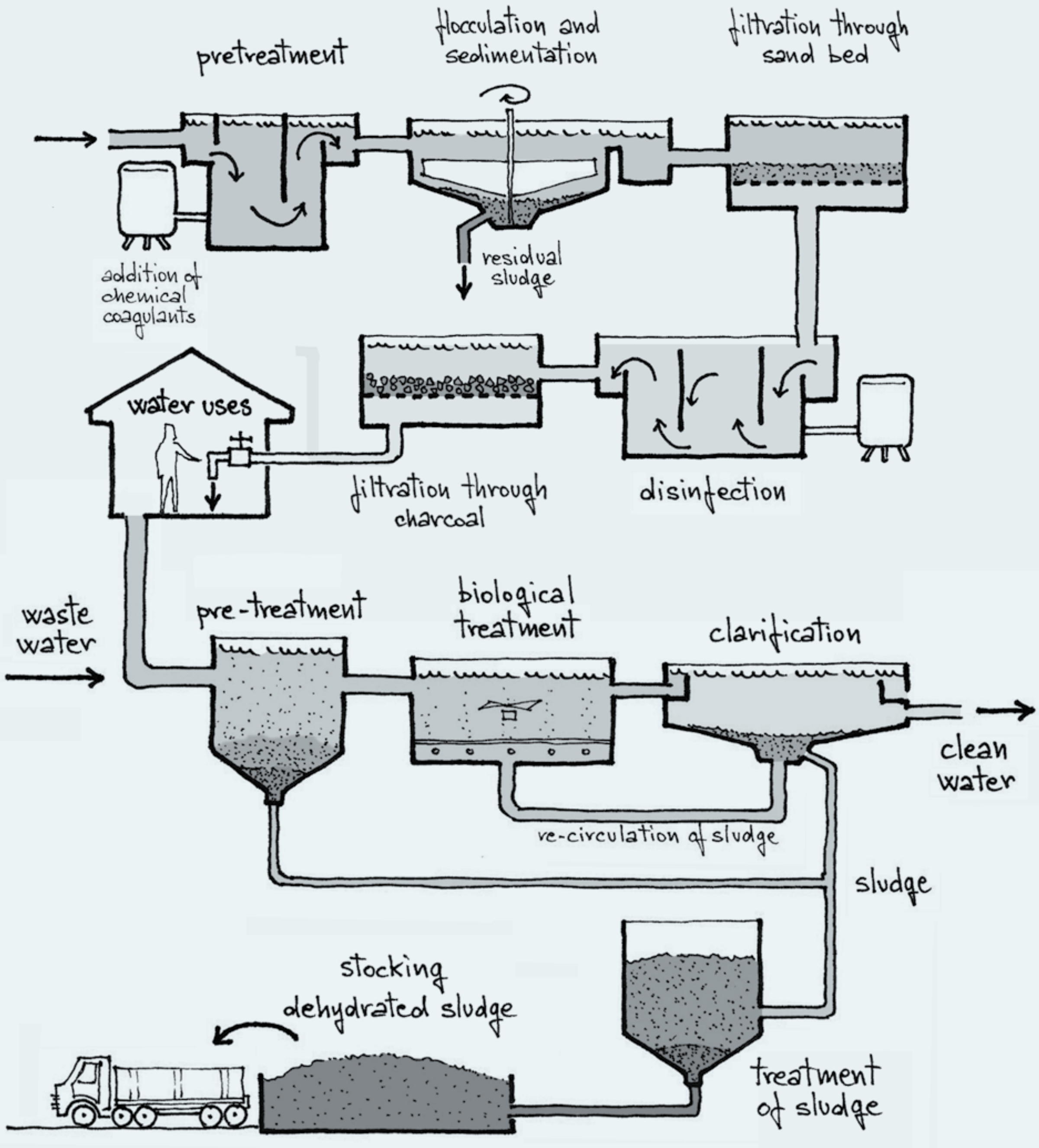
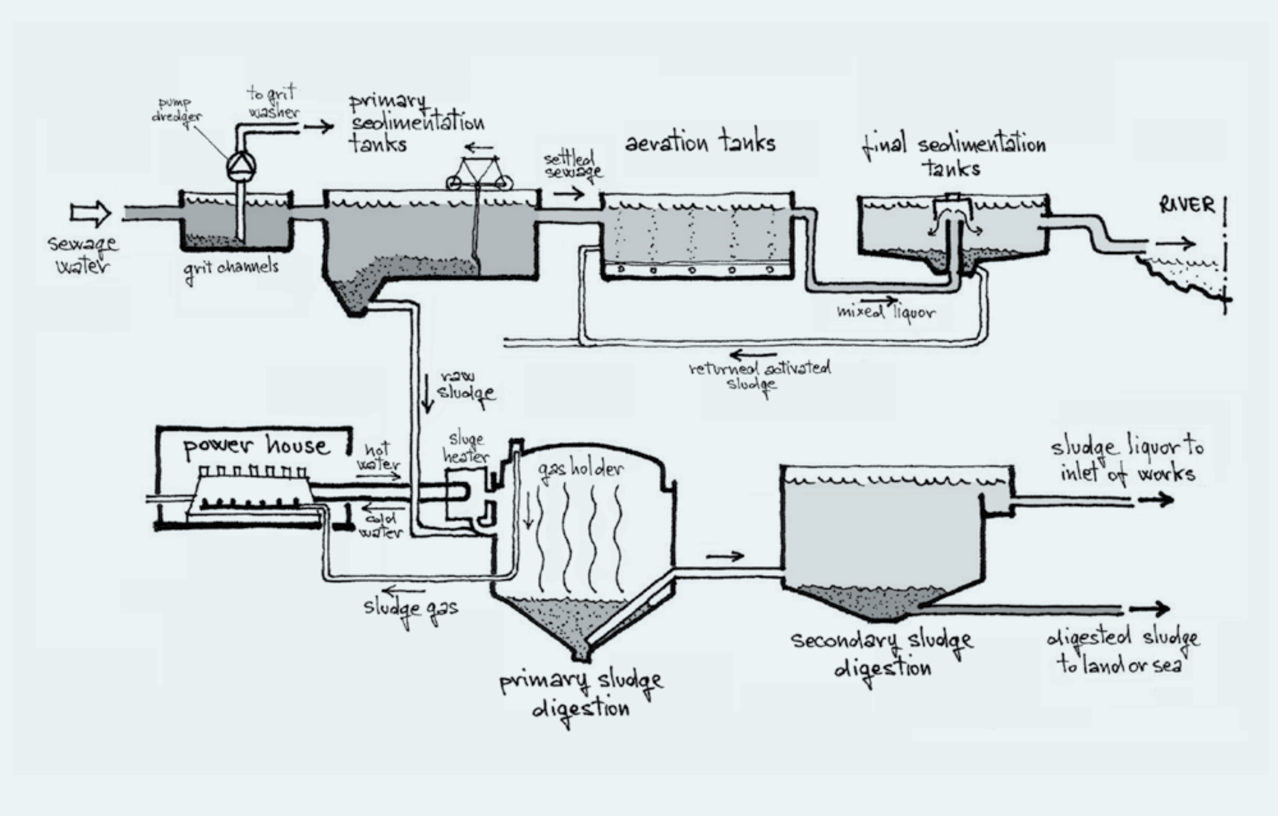


FIGURE 5.2-4 **BIOGAS PRODUCTION FROM SEWAGE WATER AT NEIGHBOURHOOD LEVEL**



Before the final disposal, sludge has to be treated. Also in this case, treatments can be bio-chemical or thermal and the most common are anaerobic digestion and gasification.

Biogas production is very promising because it could represent a very important energy source for the future and there are examples that demonstrate that it could also be used for cooking and transportation.

Application of biogas technology in urban settlements may be on-site (household level, see section 6.4) or off-site (neighbourhood level), figure 5.2-4.

The factors to consider in providing and siting of a biogas system at neighbourhood level are:

- availability of land for the construction of a plant and reuse of the effluents;
- urbanization patterns and population density;
- adaptability of existing sewerage systems (separate from incompatible industrial waste);
- socio–cultural and socio-economic constraints, and opportunities for community participation in construction, operation, maintenance and access to benefits;
- financial analysis.

When biogas is upgraded, bio-methane can be obtained. The possible uses of bio-methane into a network are equivalent to those of natural gas and can be summarized as follows:

- domestic hot water, cooking, heat production;
- cogeneration and micro-cogeneration plants, industrial use;
- fuel for motor vehicles.

5.2.7 WATER CYCLE: MAIN CRITICISMS AND SOLUTIONS

In many cities sewerage systems are not available or are not managed correctly. A century ago the same was true in a large number of cities in today's developed countries.

At that time, even when a sewerage system was available, wastewater was discharged directly into rivers, lakes or the sea. Later, slowly, water treatment started to be implemented, but with the open cycle approach: no energy was recovered with biogas plants and no treated water was reused. It is still like this in cities in most developed countries.

In most cities and towns in developing countries, it is necessary to start from scratch, and this situation can be used as an opportunity to adopt, from the beginning, the closed water cycle approach, exploiting the energy potential of wastewater and providing an answer to both the energy and water shortages (treated, non potable water can satisfy many urban and peri-urban uses). Guidelines for waste water management are:

- do not mix up different kinds of wastes. Collect solid wastes, waste water and storm water separately, but have an integrated plan to deal with them;
- promote a low-cost decentralized waste water treatment system, after verifying the technical and economic feasibility;
- develop norms based on existing standards for reuse of treated water for non-potable applications;
- water under or near a pit or septic tank can get polluted. To prevent this, septic tanks should be located 15-20 m away from the nearest water supply point and 3 m from the nearest house;
- the kitchen should be separated from animals and the toilet, to ensure hygiene.

BIOGAS IN RWANDA PRISONS

The Kigali Institute of Science, Technology and Management (KIST), has developed and installed large-scale biogas plants in prisons in Rwanda to treat toilet wastes and generate biogas for cooking. After the treatment, the bio-effluent is used as fertiliser for production of crops and fuel wood. Otherwise, depending on quantity, biogas can also serve other applications such as running grain mills, water pumps, and generation of electricity.

A prison with a population of 6,000 prisoners generates between 30 and 60 cubic metres of toilet wastewater each day. Sewage disposal from such concentrated groups of people is a major health hazard for both the prison and the surrounding area. The prisons also use fuelwood for cooking, putting great pressure on local wood supplies.

A 600 m^3 system (six linked digesters) produces a daily supply of 250 – 300 m^3 of biogas for cooking, and saves firewood and cost in the minimum of 50%. In consideration of wood saving alone, the payback period is 3 years. The service life of the biogas plant is estimated to be beyond 30 years.

Using biogas digesters to manage animal or human sewage is not a new idea, but in Rwanda has been applied on an enormous scale, and with great success. Each prison is supplied with a linked system of underground digesters, so the sight and smell of the sewage are removed. KIST staff manages the construction of the system, and provide on-the-job training to both civilian technicians and prisoners. The biogas is piped to the prison kitchens, and halves the use of fuelwood. The fertiliser benefits both crop production and fuelwood plantations.

The first prison biogas plant started operation in 2001, and has run with no problems since then.

Biogas plants are now running in six prisons with a total population of 30,000 people, and KIST is expecting to install three more each year. There is significant potential for using such systems in other institutions like schools, hospitals, and on dairy farms - work which KIST has started to undertake.

The systems installed in Rwanda have an impressive international heritage: the original design came from China, was modified by GTZ, and finally scaled up and refined by a Tanzanian engineer working in Rwanda.

The biogas system uses a number of individual digesters, each 50 or 100 m^3 in volume and built in an excavated underground pit. Toilet waste is flushed into the digesters through closed channels, which minimise smell and contamination. The digester is shaped like a beehive, and built up on a circular, concrete base using bricks made from clay or sand-cement. The sides taper gradually and eventually curve inward towards a half-metre diameter manhole at the top. It is crucial to get the bricks laid in exactly the right shape, and to make the structure watertight so that there is no leakage of material or water out of the digester. Biogas is stored in the upper part of the digester. The gas storage chamber is plastered inside with waterproof cement to make it gas-tight. On the outside, the entire surface is well plastered and backfilled with soil, then landscaped. The biogas system is finally inspected and, when approved, it is certified for operation.

FIGURE 5.2-5 **DIGESTERS CONSTRUCTION STAGES**

Sources: *http://www.ashden.org/winners/kist05 and G. P.Nembrini , A. Kimaro, Using Biogas Plants for Treatment of Urban Community Wastes to Supply Energy and Improve Sanitation, presented at the Expert Group Meeting on "Energy Access for the Urban Poor", December 2006, Nairobi*

GRYAAB WASTEWATER TREATMENT, GOTHENBURG, SWEDEN

Gryaab Wastewater Treatment Plant serves 740,000 people. The plant also treats a significant proportion of Gothenburg's storm water as well as its sewage and it is very compact, occupying only 10 hectares*.

An interesting aspect of the Gryaab plant is that it also accepts increasing amounts of organic waste (grease and oil removed from restaurant grease traps, and organic kitchen waste) into the sludge digester to produce more biogas. Biogas from Gryaab is upgraded and injected into the city's gas distribution network for distribution to eighteen filling stations. Biogas currently powers the equivalent of about a thousand cars in Gothenburg, and this number will increase as the amount of organic solid waste treated by the plant increases.

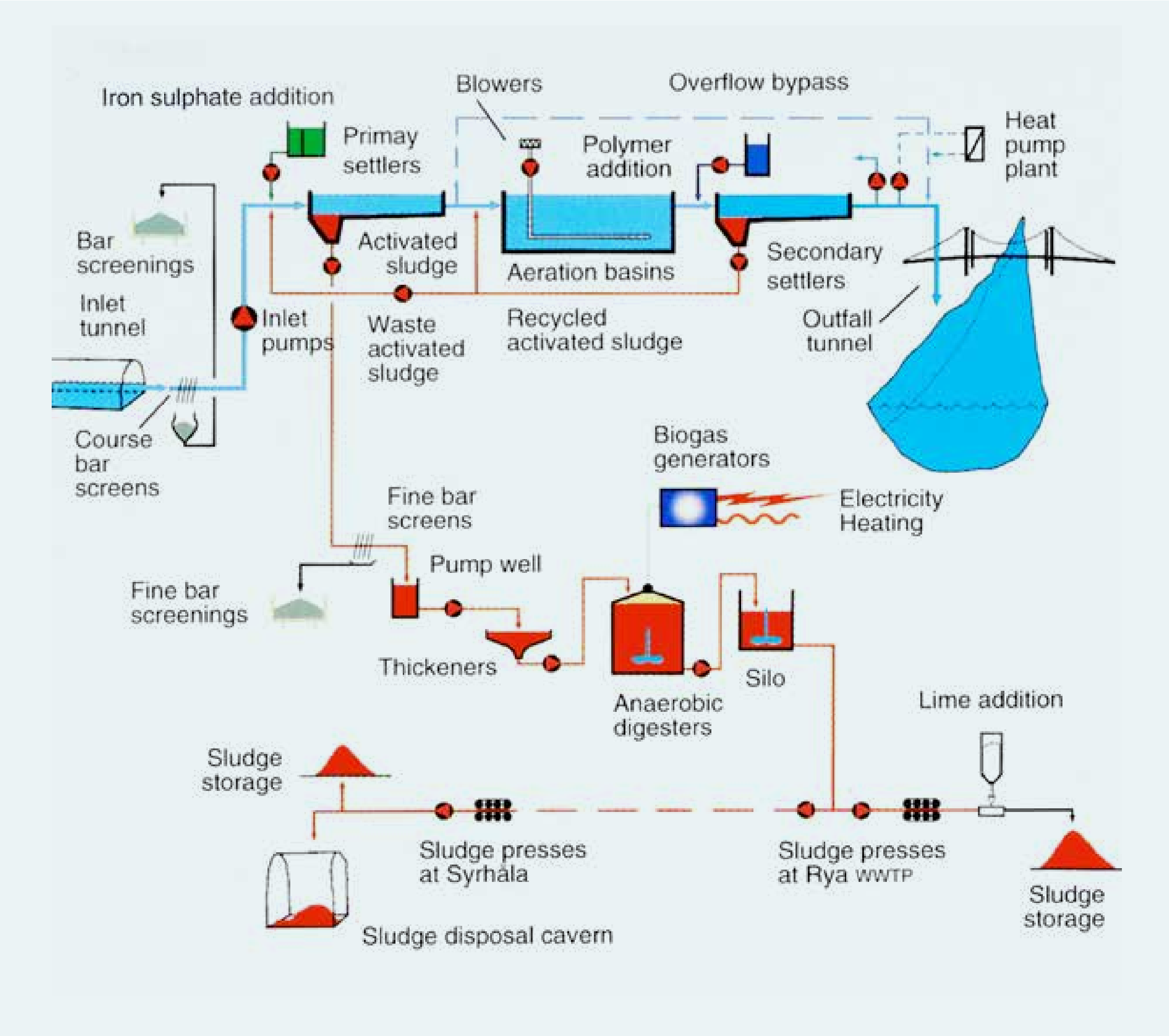
Technical data

- Approx. 5,000 m^3 of sludge with a dry solids content (DS) of 0.7% are removed from the process daily at the Rya plant;
- There are two anaerobic digesters in operation (height 29.4 m, diameter 23.5 m, volume 11,375 m^3 each, retention time approx. 20 day);
- Storage area for treated sludge is approx. 2,000 m^2, with a max. storable volume of approx. 12,000 m^3, equivalent to approx. 3 month's production;

Biogas energy production: there are three Caterpillar biogas co-generation units for electricity and heat production (max. output 770 kW electricity/unit, 1200 kW heat/unit; Göteborg Energy AB)

** http://www.gryaab.se/admin/actions/upload2/uploads/map1/Fact%20sheet,%20Gryaab%202006%202007-05-22%20EGÜ.pdf*

FIGURE 5.2-6 **FUNCTIONAL SCHEME OF THE PLANT**



5.3 SOLID WASTE MANAGEMENT

Today cities face many urgent and interrelated problems - climate change, other global environmental effects, local pollution, population increase, energy and matter depletion, water and waste cycles. It is very hard to define priorities and to take into account all the possible effects deriving from defined goals, targets and related actions.

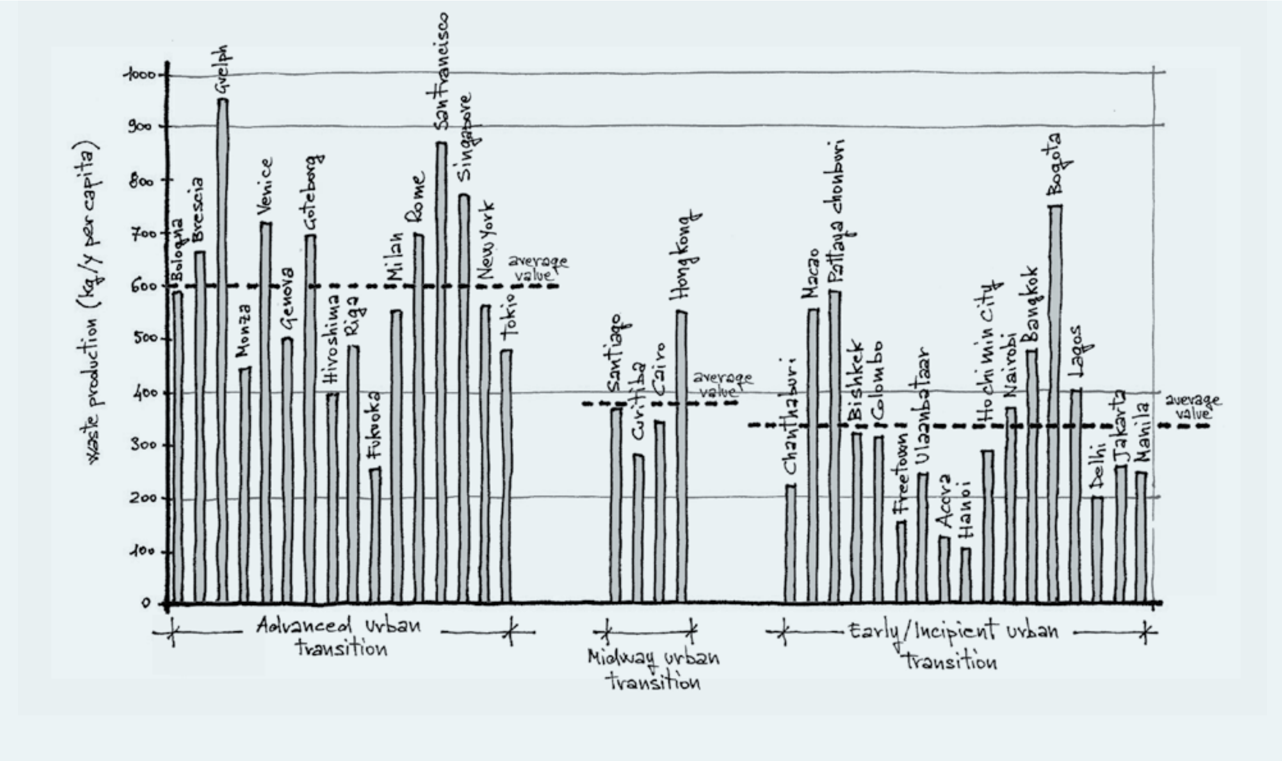
If we model cities in light of the urban metabolism theory, urban waste cannot be "simply" considered as a quantity of matter to be disposed of (in developing cities, it has to be seen above all as a sanitary problem). Consequently, recovery of material and energy from waste should, as far as possible, be promoted on the basis of the local peculiarities, features and attitudes and should integrate available technologies.

5.3.1 DATA ABOUT WASTE PRODUCTION

In general, data are collected on waste generation per capita, waste composition and main practices for waste management. These data can be highly variable as they depend on many factors (e. g. economic and social conditions, habits, type of territory etc.). It is possible to argue that the amount of waste per capita produced in cities belonging to the early urbanization stage[73] is in general lower than in others, as described in figure 5.3-1, where data are related to a sample of 37 cities.

73 In UN-Habitat 2008 cities were classified on the basis of their status of urban transition as follows: Advanced, if Urban Population >70% and Urban Population Growth <1%; Midway, if Urban Population equal to 35-70% and Urban Population Growth equal to 1-2%, Early/Incipient, if Urban Population <35% and Urban Population Growth>2%.

FIGURE 5.3-1 **SOLID WASTE PRODUCTION IN A SAMPLE OF CITIES**



Adapted from: *UN- Habitat, State of the World's Cities 2008/2009 - Harmonious Cities, Earthscan, 2008*

5.3.2 COMPOSITION OF SOLID WASTE

Waste generated in cities in the developing world consists mostly of organic material from food consumption, ashes from fuel-wood and charcoal.

Fig. 5.3-2 shows that in cities belonging to the early urban development stage the percentage of organic material is generally higher than in cities in developed countries, and is often above 50%. In cities such as Freetown, Kigali and Accra, more than 80% of the waste is organic material, compared to about 30% or less in cities such as Bologna, Goteborg, Milan, and New York.

5.3.2.1 HEATING VALUES, HUMIDITY, MAIN ELEMENTS AND CONTAMINANTS

The moisture content and the heating value[74] are the main elements to be considered when planning how the waste can be effectively treated. An analysis of contaminants and precursors of pollutant emissions should also be done in order to prevent dangerous effects during and after the management process.

It is obvious that these data can be highly variable depending on many factors.

Generally speaking, the LHV of waste can vary between 4 and 12 MJ/kg and is inversely proportional to the moisture content.

5.3.3 INTEGRATED MANAGEMENT SYSTEMS

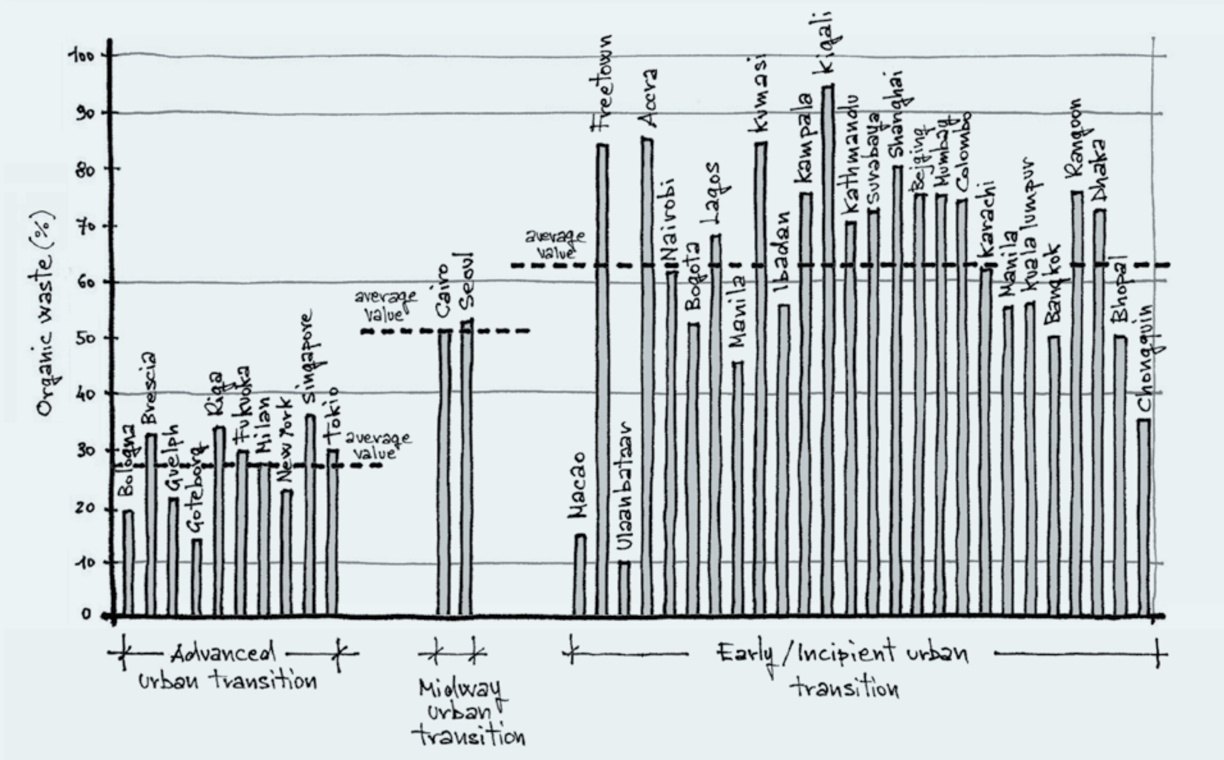
Urban waste disposal is one of the most important issues in the management of a metropolitan area. There are still many cases in which municipal solid waste is usually dumped in landfill sites or open dump sites, leading to air and water pollution.

Waste is one of the most significant outputs of the urban metabolism but, by means of internal recycling processes, it can also become a significant input if considered in the framework of an integrated waste management system that should include:

- waste separation and collection;
- recovery of materials;
- energy recovery;
- final disposal.

74 LHV means low heating value while HHV means high heating value.

FIGURE 5.3-2 **ORGANIC PERCENTAGE IN URBAN WASTE IN A SAMPLE OF CITIES, UN-HABITAT, 2008**



Apart from rational and general schemes of management, site specific factors should also be taken into consideration. These are as follows:

- composition of the waste: this affects handling and transportation options as well as options for recycling, reuse, recovery of energy and incineration;
- accessibility to waste collection points;
- cost of storage and transportation;
- social attitudes to waste collection services such as willingness to segregate waste to assist recycling; willingness to pay for waste management services; opposition to sites designated for waste treatment and disposal facilities.

A correctly integrated management system has to be based on the Three R principle (to reduce, to reuse and to recycle), for which it is necessary to implement collection and separation of waste effectively.

In this context, the role of the landfill is immediately reduced to the disposal of non-biodegradable waste and residues from other processing techniques such as incineration. Sanitary landfills should be carefully designed in order to prevent pollution of air, water and soil, and other risks to man and animals. Aesthetic considerations should also be taken into account.

5.3.4 WASTE TO MATTER AND WASTE TO ENERGY

Despite being widely debated in the last few years, the processes to recover material and energy are still often seen as antagonistic practices, while they are both essential elements of the integrated waste management system and they have to be balanced in different ways depending on the context. Unfortunately, well developed cities still concentrate on defining how much urban waste has to be recycled and how much has to be incinerated, instead of taking action to improve the cities' urban metabolism, and on conforming to standards of source separation without enough consideration of how the standards are reached and the related economic and environmental effects.

Environmental benefits due to recovery of energy and materials from waste can vary depending on the stage of development of the particular city and on the local performance of the energy generation system and of the industrial sector. For example, this can mean that the highest GHG reduction due to energy recovery from waste is reached in cities with an inefficient fossil fuel based power system.

5.3.5 Available and applicable technologies As a consequence of the characteristics of solid waste (low amount of waste per capita production, low percentage of total collected and high organic fraction) in cities at the early urban development stage, some points to consider are:

- since the problem of uncollected waste and spontaneous disposal is still very serious, waste collection should be practiced properly;
- recycling needs to be driven by the residents themselves or with the assistance of voluntary agencies; generally speaking the more accessible recycling centers are, the more waste per capita is delivered;
- for biodegradable waste, composting and anaerobic digestion may have a positive impact if preceded by adequate separation, if the processes are well managed and if there is effective use of the outputs (i. e. a demand for compost);
- thermal-chemical technologies can be attempted only after ensuring their suitability based on the composition of the waste (when there is low LHV they are not suitable) and taking into account economic aspects and difficulties in managing the plants correctly and safely;
- landfill disposal should be reduced not only because of the environmental problems, but also because of the rising costs of construction and operation;
- further landfills should have all the necessary facilities for ensuring a controlled process; in this case landfill gas could be captured and used for power generation or cogeneration, or treated and distributed for other uses; but difficulties in designing, realizing and managing this improvement still seem difficult to overcome;
- the solution to waste management is not merely technical, but also organizational. There is a great need to move away from the disposal-centric approach towards a recovery-centric approach and to overcome the lack of involvement of civil society in the management of municipal solid waste.

In Table 5.3-1 the fundamental technical requirements that should be evaluated in order to select a proper treatments are described.

TABLE 5.3-1 **REQUIREMENTS FOR ENERGY RECOVERY FROM WASTES**

Parameters	Desired range	Waste treatment technique
Moisture content	<45%	Thermo-chemical conversion: incineration, pyrolysis, gasification
Fixed Carbon	<15%	
Total inert	<35%	
Low calorific value	>5 MJ/kg	
Moisture content	>50%	Bio-chemical conversion: anaerobic digestion
Carbon/Nitrogen ratio	25-30	

Source: *ICAEN - Sustainable Building Design Manual – Sustainable Building Design Practices, TERI press, 2004)*

5.3.5.1 **THERMO-CHEMICAL TREATMENTS**

Thermo-chemical treatments are first of all a fundamental part of an integrated waste management system and secondly a way of producing energy. Energy generation depends on the following characteristics of the waste: size; moisture content; density; carbon content; volatile solids and heating value. Only if these parameters are adequate can waste be processed by thermo-chemical treatments equipped for energy recovery.

After the necessary pre-treatments, waste could be treated by different thermal processes and converted into heat and power. The most popular thermal treatment is combustion (incineration), but, especially for small and medium sized plants, pyrolysis and gasification are also applicable.

Incineration involves burning the waste at high temperatures. It can be done with or without energy recovery. In modern incinerators, hazardous and recyclable materials are removed prior to combustion. Incineration is considered useful for destroying pathogens and toxins at high temperatures, especially from clinical wastes. It is also attractive in countries which have a shortage of land. A main concern in incineration is the emission of harmful pollutants, including dioxins and furans. Nowadays suitable technologies for containing dangerous pollutants are available and accessible all over the world. Of course the personnel involved should be trained in the correct management of the plant.

Technologies for pyrolysis and gasification of urban wastes are also available at commercial scale in this field. Pyrolysis and gasification are technically and economically feasible if they are combined with the integrated waste management systems of small regions (20-80 kt/year). Compared with combustion, pyrolysis and gasification could bring benefits such as smaller space occupation, more acceptability, fewer additives, less (and more inert) slag, fuels available for storage, transportation and different uses (including gas turbine combined cycle or co-combustion). Despite the small number of commercial applications, the energy and mass balance of existing plants can deliver performances that are nearly comparable to those of combustion plants.

5.3.5.2 MECHANICAL BIOLOGICAL TREATMENT (MBT)

These are a flexible mix of mechanical and biological treatment methods that are used to recover all types of resources from a mixed waste stream. The recovered materials can then be recycled. The mechanical part is similar to the MRF (Materials Recovery Facility[75]) and the biological treatment normally consists of anaerobic digestion or composting. The process may also produce a fuel from the waste, known as Refuse Derived Fuel (RDF).

5.3.5.3 BIO-CHEMICAL TREATMENTS: COMPOSTING AND ANAEROBIC DIGESTION

Anaerobic digestion

Biogas generation could have important effects in terms of reduction of green house gases and use of renewable energies. Depending on the end use, different biogas treatments are necessary. For some applications, where it is important to have a high energy content in the gas, e. g. as vehicle fuel or for grid injection, the gas needs to be upgraded. Upgrading technologies have various advantages, most notably the production of an alternative source for methane (biomethane) which may help to reduce dependence on natural gas, which in the long run may result in a monetary profit.

Composting

When anaerobic digestion is not feasible, wet organic waste can be treated by composting. This is an aerobic process, where bacteria act on the sludge to produce more stable organic material (humus), which is very good as a soil conditioner.

5.3.6 MAIN CRITICISMS AND SOLUTIONS

According to technical literature it is possible to argue that urban waste is an underutilized source of materials and energy and, in developing cities, a dangerous source of pollutants and diseases.

Further, although waste management has an important role as a source of energy and materials and it creates new net employment, there can be many obstacles to the introduction of new urban policies: an ill-defined institutional framework, insufficient financial resources, uncertainty related to the available data, lack of skill and of specialists capable of putting policies into action , lack of information of the citizens, resistance to change. All these are obstacles that are difficult to predict.

5.3.7 BASIC GUIDELINES

Although waste management should be planned with solutions that are strictly dependent on the local situation, the following guidelines should be followed in order to overcome many of the previously mentioned problems:

- provide facilities for collection of segregated waste;
- identify facilities for the recycling of non-biodegradable wastes such as plastics, glass, and paper;
- develop norms for disposal of non-degradable and inert waste in landfills based on local standards, to ensure a safe environment in the surrounding areas. Sanitary landfills need to be carefully designed and people need to be trained in managing and maintaining them (a common mistake is to provide the infrastructure, but neglect the managerial aspects);
- establish an efficient waste reduction, recycling, and reuse (3R) programme;
- avoid or reduce toxic and hazardous materials. Recycle items such as ballasts, mercury-based lighting products, used oil, unusable batteries, etc.

75 MRF is a specialized plant that receives, separates and prepares recyclable materials for marketing to end-user manufacturers

06 RENEWABLE ENERGY TECHNOLOGIES

6.1 SOLAR PV

The photovoltaic effect consists of the transformation of electromagnetic radiation into electricity (direct current) by so-called PV cells, made of semiconductor materials.

Even today, the most used material for photovoltaic cells is silicon, which can be, depending on its molecular structure, monocrystalline, polycrystalline or amorphous deposited in thin films, in descending order of conversion efficiency (from 20 to about 8%). Other materials, characterized by a recent rapid diffusion are the indium diselenide and copper (CIS) and cadmium telluride (CdTe), both used in thin films with efficiencies around 10%.

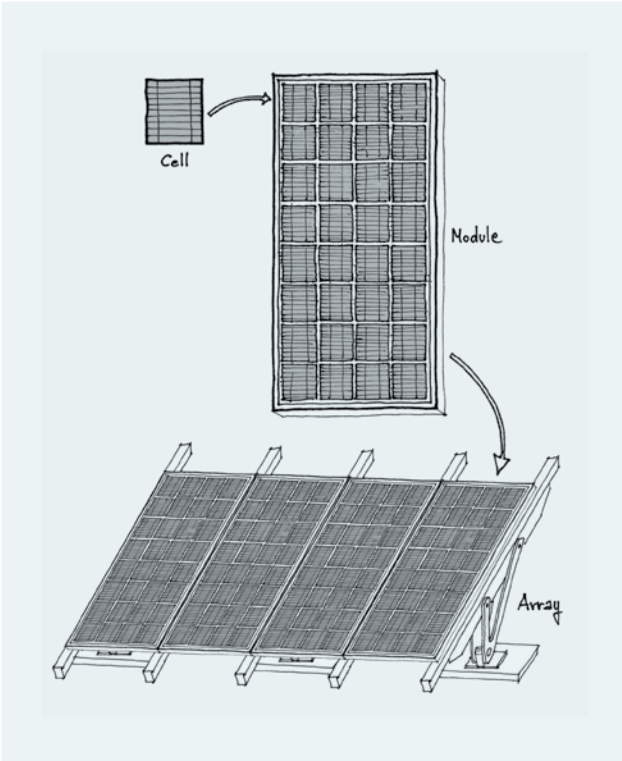
In most common applications the cell consists of a thin layer of silicon (3.5 tenths of a millimetre) square in shape, with an area generally between 100 and 150 cm^2, equipped with the necessary contacts to collect the generated current. Due to the low voltage of an individual solar cell (typically about 0.5 V), several cells are wired in series in the manufacture of a "laminate". The laminate is assembled into a protective weatherproof enclosure, thus making a photovoltaic module or solar panel; modules may then be strung together into a photovoltaic array (Fig. 6.1-1).

Commercial modules are available with areas ranging from approximately 0.5 to 2 m^2, and a weight of about 15 kg/m^2. They can be installed on flat (Fig. 6.1.2) or on pitched roofs (Fig. 6.1.3).

Developed for architectural purposes are the glass-glass modules (Fig. 6.1.34), where the interstices between the cells let the light through, or where the thin films are deposited in such a way as to result in their being semi-transparent.

A photovoltaic system consists of a number of electrical and electronic devices, which can be conventionally divided into two main groups: the photovoltaic devices (modules) and BOS (balance of system), which includes all the other elements (from support structures to wiring). The modules (the generator) are connected to the rest of the system, whose most important component is the inverter, a device capable of converting the direct current from the generator into alternating current.

FIGURE 6.1-1 **CELLS COMBINE IN MODULES OR PANELS, PANELS COMBINE TO FORM AN ARRAY**



The power of a photovoltaic device (cell, module or system) is expressed in peak watt (W_p), which represents the nominal power that the unit is capable of delivering in reference conditions (STC, standard test conditions), corresponding to its electrical output with an incident solar irradiance equal to 1000 W/m^2 with a cell temperature of 25 °C. To give an idea, a module of about 1.3 m^2 with crystalline silicon cells is rated between 180 and 260 W_p (according to the quality of the cells).

FIGURE 6.1-2 **PV ON FLAT ROOF**

FIGURE 6.1-3 **PV ON PITCHED ROOF**

Photo credit (top): *USFWS Pacific Southwest Region -http://www.flickr.com/*

The space occupied by the inverter varies depending on the power, and it ranges from devices the size of a briefcase, for a few kW, to larger devices, approximately the size of a refrigerator, for several hundred kW.

Depending on the type of use, photovoltaic systems can be divided into two categories: stand-alone and grid connected (Fig. 6.1.5). In the former, a storage system, i.e. a battery, is interposed between the generator and the inverter. This stores the electric energy when production exceeds consumption and makes it available when consumption exceeds production. When systems are connected to the grid all the energy produced, or the portion that is not directly used on site, is fed into the grid. During periods of little or no sunlight, the grid itself integrates the users' needs.

Productivity of a photovoltaic system

The electricity produced by a photovoltaic system during a given period can be estimated using the following simplified formula:

$$E_{PV} = PR \times P_{PV} \times S \qquad (6.1\text{-}1)$$

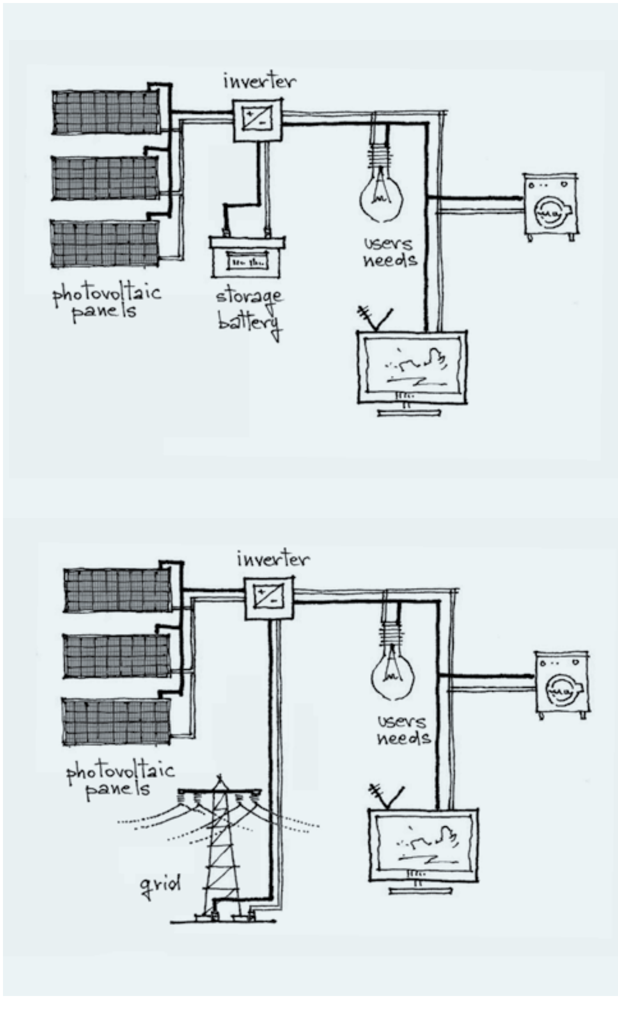
where:
E_{PV} = the amount of electricity produced during the period [kWh];
PR = the performance ratio of the PV system; the average value is usually in the range 0.75-0.8; more for very good systems;
P_{PV} = the nominal power of the PV system [kW_p];
S = the solar irradiation incident on the module surface during the period [kWh/m^2].

FIGURE 6.1-4 **LEFT: TGV RAILWAY STATION PERPIGNAN (FRANCE), ARCHITECTURE: AREP**

Photo credit Laurent Lacombe - *http://upload.wikimedia.org/wikipedia/commons/c/cf/Projet_BIPV_-_Gare_TGV_de_Perpignan.jpg; right: California Academy of Science, San Francisco, USA, Architecture: Renzo Piano Workshop*

The productivity of a photovoltaic system is highly dependent on the climatic context in which it is located. The amount of electricity produced is, in fact, directly proportional to the availability of solar radiation and, to a much smaller extent, inversely proportional to the working temperature of the cells. It is therefore extremely important to define the correct inclination and orientation of the modules, in order to maximize the incident radiation and favour heat loss. At the latitudes of EAC countries, the optimum tilt angle is 0° (horizontal), but up to 15° there is no significant decrease in production. Hence the fact that, contrary to what is generally proposed for higher latitudes, it is not appropriate to put PV panels on the walls, or as overhangs for windows shading the south or north façade, since they would remain in the shade for half the year.

FIGURE 6.1-5 **STAND ALONE (TOP) AND GRID CONNECTED (BOTTOM) PV SYSTEMS**



As an indicative figure, in EAC a 1 kW_p well designed photovoltaic system can produce between 1500 and 1650 kWh electricity annually, depending on the site of installation, and thus the amount of solar radiation available. In case of modules with polycristalline cells, this means a total collector surface of about 7.5 m^2.

Architectural integration of photovoltaic systems

Architectural integration represents an interesting opportunity for photovoltaics, with very promising growth prospects, even in strictly economic terms. In fact, the installation of the modules on the building envelope provides a variety of advantages, such as the use of the land surface already occupied by buildings, the savings on support structures, the replacement (with the same performance) of materials and components such as traditional roof elements, and the possibility of using the energy produced on site.

In order to obtain the best performance of a photovoltaic system, whether integrated into the building envelope or not, careful planning is necessary. The modules must be located in such a way as to intercept the maximum possible solar radiation, avoiding shade produced by trees, surrounding buildings or parts of the building itself. Ventilation of modules, by leaving a gap between their bottom surface and the roof or other building components on which they are mounted, is an important prerequisite to avoid lower performances than expected.

When the modules are mounted on a roof, care must be taken not only to leave a ventilated gap, but also to increase the roof insulation, to avoid a significant heat flow due to the panels' relatively high temperature reaching the indoor environment.

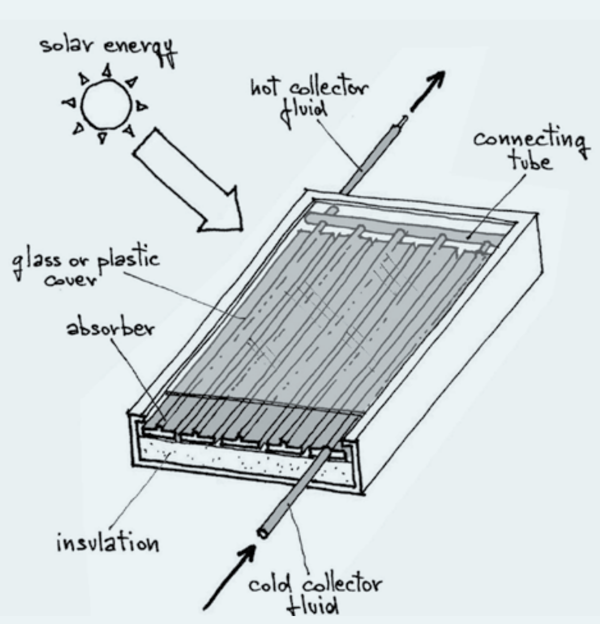
6.2 SOLAR THERMAL

Solar thermal systems convert solar radiation directly into heat. Their use is compatible with all the applications that require thermal energy at a relatively low temperature, such as the production of hot water and air conditioning in summer.

6.2.1 SOLAR COLLECTORS

Solar energy is captured and converted into thermal energy through solar collectors: the market offers three types of products: flat plate (Fig. 6.2-1), evacuated (Fig. 6.2-2) and unglazed (Fig. 6.2-3) solar collectors.

FIGURE 6.2-1 **FLAT PLATE SOLAR COLLECTOR**



The flat solar collectors are a very simple concept: an absorbing plate, integrated with the pipes for the heat transfer fluid, is placed into a box insulated at the back and along the sides. The absorber plate surface exposed to solar radiation is normally black, painted or "selective" (a treatment that allows the performance to be improved thanks to the low emissivity in the far infrared). A transparent cover, located in front of the plate, reduces the convective losses and, mainly, the radiative ones in the far infrared (greenhouse effect).

FIGURE 6.2-2 **EVACUATED SOLAR COLLECTOR (MODEL SYDNEY)**

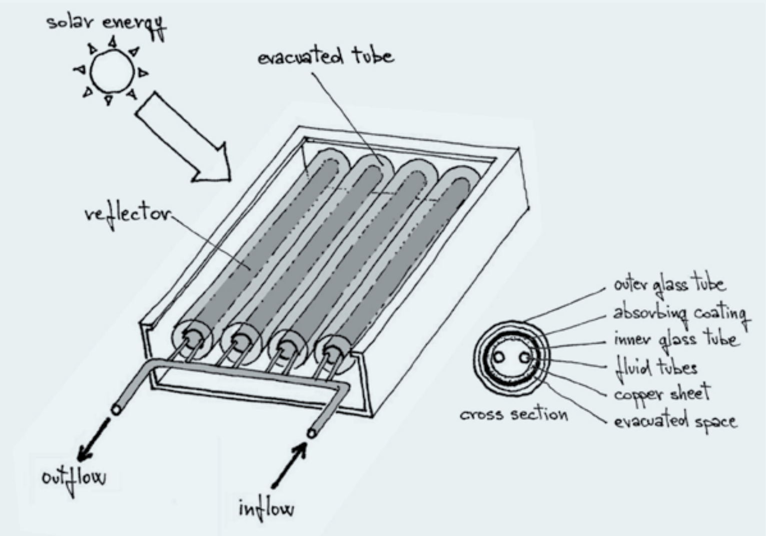
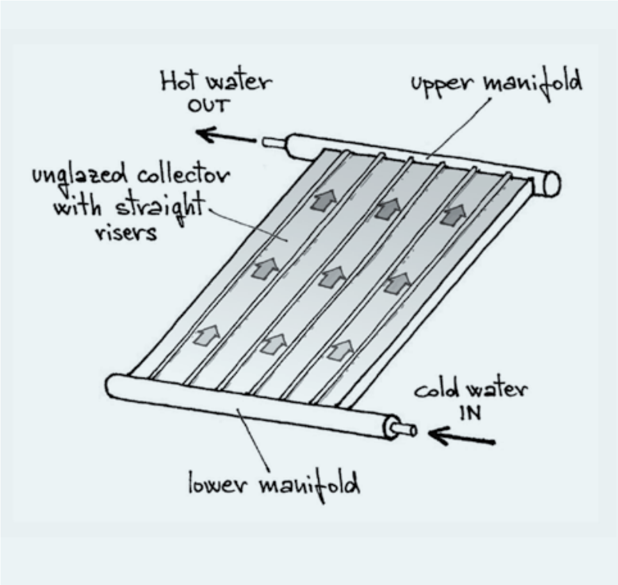


FIGURE 6.2-3 **UNGLAZED SOLAR COLLECTOR**



The evacuated collectors consist of a series of evacuated glass tubes, each of which contains an absorber and pipes through which a heat transfer fluid flows. The vacuum reduces convection heat loss between the absorber and the glass, increasing efficiency and allowing temperatures in excess of 100 °C to be achieved. To increase the amount of solar radiation on the absorbing plate, some models of evacuated collectors are provided with a reflector foil, often appropriately shaped.

Another type is the unglazed collector, or plastic absorber, which is simple and quite inexpensive. These collectors are specially designed for low-temperature applications and are made from ultraviolet (UV) resistant plastic. The heat losses are higher than in the two types mentioned above, but the good cost-benefit ratio makes them a remarkable product, especially in hot climates.

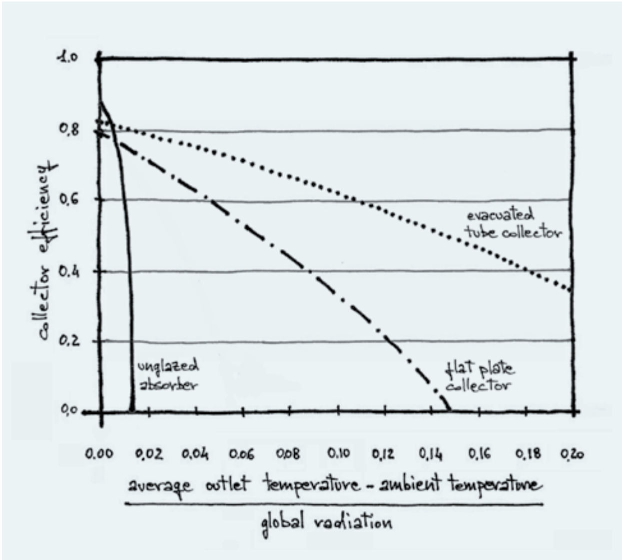
The choice of the most suitable technology depends on the final use, i. e. on the temperature they should work at, and on the mean external air temperature: for low temperatures, i. e. up to 50 - 60 °C and in tropical climates the better performance of the evacuated collectors usually does not offset their higher cost.

6.2.1.1 **COLLECTOR EFFICIENCY**

The collection efficiency for a solar collector determines its performance and thus its ability to transform the absorbed solar energy into heat.

The efficiency of a solar collector depends on its construction characteristics (absorption coefficient of the plate, optical transmittance of the glass and overall heat loss coefficient) but also on the operating conditions (average operating temperature, external air temperature and incident solar radiation), as well as the orientation and inclination. In the EAC countries, the best performance is obtained when the collector is horizontal, as for PV panels but, to avoid the stagnation of air bubbles and dust accumulation, it is necessary to give them a little inclination.

FIGURE. 6.2-4 **EFFICIENCY OF FLAT PLATE AND EVACUATED COLLECTORS**

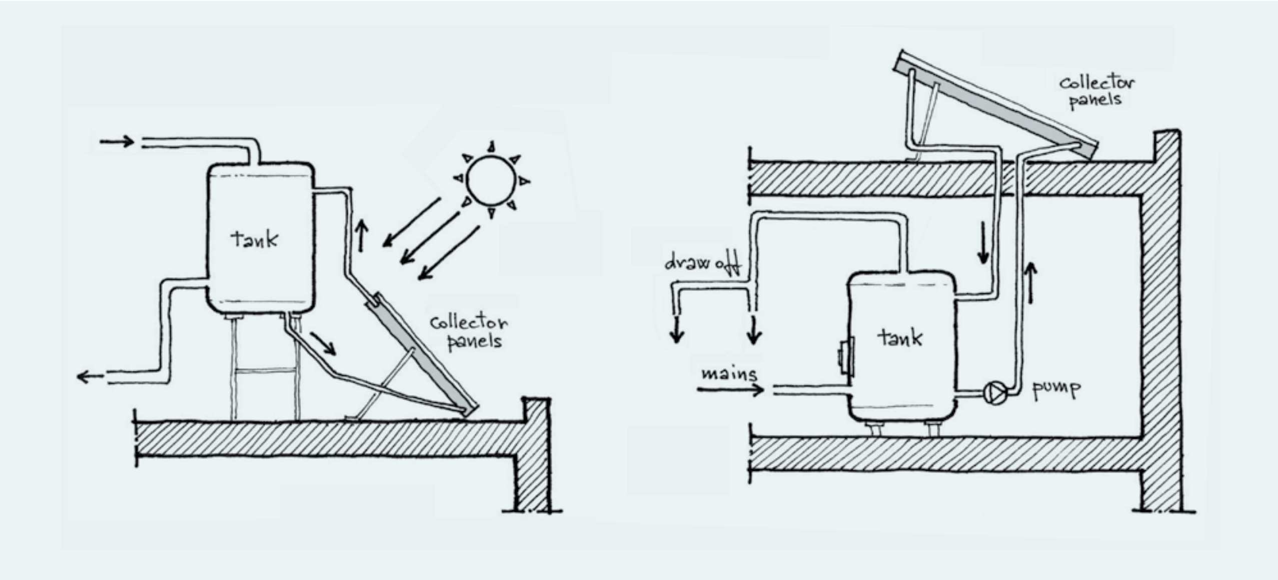


The efficiency of a solar collector (Fig. 6.2-4) is a function of the incident solar radiation and of the temperature difference between the fluid and the outside air (the smaller the difference the greater the efficiency); therefore in tropical climates they work at their best.

6.2.2 HOT WATER PRODUCTION

Solar collectors, with an overcast sky or at night, do not provide hot water. To reduce the inconvenience a storage tank is used to store the excess heat produced when the sun is shining. The heat stored is used when solar radiation is low or at night.

FIGURE 6.2-5 **NATURAL (LEFT) AND PUMP ASSISTED (RIGHT) CIRCULATION SOLAR SYSTEM**

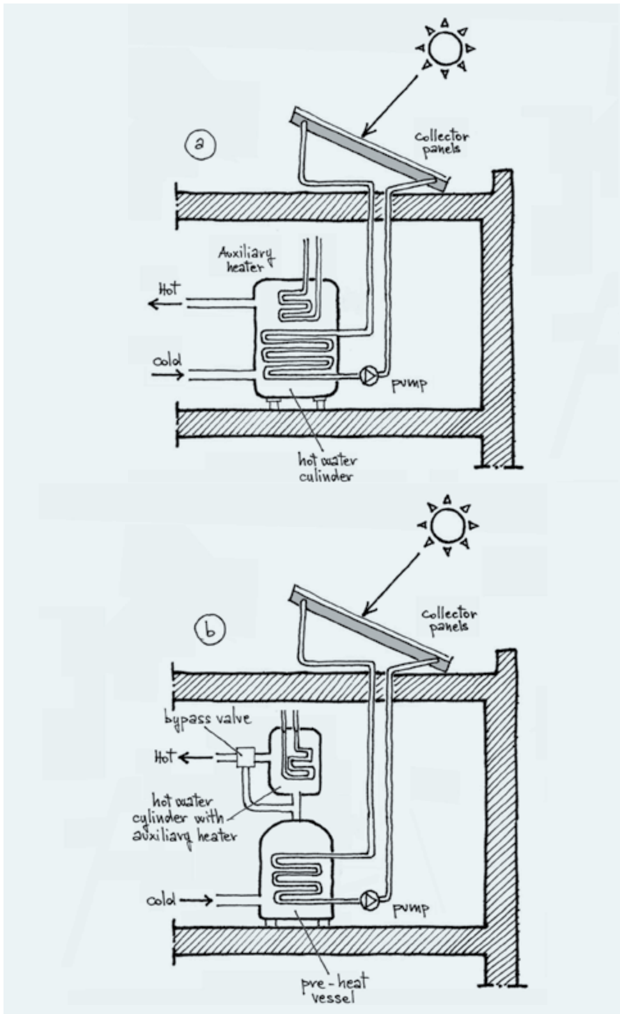


In cold and temperate climates, because of the low air temperature, in the absence of sun the water in the absorber can freeze, damaging it. To avoid this, the water circulating in the collectors is mixed with an anti-freeze liquid and goes to a heat exchanger situated in the storage tank, in a closed circuit (Fig. 6.2-6). Thus, the water coming from the mains is heated in the storage tank, from which it is delivered to the users according to their needs.

In EAC climates, except for high upland, freezing cannot take place, and the heat exchanger may not be necessary (Fig. 6.2-5). However, to prevent limestone deposits or corrosion damaging the collector, the closed loop with the heat exchanger (without any anti-freeze liquid) is recommended. The fluid in the collector loop is circulated either by gravity (thermosyphon principle) or by an electric pump that is activated by a control unit when the water temperature at the collector outlet is higher than that in the storage tank (Fig. 6.2-5).

In gravity systems the fluid circulates by means of natural convection. When fluid in the collector is heated by solar radiation, it expands, becomes less dense, and rises to the top of the storage vessel, and it is replaced by cooler, heavier fluid from the bottom of the storage tank. The storage tank must be higher than the collector, to avoid the reverse flow, with consequent dissipation of stored heat through the collector when solar radiation is low or at night. If the height difference is not sufficient, a non-return valve is required. Such systems have the advantage that no pump or active controls are required, and thus they are cheaper and more reliable.

FIGURE 6.2-6 **PUMPED SOLAR WATER HEATING SYSTEMS (A) WITH SINGLE STORAGE VESSEL (B) WITH SEPARATE PRE-HEAT VESSEL**



If a backup generator is needed, storage tanks generally have two heat exchange coils. The one positioned at the bottom is connected to the solar circuit, while the one at the top is connected to an auxiliary heat source (Fig. 6.2-6). In small, single family units an electric resistance generally substitutes the heating coil (Fig. 6.2-7); in larger ones, a boiler is required. If the solar heating system is not able to meet the desired water temperature (approximately 40° C), the auxiliary heater provides the necessary supplemental heat. An appropriate control system (usually a simple thermostat) is required.

Usually, solar thermal systems are designed to provide about 70% of the hot water demand and the auxiliary heater provides the rest. To provide more than 70% would not be economically profitable. For this purpose, the size of the storage tank is about 50 - 70 liters per square meter of collector area. For a first estimate of the collector area needed in EAC climates, the graph in figure 6.2-8 can be used.

The graph gives the collector area needed to produce 100 litres/day of hot water at 40 °C, with an annual solar fraction 76 of 0.7, as a function of the annual solar radiation incident on horizontal surface (see Appendix 4 for data). The area needed for production of different amounts of hot water is linearly proportional.

FIGURE 6.2-7 **SINGLE FAMILY, INTEGRATED STORAGE SOLAR DHW SYSTEM**

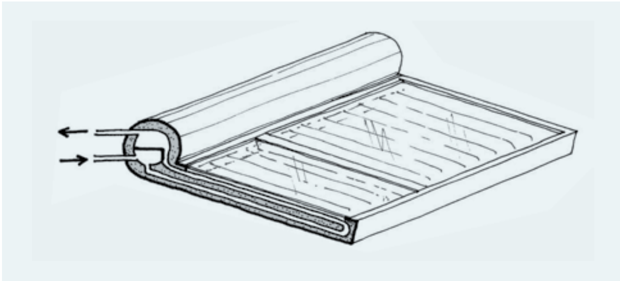
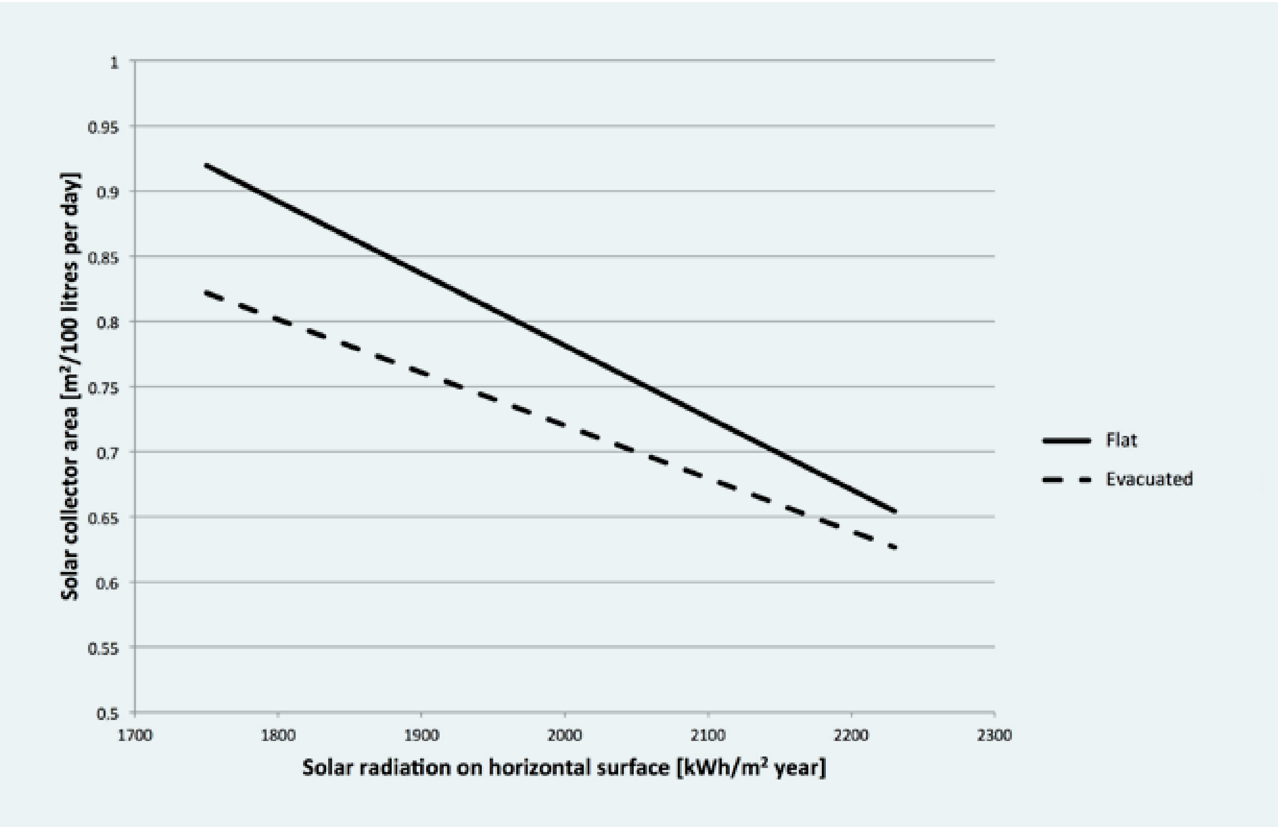


FIGURE 6.2-8 **COLLECTOR AREA NEEDED FOR 100 LITRES/DAY HOT WATER PRODUCTION AS A FUNCTION OF ANNUAL SOLAR RADIATION INCIDENT ON HORIZONTAL SURFACE, FOR FLAT PLATE AND EVACUATED COLLECTOR. HOT WATER TEMPERATURE = 40 °C; SOLAR FRACTION = 0.7.**



76 *The solar fraction is the fraction of the total heat needed which is provided by solar energy, i.e. if to provide 50 liters of hot water per day are needed 500 kWh/year, a solar fraction 0.7 means that 70% (350 kWh/year) of this heat is provided by the solar system.*

6.2.3 SOLAR COOLING

Solar thermal collectors can also be used for cooling. The thermal energy generated by the solar system is used to feed the cooling process. There are two types of systems:

closed systems: the solar system supplies hot water to an absorption chiller, integrating the conventional heat source;

open systems: the solar system provides heat for regenerating a desiccant wheel.

6.2.3.1 SOLAR COOLING WITH ABSORPTION CHILLER

A Solar Cooling system with absorption chiller has been out of the experimental stage for several years. The heart of the system is an absorption chiller that generates chilled water. It is powered by the hot water produced by solar collectors, (Fig. 6.2-9).

For an initial assessment, in a Solar Cooling system, the ratio of the surface of the solar collectors to that of the space to be conditioned varies from 0.1 to 0.3 as a function of location (and thus insolation) and the specific thermal load of the building.

6.2.3.2 DESICCANT COOLING

The cooling cycle is based on the combination of evaporative cooling and dehumidification by means of a hygroscopic material (Fig. 6.2-10).

FIGURE 6.2-9 **SOLAR POWERED AIR CONDITIONING SYSTEM**

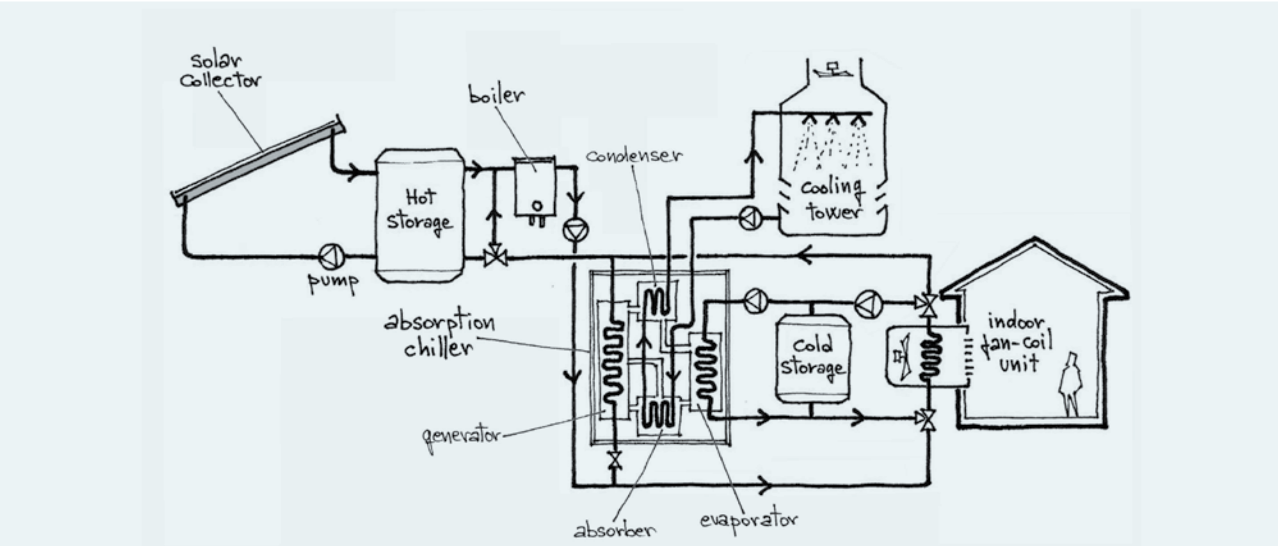
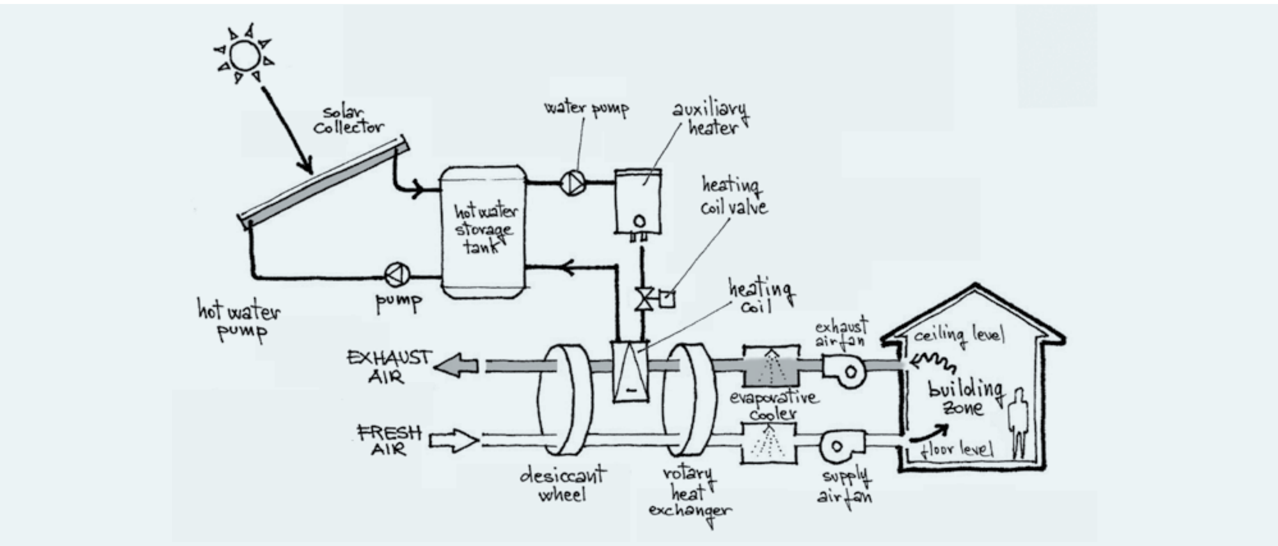


FIGURE 6.2-10 **MAIN COMPONENTS OF A SOLAR-POWERED DESICCANT COOLING SYSTEM**



The external warm, moist air enters the lower part of a slowly rotating desiccant wheel, which is packed with silica gel (or some other absorbent or adsorbent material) between two wire meshes. Inlet air is dehumidified and heated (condensation of moisture is an exothermic process). Heated air is then passed through and cooled by a rotary heat exchanger. This air is subsequently cooled through a process of adiabatic humidification and introduced into the building zone. The exhaust air is first humidified to saturation, to cool it down further, and then passed through the upper part of the heat transfer wheel, cooling it. Further heating is provided by the solar system. The hot air (50 - 75 °C) is passed through the upper part of the desiccant wheel, extracting the humidity, and thus regenerating it, to ensure continuity of the dehumidification process. Auxiliary heating with conventional energy source can be provided to the storage tank, and a back-up conventional cooling coil can be positioned after the evaporative cooler, before air enters the zone, to meet the load when outside air is too humid.

The COP (Coefficient of Performance, see chapter 4) of this system is about 0.5 - 0.6, i.e. very close to that of a solar system with absorption cooling. Therefore, for solar desiccant cooling also, the ratio of the surface of the solar collectors to that of the space to be conditioned ranges between 0.1 and 0.3.

6.3 WIND ENERGY

A small wind energy system for agricultural, industrial and urban contexts is a technology that is currently being explored and efforts are being made to reduce its cost. It can provide very good results in terms of energy savings. The small turbines, while being similar to the large ones, have a much simpler technology. A 20 kW generator, for example, has a tower of 12-18 m and the rotor diameter is about 8 meters. The noise level is limited to around 45 dB (a whisper is equivalent to 40 dB). The buildings for which it is possible to envisage the installation of mini wind turbines have very diverse uses. They include residential buildings, hotels, and buildings for commercial or manufacturing activities. The energy produced can be stored in batteries (in the case of isolated users) or fed into the local distribution grid.

Wind turbines can be of two different types: horizontal axis (Fig. 6.3-1) and vertical axis (Fig. 6.3-2).

In the former, the most common, the rotation axis is horizontal and, therefore, the blades rotate in a vertical plane. A typical horizontal axis wind turbine generally has three blades (there are cases of two-bladed and single blade models). A rudder keeps the blades' plane always facing the wind direction. A control system slows down or blocks the rotation speed when there is high wind.

FIGURE 6.3-1 **HORIZONTAL AXIS WIND TURBINE**

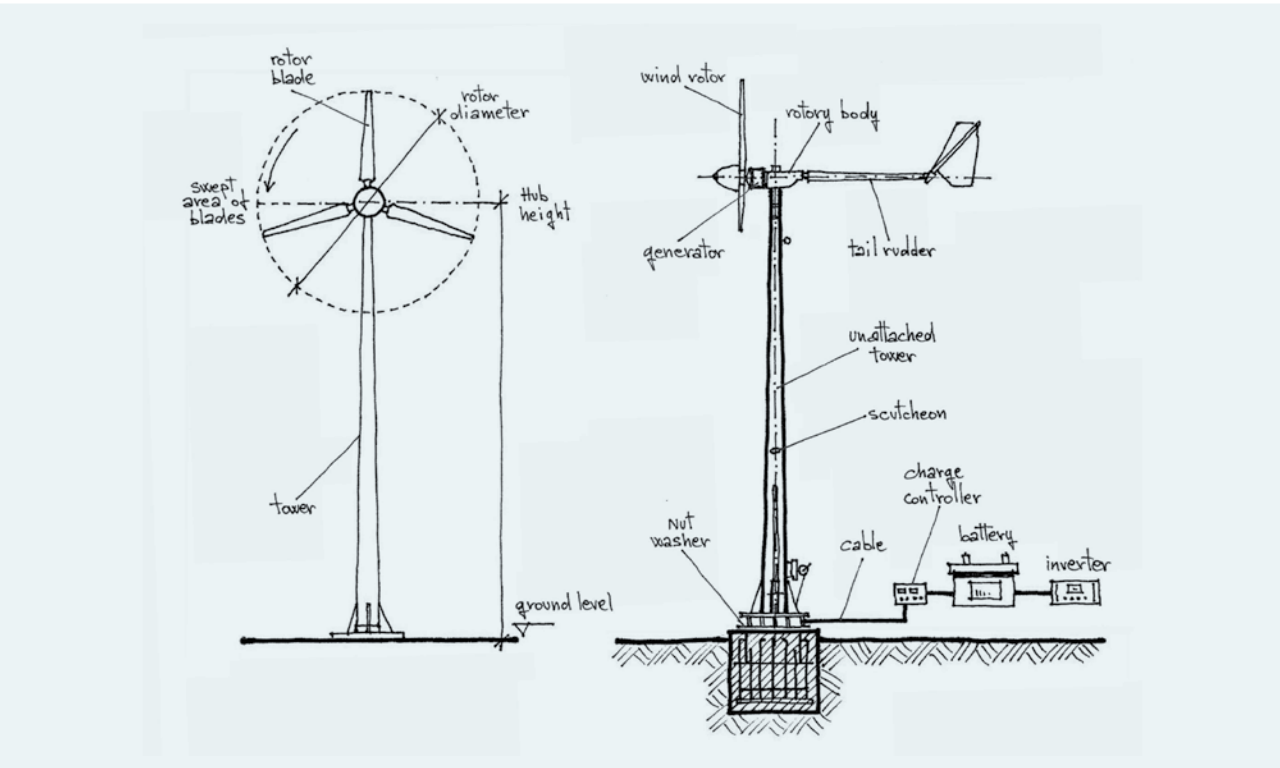
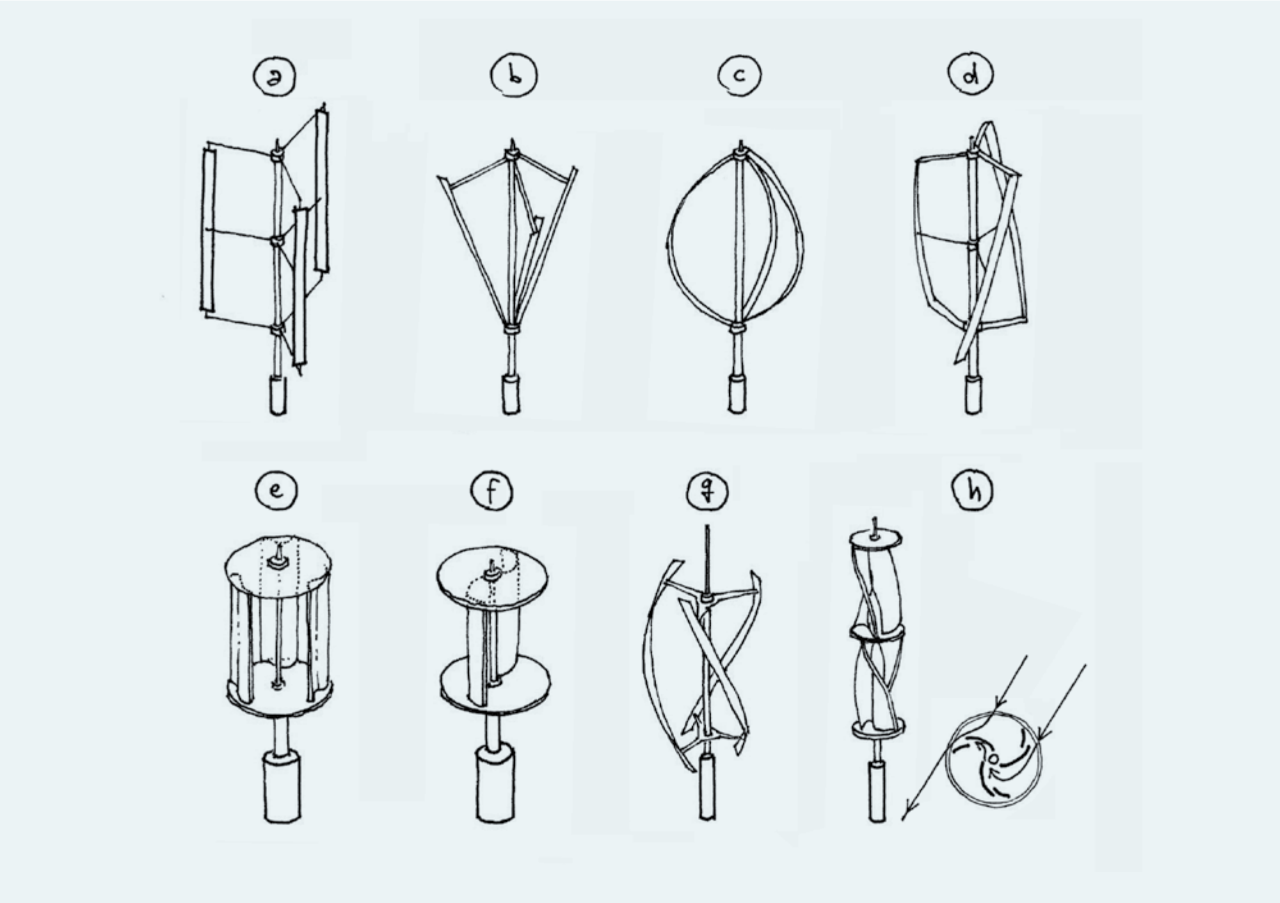


FIGURE 6.3-2 **VERTICAL AXIS WIND TURBINES. (A), (B), (C) DARREIUS TYPE; (D) GORLOV TYPE; (E) SQUIRREL CAGE DARREIUS; (F) SAVONIUS TYPE; (G) AND (H): INNOVATIVE TURBINES DESIGN**



Vertical axis wind turbines do not need a system to follow the variable wind direction, and for this reason they are generally very robust and durable, since they are mechanically simpler.

Small wind turbines can be installed on a roof, but it is necessary to be very careful about possible vibrations transmitted to the building structure bearing them. Vibrations may cause fatigue phenomena and noise. Furthermore, strong turbulence can occur above the roof, which is unfavorable to horizontal axis devices because of extra stress on the turbine blades and lower energy production (these problems are far less critical in vertical axis turbines). To overcome this problem, the hub of the wind turbine should be 1.4-1.5 times higher than the building. For example, in a 50 m tall building, the height of the hub should be between 20 and 25 m above it. The positioning of the turbine must always be windward of obstacles and the supporting tower must be at least 10 m higher than any obstacle within 100 m. It may be worthwhile to install this type of system on the ground about ten metres from the user, in order to have a noise level equal to that of background noise.

In general, for installations on the roof, a few kW vertical axis turbines are recommended due to their low noise level. Because of the shape of the rotor these turbines have a very limited visual impact. The only downside is the higher than the average cost.

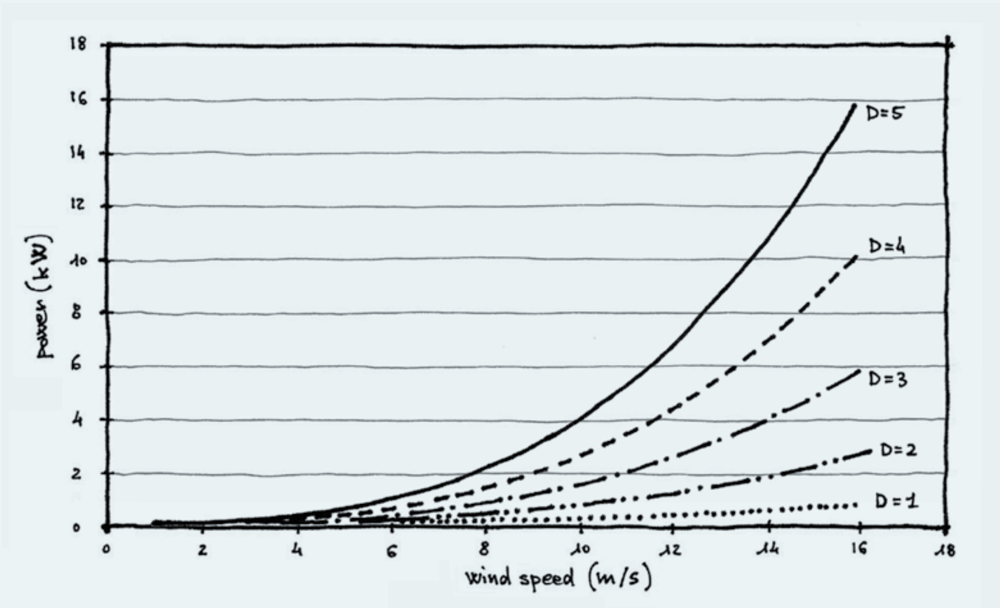
The following formula can be used to evaluate the electric power that a horizontal axis wind turbine can produce (see also figure 6.3-3):

$$P = \alpha D^2 v^3 \qquad (6.3\text{-}1)$$

where:

P = electric power delivered [W];
α = 0.12 – 0.17;
D = diameter of the rotor [m];
v = wind speed [m/s].

FIGURE 6.3-3 **ELECTRIC POWER PRODUCED BY A HORIZONTAL AXIS WIND TURBINE (α = 0,15); D = DIAMETER [M]**

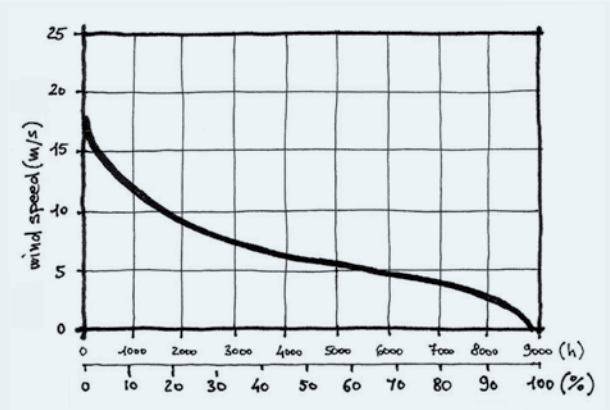


Since the power is a function of the cube of wind speed, it is not possible to evaluate the mean power obtainable by a given device simply by using the mean wind speed. Energy production depends on the wind speed distribution (wind duration curve, figure 6.3-4). An example can better highlight the importance of the wind duration curve. Let's take two extremes for a wind turbine whose diameter is 5 m:

a) wind speed is constant all the time and equal to 8 m/s;

b) wind speed is 16 m/s half the time and for the other half is zero.

FIGURE 6.3-4 **DURATION CURVE**



In both cases the average wind speed in the period is 8 m/s. From the graph of fig. 3 it can be derived that in case a) the mean power produced is 2 kW and in case b) is 15.5/2 = 7.75 kW.

6.4 BIOMASS

In developing countries 2.5 billion people rely on biomass, such as fuelwood, charcoal, agricultural waste and animal dung, to meet their energy needs for cooking[77]. In Sub-Saharan Africa this amounts to more than 600 million[78] people.

In many countries, like Kenya[79], these resources account for over 90% of household energy consumption.

According to the best available figures, household energy use in developing countries totalled nearly 10% of world primary energy demand in 2004. Household use of biomass in developing countries alone accounts for almost 7% of world primary energy demand[77].

77 *IEA, World Energy Outlook 2006*

78 *The World Bank, Household Cookstoves, Environment, Health, and Climate Change, 2011*

79 *Winrock International/USAID, The Kenyan Household Cookstove Sector: Current State and Future Opportunities, 2011 - http://www.relwa.org/sites/default/files/Kenya-Stoves-Assessment-web.pdf*

Presently biomass is used very inefficiently, but its potential, if modern technologies are used, is enormous. Since biomass is used primarily for cooking, the adoption of more efficient cookstoves is crucial. But biomass can also be exploited by means of more advanced technologies, expanding its use to productive activities, reducing energy waste and GHG emissions and improving the quality of life.

6.4.1 BIOMASS COOKSTOVES

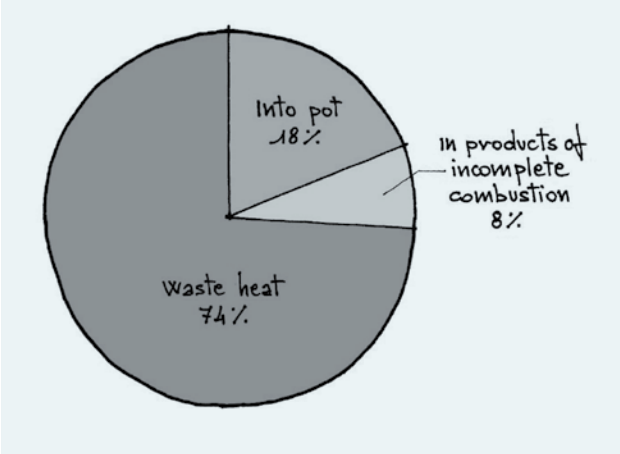
The smoke from indoor cooking with biomass is associated with a number of diseases, including acute respiratory illnesses and even cancer, with women and young children disproportionately affected. It is estimated that smoke from cooking fuels accounts for nearly 2 million deaths annually[80], which is more than the deaths from malaria or tuberculosis; by 2030 over 4,000 people will die prematurely each day from household air pollution[81]. The number of premature deaths is highest in south-east Asia and sub-Saharan Africa[77]. In Kenya, without systematic changes in household fuel use, biomass-based fuel use would result in an estimated 9.8 million premature deaths between 2000 and 2030[82].

Using traditional biomass stoves for household cooking in developing countries requires extensive local fuel collection and is linked to local environmental problems. Unsustainable production of charcoal in response to urban demand, particularly in sub-Saharan Africa, places a strain on biomass resources. Charcoal production is often inefficient and can lead to localised deforestation and land degradation around urban centres; in Kenya only 43% of charcoal supply is sustainably harvested[79]. Scarcity of wood typically leads to greater use of agricultural residues and animal dung for cooking. When dung and residues are used for fuel rather than left in the fields or ploughed back into fields, soil fertility is reduced and propensity to soil erosion is increased. Where demand for local biomass outstrips the natural regrowth of resources, local environmental problems can result.

The amount of biomass cooking fuel required each year can amount to up to 2 tons per family[78]. Such a large amount is due to two reasons:

- the heating value of the fuel used is low;
- open fires and primitive stoves are inefficient at converting energy into heat for cooking (Fig. 6.4-1).

FIGURE 6.4-1 **ENERGY FLOWS IN A TYPICAL WOOD-FIRED COOKING STOVE**



Adapted from: *J. P. Holdren, K. R. Smith, Energy, the environment, and health; in: UNDP, World Energy Assessment – Energy and the Challenge of Sustainability, 2000*

There is mounting evidence that biomass burned inefficiently contributes to climate change at regional and global levels, suggesting that the climate change debate needs to take household energy issues into consideration. In developing countries, about 730 million tons of biomass are burned each year, amounting to more than 1 billion tons of carbon dioxide (CO_2) emitted into the atmosphere[83]. Other products of incomplete combustion and climate forces further exacerbate the problem (Fig. 6.4-2). With better fuels and more efficient cookstoves, such emissions could be reduced. On the other hand, under conditions of sustainable production and more efficient fuel use, biomass energy is renewable.

It is estimated that the new generation of advanced biomass cookstoves would reduce CO_2 emissions by about 25–50 per cent[84]. While some of this reduction might not be counted toward CO_2 reduction because it derives from sustainable biomass, a substantial fraction could come from the biomass resources contributing to resource depletion.

80 *WHO (World Health Organization) and UNDP (United Nations Development Programme). The Energy Access Situation in Developing Countries. New York: United Nations Development Programme, 2009*

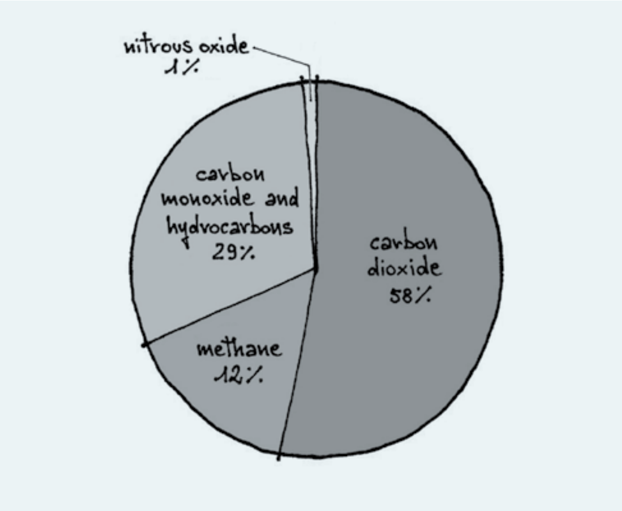
81 *EA, World Energy Outlook 2010 - www.worldenergyoutlook.org.*

82 *Bailis, R., M. Ezzati, and D. M. Kammen, Mortality and Greenhouse Gas Impacts of Biomass and Petroleum Energy Futures in Africa, Science 308: 98–103*

83 *The World Bank, Household Cookstoves, Environment, Health, and Climate Change, 2011*

84 *The World Bank, Household Cookstoves, Environment, Health, and Climate Change, 2011*

FIGURE. 6.4-2 **GREENHOUSE GAS EMISSIONS FROM A TYPICAL BIOMASS COOKSTOVE**



Adapted from: *J. P. Holdren, K. R. Smith, Energy, the environment, and health; in: UNDP, World Energy Assessment – Energy and the Challenge of Sustainability, 2000*

6.4.1.1 **IMPROVED STOVES**

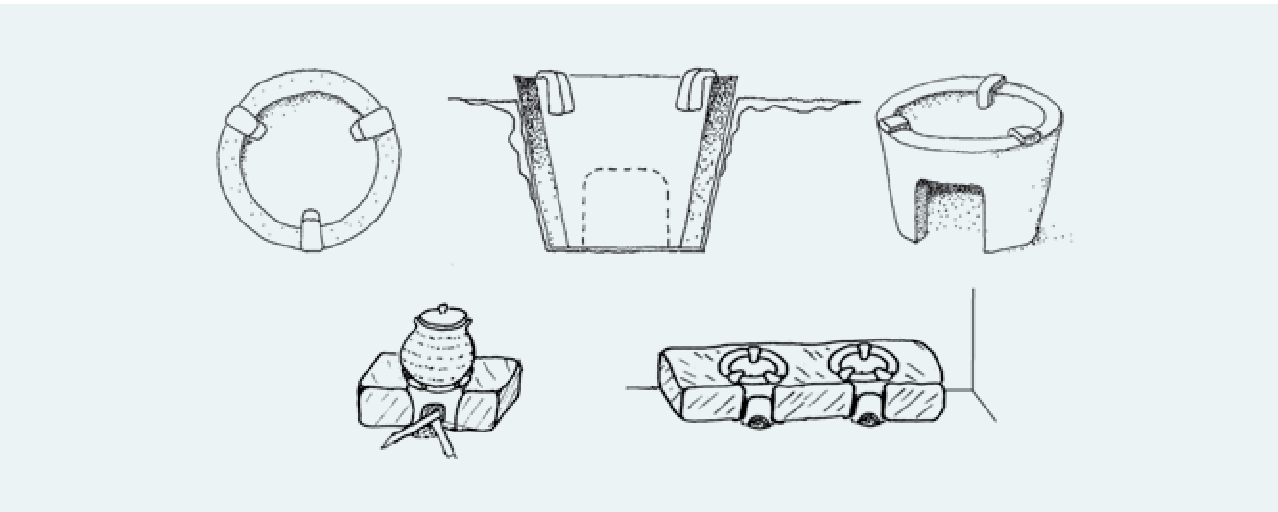
Many types of improved stoves have been developed in the world – with and without a chimney – varying in complexity depending on purpose, frequency of use, volume of pot required, and investment cost. Among the most popular in the EAC are the Maedeleo and the Jiko stoves. They do not solve the problem of smoke, but reduce fuel consumption by up to 50%, compared to a three stone fire.

The simple Maendeleo Stove (Fig. 6.4-3) is based on the production of a ceramic liner which is placed into a clay and stone wall used as insulation, reducing heat loss. Some households have two or more Maendeleo stoves.

This model of stove does not require any additional materials apart from clay and stones. It is therefore very easy to implement in rural settings for domestic purposes. Maintenance is minimal, only requiring clay and stones to repair cracks. Its thermal efficiency (ratio: heat produced/ heat to the pot) is 25-30% with a fuel saving of 40-60%[85].

The Ceramic Jiko portable clay stove is practical as it is versatile for indoor or outdoor cooking, dependent on weather conditions. It does not require cooking facilities to be built. It is made using a simple mould and measuring tools to cut out the air inlet and place the handles and pot rests. The basis of the design is to protect the fire, reduce smoke and direct the flames and hot air up to the pot. An alternative design commonly referred to as the Kenya Ceramic Jiko (Fig. 6.4-4) uses the same principle but based on a metal cladding with a ceramic liner. Jikos in general can be either wood or charcoal fuelled and their thermal efficiency is about 30%; fuel saving 25-50%[86]

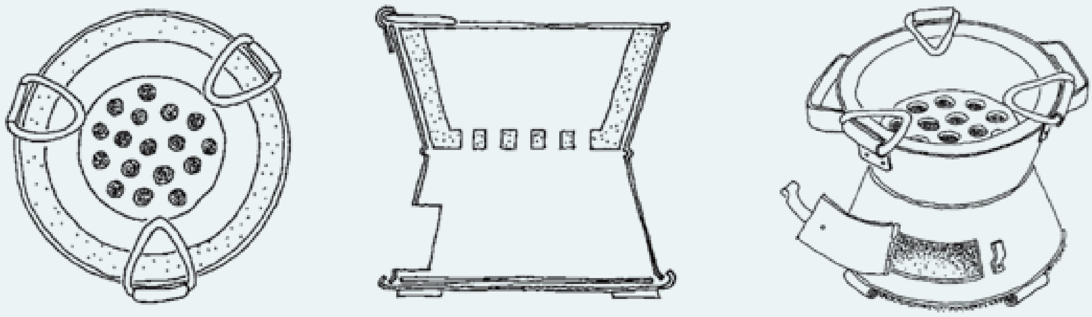
FIGURE 6.4-3 **MAENDALEO STOVE**



Adapted from: *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*

85 *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*
86 *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*

FIGURE 6.4-4 **KENYA CERAMIC JIKO**



Source: *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*

More advanced designs employ metal, bricks and cement and are generally used for fixed stoves. The most popular type of fixed and movable stove is the "rocket stove". It is scalable and comes in a multitude of forms, all using the same principle and adapting it to the capacity requirements and purpose of the stove. The principle of the rocket stove, as shown in figure 6.4-5, is a narrow combustion chamber in the form of an elbow which sucks in air at the bottom, heats it, and as it is heated, it rises up out of the top of the chamber directly onto the pot. If a "pot skirt" is used, the heat can be made to also go up the sides of the pot, further increasing the rate of heat transferral. The woodfuel is placed on a shelf at the base of the stove, using only the ends of the wood making fuel consumption more economical. This principle is applied in various different models; fuel saving is above 50% compared to a three stone fire. A type of fixed rocket stove is shown in figure 6.4-6.

FIGURE 6.4-5 **ROCKET STOVE WORKING PRINCIPLE**

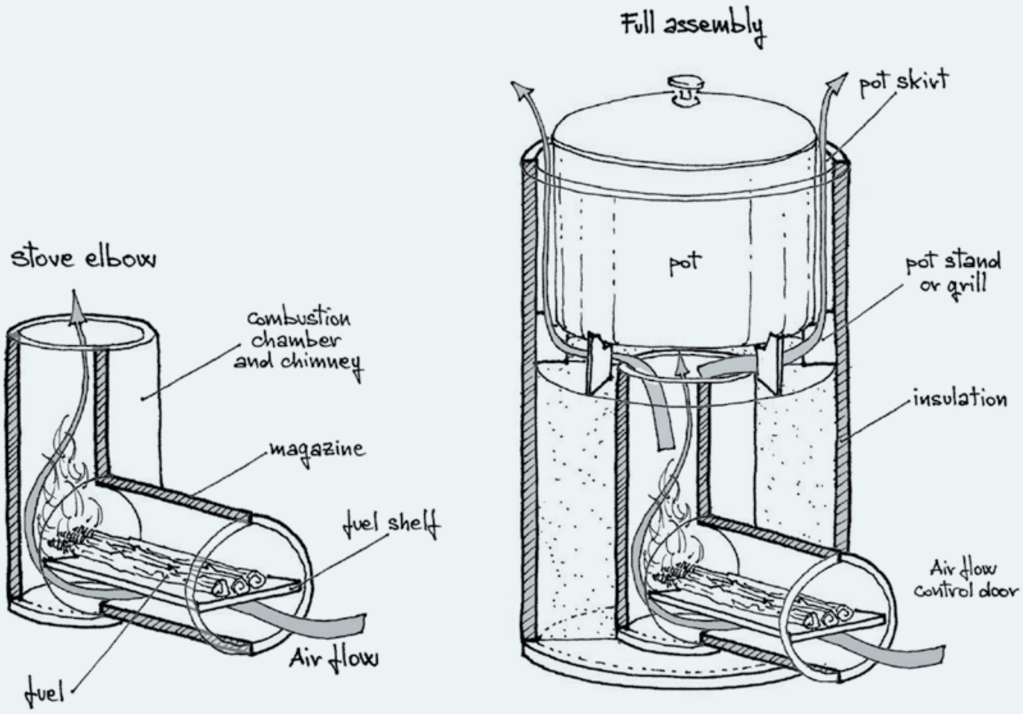
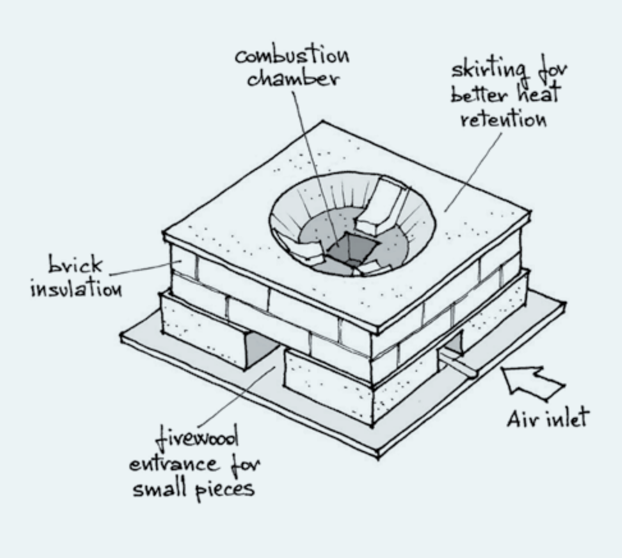


FIGURE 6.4-6 **BRICK ROCKET STOVE**



The Rocket Lorena is a domestic clay-based, wood-fired stove which can be made to take more than one pot (Fig. 6.4-7). The benefits of the model are that all smoke is expelled out of the indoor area through the chimney; it also cooks efficiently, cutting down fuel consumption. The Rocket Lorena can also be fuelled using briquettes made from animal dung. The Jiko Janja is similarly designed but constructed using brick and cement.

6.4.1.2 **KITCHEN STOVES**

Kitchen stoves are on-site combustion devices for domestic cooking and space heating. They are normally self-contained, and provide higher efficiency and low pollution, due to the use of a refractory liner in the combustion chamber allowing a very high flame temperature. They were developed for the market in developed countries.

A kitchen stove typically integrates a cooker and an oven, heated by the hot air and smoke flow (Fig. 6.4-8). Hot water production is also an option with this kind of device.

In some cases the stove has a fan powered either by a battery, an external source of electricity, or a thermoelectric generator. This fan blows high velocity, low volume jets of air into the combustion chamber, which, when optimised, results in much more complete combustion of the fuel.

6.4.1.3 **FIREPLACE HEATING SYSTEM**

While a conventional fireplace is a local heating device directly providing mainly radiant heat to a limited area of a building, in a fireplace heating system hot air can be channelled into air ducts and sent to different rooms of the building.

FIGURE 6.4-7 **THREE POT LORENA MUD ROCKET STOVE**

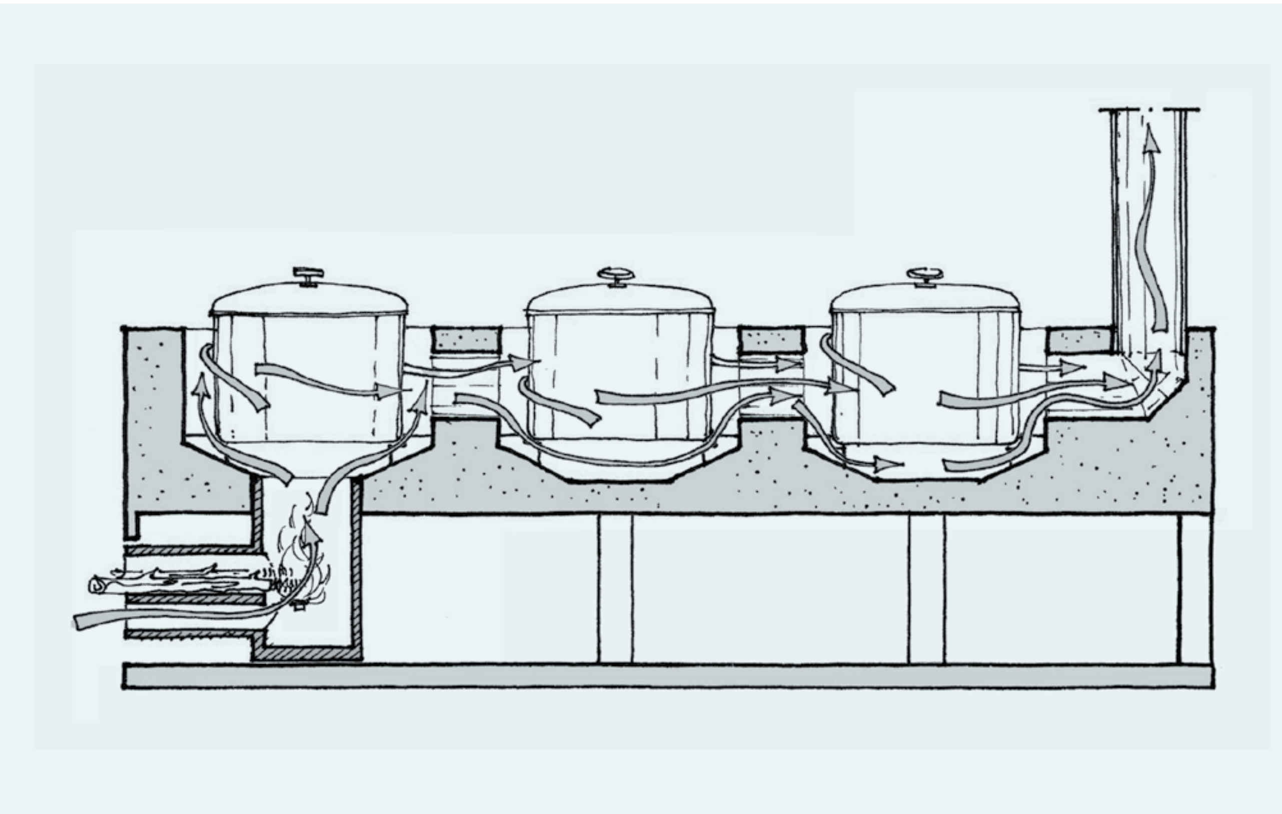
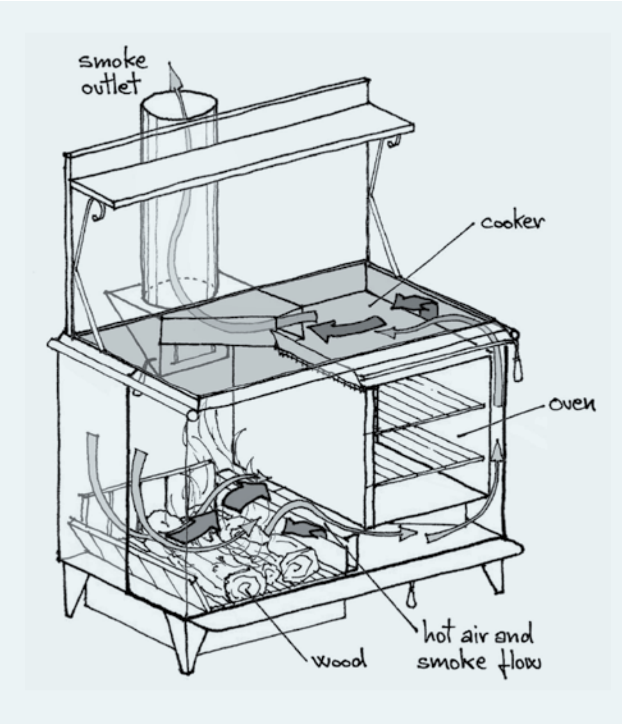


FIGURE 6.4-8 **KITCHEN STOVE**



A fireplace heating system consists of a high-efficiency fireplace (whose combustion temperature is increased with the use of a glass shield closing the firebox), equipped with fans to circulate heated air and an air-to-water heat exchanger usually placed in the upper part of the combustion chamber (Fig. 6.4-9). Moreover, in some products, an additional fraction of energy can be recovered thanks to the water circuit, by which cold water is circulated by a pump in the heat exchanger and used for heating purposes or to produce DHW.

6.4.1.4 **PELLET/BRIQUETTE HEATING STOVE**

Wood burning heating stoves can be fuelled with pieces of wood but can also be equipped with an automatic loading system (Fig. 6.4-10); in such case, wood chips, pellets, briquettes, seeds, shells or any other kind of dry biomass can be efficiently burned. The loading system typically consists of a hopper and a screw feed, managed by an electronic control; heat output is controlled by a thermostat, which regulates how much fuel has to be fed into the heating chamber. Domestic systems are normally provided with an internal hopper which may contain from 15 to 30 kg of melted biomass, assuring several days of functioning without manual refill. Ash drops down into an ash pan, which, thanks to the high efficiency and combustion temperatures, only requires occasional emptying (typically few times a year). Fireplace heating systems with automatic fuel and combustion control and air-to-water heat exchanger for DHW production can have an overall efficiency close to 90% and typically provide a thermal power from a few kilowatts to 30 - 35 kW.

FIGURE. 6.4-9 **FIREPLACE HEATING SYSTEM WITH FORCED-VENTILATION**

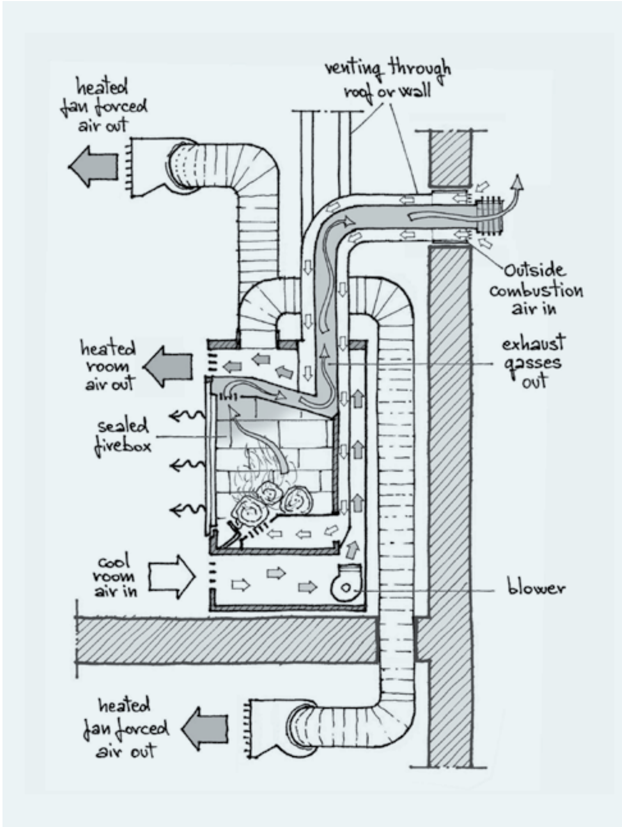
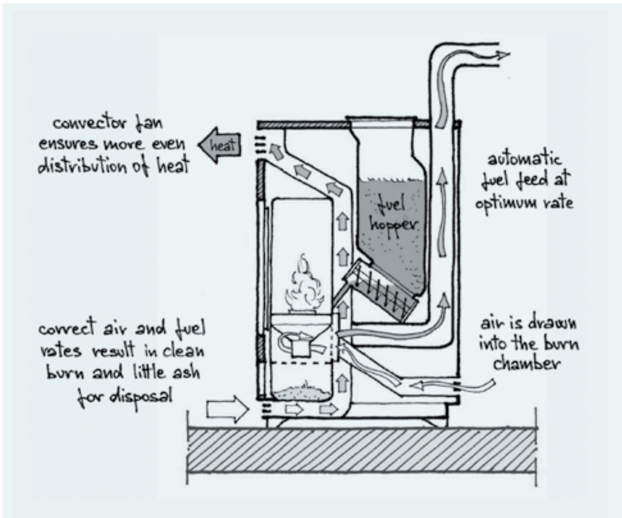


FIGURE 6.4-10 **HEATING WOOD STOVE WITH AUTOMATIC FUEL AND COMBUSTION CONTROL**



Problems related to environmental pollution due to the smoke produced by fireplaces and wood burning heating stoves must be given careful consideration. If automatic fuel and combustion control systems can assure optimal burning in all operating conditions, this will significantly reduce airborne particulate.

6.4.2 BEYOND SIMPLE BIOMASS BURNING

Biomass is a promising alternative source of energy to fossil fuels for many reasons: availability, different typologies, programmability and storage, technological maturity, and there is new research in the field of small cogeneration, bio-methane distribution and second-generation biofuel production.

In fact different technologies are available today depending on the type of biomass to be processed, the final energy needs to be satisfied and on the economic conditions.

6.4.2.1 CHARACTERISATION OF BIOMASS

Processable biomass includes plants (trees, agricultural plants, bush, grass, algae, etc.), agricultural residues (crop and agro-processing), and wastes (the organic content of municipal waste, animal and human wastes), Table 6.4-1. The resource is highly decentralized and scattered.

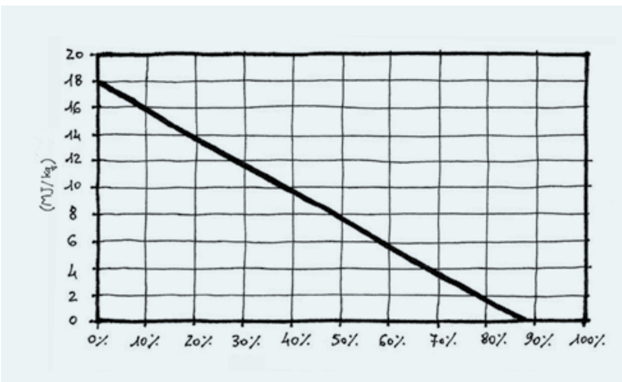
The LHV (Low Heating Value) ranges from 8 to 16 MJ/kg depending on the humidity level (Fig. 6.4-11).

TABLE 6.4-1 **BIOMASS CLASSIFICATION ACCORDING TO THE SUPPLY SECTOR**

Supply sector	Type	Examples
Forestry	Dedicated forestry	Short rotation forestry (e.g. willow, poplar, eucalyptus or others, depending on the climate)
	Forestry by-products	Wood blocks, wood chips from thinning
Agriculture	Dry wood-cellulosic energy crops	Herbaceous crops (e.g. miscantus, or others, depending on the climate)
	Oil, sugar and starch energy crops	Oily seeds (rape, sunflower etc.)
	Agricultural residues	Straw, pruning from vineyards and fruit trees
	Livestock waste	Wet and dry manure
Industry	Industrial residues	Wood waste, sawdust
		Fibres from paper industry
Waste	Dry wood-cellulosic	Residues from parks and gardens
	Contaminated waste	Demolition wood
		Organic fraction of solid waste
		Landfill gas
		Sewage sludge

Source: *European Biomass Industry Association - http://www.eubia.org/index.php/about-biomass/biomass-characteristics*

FIGURE 6.4-11 **LHV OF BIOMASS VERSUS HUMIDITY CONTENT**



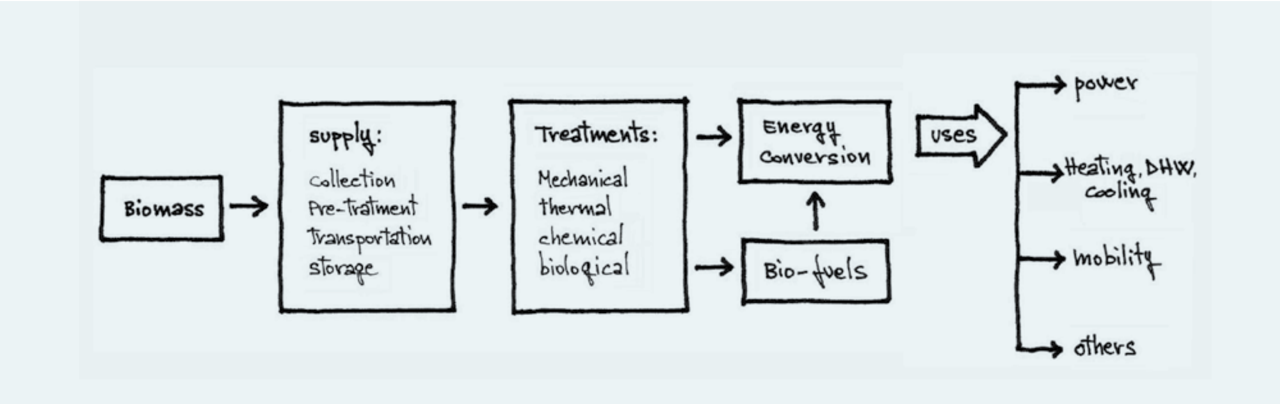
Adapted from: *P. Caputo, Impianti a biomassa. Dal riscaldamento alla trigenerazione. Edizioni Ambiente, Milano, 2011*

Unlike other renewable sources, to analyse the energy conversion of biomass it is necessary to consider the complex chain of the overall process (Fig. 6.4-12) in which harvesting and supply have capital importance.

Heating values, humidity, density and contaminants

Biomass is dealt with in the same way as urban waste (see also section 6.3).The moisture content (Table 6.4-2) and the heating value (Table 6.4-3) are the main elements to be considered when planning how the waste can be effectively treated. In addition, an analysis of contaminants and pollutants has to be carried out in order to prevent environmental hazards due to emissions during and after the treatment process. These data can be highly variable depending on the type of biomass and on the pre-treatment and storage mode.

FIGURE 6.4-12 **BIOMASS TO ENERGY PROCESSES**



***Adapted from:** P. Caputo, Impianti a biomassa. Dal riscaldamento alla trigenerazione. Edizioni Ambiente, Milano, 2011)*

TABLE 6.4-2 **MOISTURE CONTENT FOR SELECTED BIOMASS RESOURCES**

Biomass resource	Moisture content (% on weight basis)
Industrial fresh wood chips and sawdust	40-60%
Industrial dry wood chips and sawdust	10-20%
Fresh forest wood chips	40-60%
Chips from wood stored and air-dried several months	30-40%
Waste wood	10-30%
Dry straw	15%

***Source:** European Biomass Industry Association - http://www.eubia.org/index.php/about-biomass/biomass-characteristics)*

6.4.2.2 AVAILABLE AND APPLICABLE TECHNOLOGIES FOR TRANSFORMING BIOMASS INTO ENERGY

Generally speaking, thermochemical processes are applied when the moisture content and the ratio C/N (Carbon/Nitrogen) are quite high, otherwise biochemical processes are applied. In most cases mechanical and other conditioning treatments are scheduled between collection and the subsequent steps in the chain.

Depending on its properties, biomass can be used in many applications for energy conversion, from small stoves to big cogeneration plants.

TABLE 6.4-3 **SOME CHARACTERISTICS OF BIOMASS FUELS COMPARED TO OIL AND COAL**

Fuel	[GJ/t]	[tOE/t]	[kg/m^3]	[GJ/m^3]
Fuel oil	41.9	1.00	950	39.8
Coal	25.0	0.60	1000	25.0
Pellet (8% moisture)	17.5	0.42	650	11.4
Pile wood	9.5	0.23	600	5.7
Industrial softwood chips (50% moisture)	9.5	0.23	320	3.0
Industrial softwood chips (20% moisture)	15.2	0.36	210	3.2
Forest softwood chips (30% moisture)	13.3	0.32	250	3.3
Forest hardwood chips (30% moisture)	13.3	0.32	320	4.3
Straw chopped (15% moisture)	14.5	0.35	60	0.9
Straw big bales (15% moisture)	14.5	0.35	140	2.0

***Source:** European Biomass Industry Association - http://www.eubia.org/index.php/about-biomass/biomass-characteristics)*

Thermochemical treatments

Different biochemical or thermal treatments can be used to convert biomass into heat and power. The most common is the thermal treatment of combustion, but, especially for small and medium sizes, pyrolysis and gasification are also applicable.

Small scale

Potential small scale uses of biomass in the EAC include stoves, water heaters and gasification systems.

The design of gasifiers depends on the type and quantity of fuel used and whether the gasifier is portable or stationary. Gas producers are classified according to how the air blast is introduced into the fuel column. The most commonly made gasifiers are classified as: Updraft gasifier, Downdraft gasifier, Twin-fire gasifier, Crossdraft gasifier, Plasma Gasification, Transport Gasifier and Circulating Fluidized Bed gas gasifier.

Gasifiers are available from 5 kW capacity, are suitable for a variety of biomass and have been developed in many countries.

The suitability of a particular type depends on the application and the type of biomass. For use in internal combustion engines, a downdraft gasifier is the most suitable. Updraft and crossdraft gasifiers are suitable for thermal applications.

In a downdraft gasifier, air is introduced into a downward flowing packed bed or solid fuel and the gas is drawn off at the bottom (Fig. 6.4-13a). Lower overall efficiency and difficulties in handling higher moisture and ash content are common problems in small downdraft gas producers.

An updraft gasifier (Fig. 6.4-13b) has clearly defined zones for partial combustion, reduction, and pyrolysis. Air is introduced at the bottom, and acts as counter-current to the fuel flow. The gas is drawn off at a higher position. The updraft gasifier achieves the highest efficiency as the hot gas passes through fuel bed and leaves the gasifier at a low temperature. The sensible heat given by gas is used to preheat and dry fuel. Disadvantages of updraft gas producers are the excessive amount of tar in the raw gas and the poor loading capability.

In cross draft gasifiers the ashbin, fire and reduction zones are separated. These design characteristics limit the type of fuel that can be used to low ash fuels such as wood, charcoal and coke. The relatively higher temperature in a cross draft gas producer has an obvious effect on gas composition such as high carbon monoxide, and low hydrogen and methane content when dry fuel such as charcoal is used. A crossdraft gasifier operates well on dry air blast and dry fuel.

FIGURE 6.4-13 **SKETCH OF DOWNDRAFT (A) AND UPDRAFT (B) GASIFIERS**

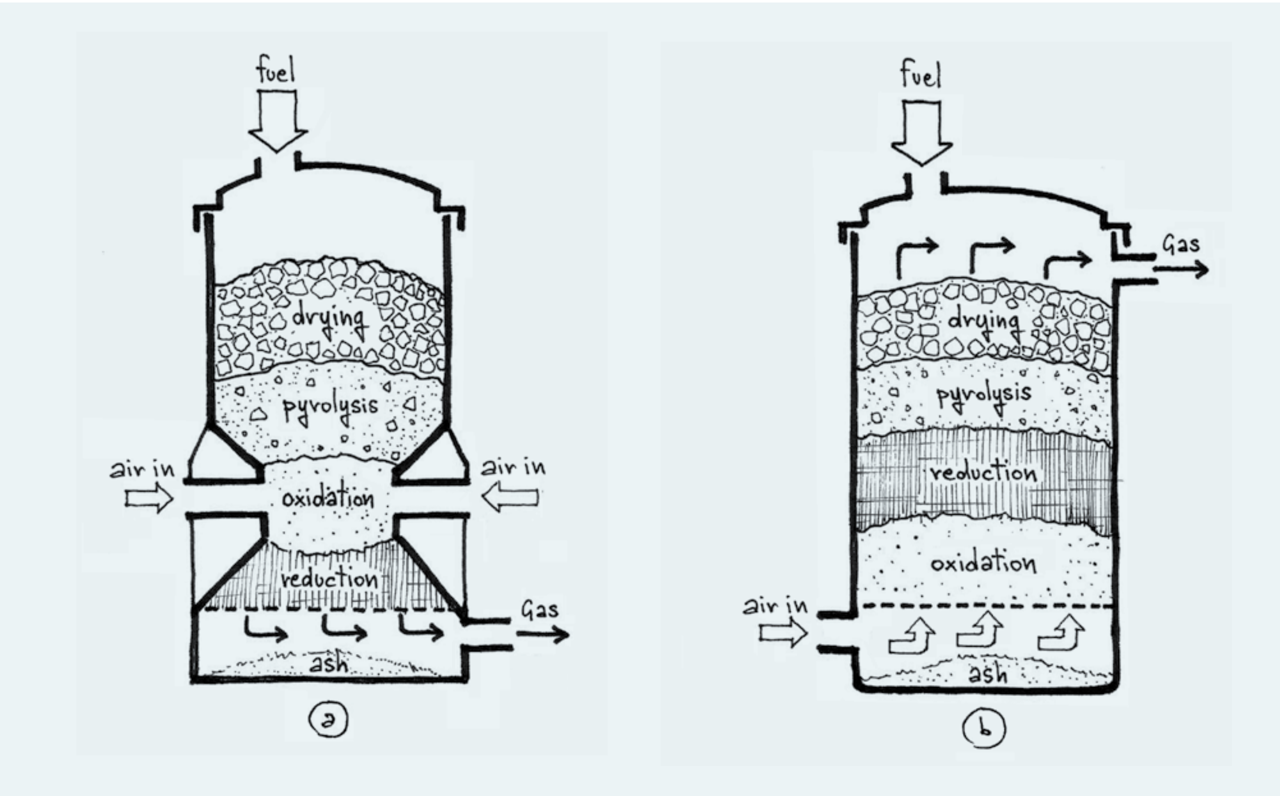
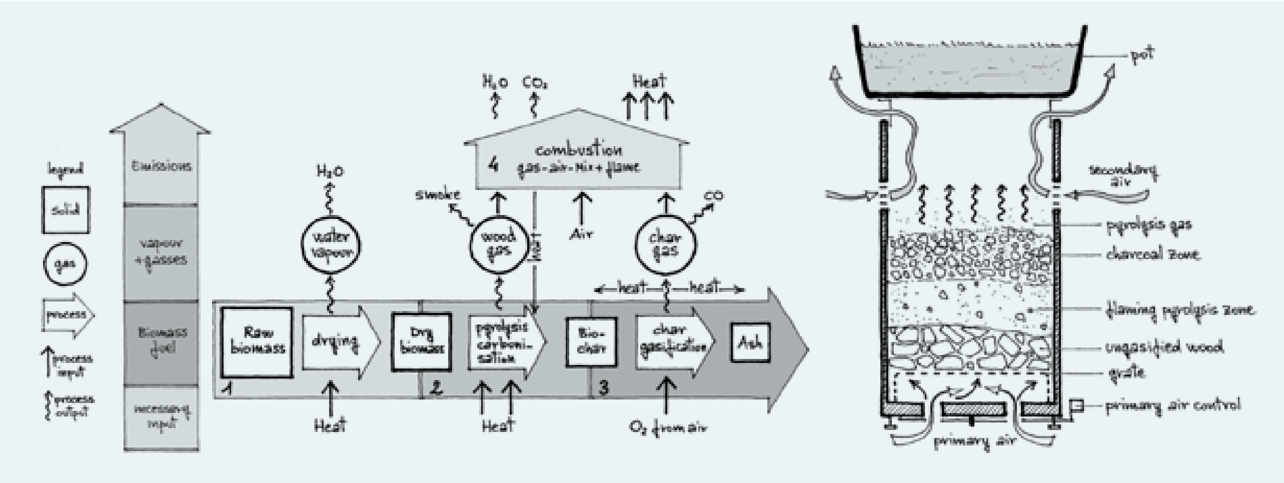


FIGURE 6.4-14 **MICRO-GASIFIER OR WOOD-GAS-STOVE WORKING PRINCIPLE**



Adapted from: *C. Roth, Micro Gasification: Cooking with gas from biomass, GIZ HERA, 2011*

Wood-to gas stoves

The use of gasification technologies to produce a much cleaner and more efficient cooking stove is a relatively new concept. Using a micro-gasifier, solid biomass is converted into wood gas that burns when mixed with oxygen and ignited. Fig. 6.4-14 illustrates the principle behind the design.

The process to create heat from solid biomass goes in stages[87]:

- as biomass is heated, it evaporates excess moisture and its surface temperature increases,
- at elevated temperatures, biomass pyrolysis into combustible vapours and a solid, known as char,
- red hot char can be converted to ash if sufficient oxygen is available,
- mixed with oxygen the vapours and gases generated can be combusted when ignited

In each step vapours and gases are released and the solids reduce in mass and volume.

If complete combustion is attained, emissions should be clean and only contain carbon dioxide and water vapour and biochar remains at the base of the stove. It can be used for other purposes or as fertilizer. If combustion is not complete, then smoke and vapours composed of unburned fuel and carbon monoxide will result.

Most micro-gasifiers for cooking use are lit at the top of the fuel-bed. This is an easy way to keep the heat close under the cooking pot. Many micro-gasifiers work with a batch-load of fuel, meaning the fuel container is filled once and then lit at the top.

The advantages of wood-gas-stoves over the improved stoves are[87]:

- Cleaner burning of biomass (much less soot, black carbon and indoor/outdoor air pollution)
- Higher efficiency due to more complete combustion
- A wide variety of small-size biomass residues can be used (no need for stick-wood or charcoal)
- Biomass fuels are often within the immediate area of the users (affordable access at own convenience), easy to transport and easy to store after gathering
- Gas from dry biomass can be achieved with very simple inexpensive technology directly in the burner unit (portable, no piping or special burner-head needed)
- Performance similar to biogas (but not dependent on water and bio-digester) and approaching the convenience of fossil gases
- Gas available on demand (unlike electricity or LPG that are dependent on local providers and imports, and unlike solar energy that is dependent on clear weather and daylight hours)
- Easy lighting permits cooking to start within minutes (contrasted with charcoal slowness)
- Gasifier units can be attached to existing stove structures to broaden the range of usable fuels, giving users the choice to use what is available at the moment
- Can create charcoal as by-product of cooking
- Enable carbon-negative cooking if char is saved and used as biochar

87 *C. Roth, Micro Gasification: Cooking with gas from biomass, GIZ HERA, 2011*

The disadvantages are:

- Regulation of firepower can be difficult.
- Difficulties to extinguish gas-generation at the end of the cooking process before all fuel is consumed
- Inflexibility of cooking times with batch-feeding device that cannot be refuelled during operation
- Require fire-starting material to initiate pyrolysis in the gas-generator
- If the flame of the combustion unit extinguishes and the gas-generator keeps on producing woodgas, thick smoke leaves the unit unburned.

There are a variety of wood-gas-stoves available in the market, with thermal efficiency up to 40%[88] and a fuel saving ranging from 30 to 50%[89], compared with the three-stone open fire.

Medium-large scale

In general, technologies suitable for a size between 10 and 50 MW of electric power are considered. For these sizes, heat generation, electricity generation or both are possible .

All these plants are equipped with a suitable depuration line for reducing dust, ash and other pollutants that may be emitted.

Storage and final disposal of ash and dust are also taken into account in the design.

Stirling engines and Organic Rankine Cycles (ORC) are other smart and efficient technologies which produce power or cogenerate power and heat (to be converted into cooling energy by means of absorption chillers) from different kinds of biomass.

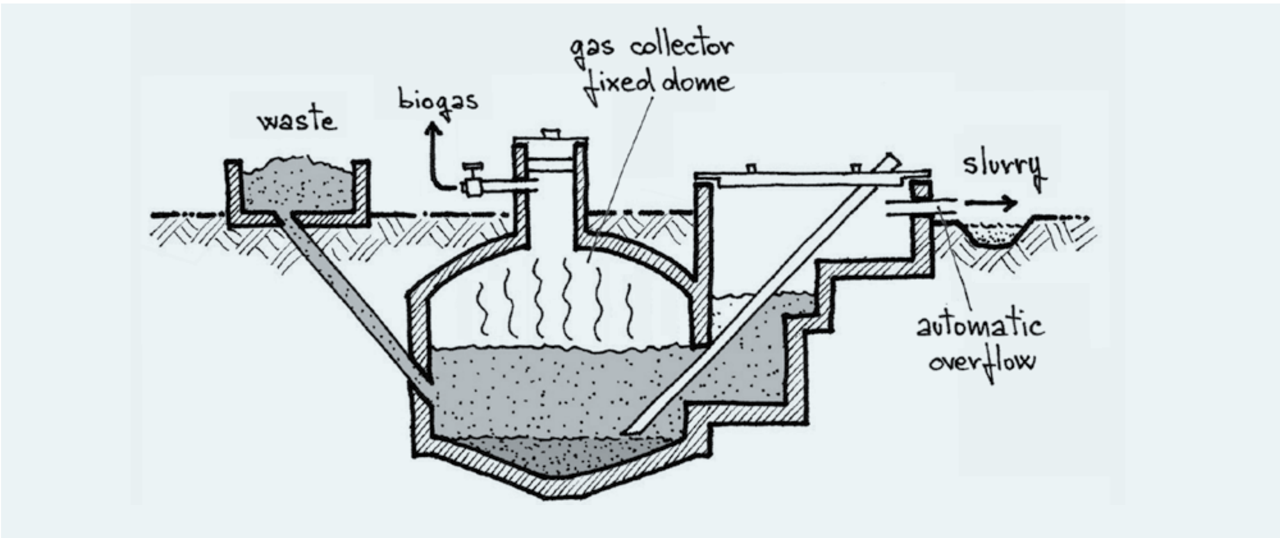
Biogas and bio-methane

Biogas is defined as a gas produced by the fermentation of particular kinds of biomass in the absence of oxygen (anaerobic digestion). This process takes place in the digester (Fig. 6.4-15).

Anaerobic digestion is the process of converting organic matter to biogas by microbial action in the absence of air. The process has two benefits: it yields biogas, which can replace conventional fuels and it provides digested sludge, which can be used as a high nutrient fertilizer. The bacteria decompose the organic wastes to produce a mixture of methane and carbon dioxide gas (biogas). After digestion, the sludge is passed to a sedimentation tank where it is thickened. The thickened sludge needs to be treated further prior to reuse or disposal.

Table 6.4-4 shows that the biogas yield of these different substrates is heavily dependent on the type and concentration of the organic matter. The fermentation of manure alone results in relatively low biogas yields, but it has a positive effect on the stability of the process due to its high buffering capacity and its high content of trace elements. In order to increase the gas yield most biogas plants today are operated by co-fermentation of manure together with non-agricultural organic wastes, and residues and energy are harvested.

FIGURE 6.4-15 **SCHEME OF A BIOGAS DIGESTER.**



88 T. B. Reeda, E. Anselmo and K. Kircherc, Testing & Modeling the Wood-Gas Turbo Stove, http://journeytoforever.org/biofuel_library/TurboStove.pdf

89 S. Carter, S. Shackley, Biochar Stoves: an innovation studies perspective, UK Biochar Research Centre (UKBRC), School of GeoSciences, University of Edinburgh, 2011

TABLE 6.4-4 **BIOGAS YIELD FROM DIFFERENT SUBSTRATES**

Substrate	m^3 of Biogas per ton of wet biomass
Cow manure	25
Pig manure	30
Yard manure	60
Beet leafs	60
Fodder beets	90
Sudan grass	130
Grass silage	160
Maize silage	230
Cereal residues	550
Old bread	600
Baking wastes	714
Used grease	960

Adapted from: *F. Cotana and D. Giraldi, Renewable energy for agricultural companies: a biogas micro-chp project - http://www.ciriaf.it/ft/File/Pubblicazioni/pdf/1447.pdf*

Generally speaking, data from technical literature state a production greater than 100 m^3 of biogas for each ton of matter (suitable mix of agricultural and breeding by-products) treated by anaerobic digestion. Greater or lower values are possible in a range of about 20 to 300 m^3/t depending on the characteristics of the different substrates and on the management conditions. Taking into account the output from waste water management, on the basis of available experience in the EU and of technical literature, 15-30 litres of biogas produced by anaerobic digestion of sludge per person and per day and a low heating value (LHV) of 6.5 kWh/m^3 can be assumed. At household scale, including kitchen wastes, the production may reach 30-60 litres per person per day[90].

Household digesters can be split into two parts: one buried or aboveground, where the biomass is conveyed and where the digestion process takes place and the other a separate gasholder, which can be simply a large plastic inflatable container (Fig. 6.4-16).

The production of a household biogas digester only partially substitutes other sources of energy as shown in Tables 1 and 2, but significant savings in fuelwood for cooking can be made.

90 G. P.Nembrini, A. Kimaro, Using Biogas Plants for Treatment of Urban Community Wastes to Supply Energy and Improve Sanitation, presented at the Expert Group Meeting on "Energy Access for the Urban Poor", December 2006, Nairobi

FIGURE 6.4-16 **ABOVE GROUND PLASTIC INFLATABLE GASHOLDER**

Photo credit: *UN-Habitat/Vincent Kitio*

TABLE 6.4-5 – **BIOGAS CONSUMPTION OF SELECTED APPLIANCES***

	Appliance	Litre/hour
1)	Household burner	200 - 500
2)	Institutional burner	1,500 – 2,500
3)	Gas lamp	150 - 200
4)	Refrigerator (100litre)	50 - 80

TABLE 6.4-6 – **BIOGAS CONSUMPTION OF SOME APPLICATIONS***

	Application	Litre
1)	Boiling 1litre of water	40
2)	Boiling 5 litre of water	165
3)	Cooking ½ kg rice	140
4)	Cooking 1 kg rice	175
5)	Cooking ½ kg beans	300
6)	Generation of 1 kWh	700

* ***Source:*** *IEA, World Energy Outlook 2006*

6.4.3 MOST PROMISING USES: WHICH KIND OF ENERGY DEMAND CAN BE EFFECTIVELY MATCHED

A large number of technologies are now available which, when integrated into buildings, would result in substantial reductions in conventional energy demand.

In the building sector in tropical regions biomass and bio-fuels can contribute to meeting the electric loads, the water heating loads and the cooling loads if CHP systems are adopted and coupled with absorption chillers.

In detail:

- as far as direct burning of solid biomass is concerned, boilers and steam power plants can be adopted;
- as far as conversion of biomass to gaseous fuel is concerned, the output of a biomass gasifier can be used for a variety of purposes such as cooking, drying, heating water, generating steam, etc. The gas produced can be used as fuel in internal combustion engines to obtain mechanical shaft power or electrical power. Similarly, biogas is an excellent fuel for cooking and lighting. It can also be used as fuel in engines. As cooking accounts for a significant proportion of household energy consumption, integration of the use of the above options with buildings leads to considerable energy savings.

6.4.4 CRITICISMS AND SOLUTIONS

In sustainable communities of the future, characterized by high energy efficiency, biomass could be an important part of the energy system. Even if the supply of biomass could be a problem due to logistical problems such as transportation, this should not be considered an insurmountable obstacle. But the issue needs to be addressed with due care since there is a growing concern about the negative effects of deforestation caused by shifting cultivation and charcoal production. Deforestation causes damage to the local flora and fauna and, if it is followed by cultivation, can significantly reduce organic matter in the soil. Further deforestation can cause a worsening of the CO_2 balance, totally invalidating the benefits from the use of biomass.

The possibility of improving biomass production through specialised cultivations (i.e. energy crops, short rotation forestry etc.) should be carefully assessed; detailed research has to be carried out in order to evaluate all the effects of any modification. This is a key point for protecting biodiversity and local agricultural traditions.

Despite the debate about food and non-food biomasses, recently the scientific community has agreed that bio-energy may need to play a part in a future low carbon energy mix. If land is used more sustainably and productively, and if residues and wastes are reused, it will be possible to produce bio-energy, feed a growing population and conserve the environment at the same time.

6.5 HYDROPOWER

Hydropower is energy from water sources such as the ocean, rivers and waterfalls. The term "Mini- hydro" can apply to sites ranging from a tiny scheme to electrify a single home, to a few hundred kW. Small-scale hydropower is one of the most cost-effective and reliable energy technologies that can be used for generation of clean electricity. The key advantages of mini- hydro are[91]:

- high efficiency (70 - 90%);
- high capacity factor[92] (typically >50%);
- high level of predictability, varying with annual rainfall patterns;
- slow rate of change; the output power varies only gradually from day to day (not from minute to minute);
- a good correlation with demand i.e. output is maximum in winter; long-lasting and robust technology; systems can readily be engineered to last for 50 years or more.

It is also environmentally benign. Small hydro is in most cases "run-of-river"; in other words any dam or barrage is quite small, usually just a weir, and little or no water is stored. Therefore run-of-river installations do not have the same kinds of adverse effects on the local environment as large-scale hydro.

6.5.1 HYDRO POWER BASICS

Hydraulic power can be captured wherever a flow of water falls from a higher level to a lower level. The vertical fall of the water, known as the "head", is essential for hydropower generation; fast-flowing water on its own does not contain sufficient energy for useful power production; hence two quantities are required: a flow rate of water *Q*, and a head *H***.** It is generally better to have more head than more flow, since this keeps the equipment smaller.

91 *Mini-Hydro Power, 2010, http://w3.tm.tue.nl/fileadmin/tm/TDO/Indonesie/Hydro_Power.pdf*

92 *Capacity factor is a ratio summarizing how hard a turbine is working, expressed as:Capacity factor (%) = Energy generated per year (kWh/year) / {Installed capacity (kW) x 8760 hours/year}*

The Gross Head (*H*) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head.

Flow Rate (*Q*) is the volume of water passing per second, measured in m^3/sec. For small schemes, the flow rate may also be expressed in litres/second.

The general formula for any hydro system's power output is:

$$P = \eta \rho g Q H \quad (6.5\text{-}1)$$

where:

- P = the mechanical power produced at the turbine shaft [W];
- η = the hydraulic efficiency of the turbine, ρ is the density of water (1000 kg/m^3);
- g = the acceleration due to gravity (9.81 m/s^2);
- Q = the volume flow rate passing through the turbine [m^3/s];
- H = the effective pressure head of water across the turbine [m].

The best turbines can have hydraulic efficiencies ranging from 80 to over 90%, although this will reduce with size. Micro-hydro systems (<100kW) tend to be 60 to 80% efficient.

The annual energy output of a hydro power plant can be estimated using the Capacity Factor (CF) as follows:

$$\text{Energy} = P \times CF \times 8760 \text{ [Wh/year]} \quad (6.5\text{-}2)$$

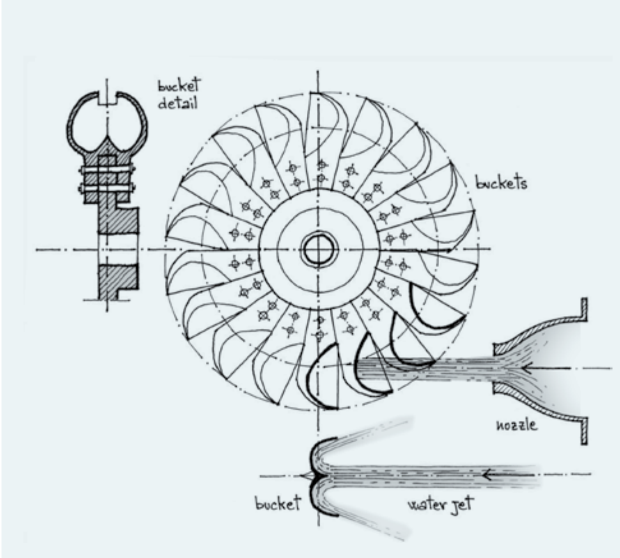
6.5.2 TYPES OF TURBINE

Turbines can be categorized mainly into two types: impulse turbine and reaction turbine.

There are various types of impulse turbine.

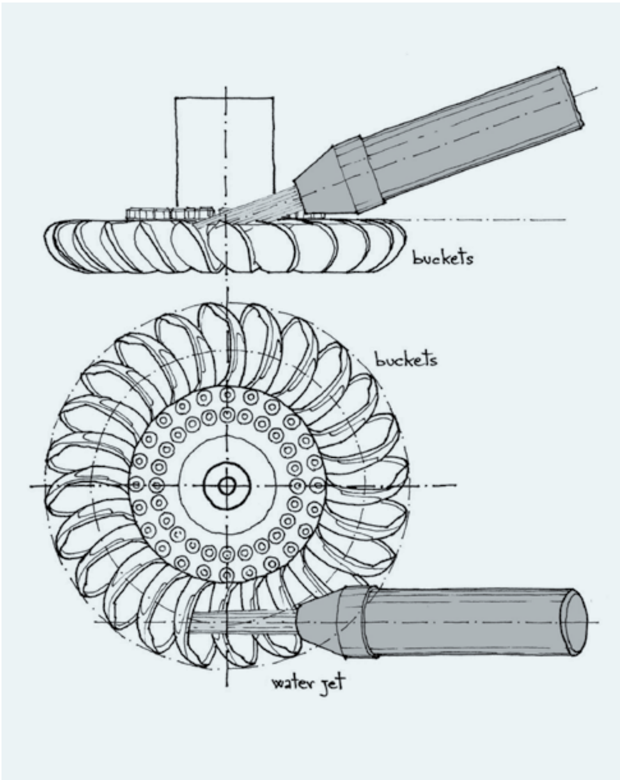
The *Pelton* turbine (Fig. 6.5-1*)* consists of a wheel with a series of split buckets set around its rim; a high velocity jet of water is directed tangentially at the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through 180°. Nearly all the kinetic energy of the water goes into propelling the bucket and the deflected water falls into a discharge channel.

FIGURE 6.5-1 **PELTON WHEEL**



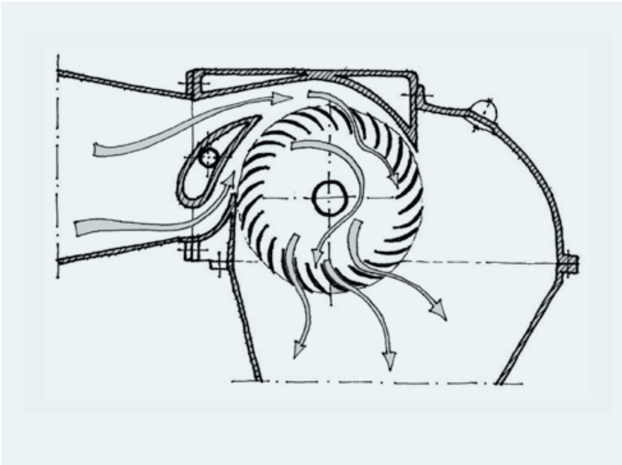
The *Turgo* turbine (Fig. 6.5-2) is similar to the Pelton but the jet strikes the plane of the runner at an angle (typically 20°) so that the water enters the runner on one side and exits on the other. Therefore the flow rate is not limited by the discharged fluid interfering with the incoming jet (as is the case with Pelton turbines). As a consequence, a Turgo turbine can have a smaller diameter runner than a Pelton for an equivalent power.

FIGURE 6.5-2 **TURGO TURBINE**



The *Crossflow* turbine (Fig. 6.5-3) has a drum-like rotor with a solid disk at each end and gutter-shaped "slats" joining the two disks. A jet of water enters the top of the rotor through the curved blades, emerging on the far side of the rotor by passing through the blades a 2nd time. The shape of the blades is such that on each passage through the periphery of the rotor the water transfers some of its momentum, before falling away with little residual energy.

FIGURE 6.5-3 **CROSSFLOW TURBINE**



Reaction turbines exploit the oncoming flow of water to generate hydrodynamic lift forces to propel the runner blades. They are distinguished from the impulse type by having a runner that always functions within a completely water-filled casing. All reaction turbines have a diffuser known as a 'draft tube' below the runner through which the water discharges. The draft tube slows the discharged water and reduces the static pressure below the runner and thereby increases the effective head.

Propeller-type turbines (Fig. 6.5-4) are similar in principle to the propeller of a ship, but operating in reversed mode. Various configurations of propeller turbine exist; a key feature is that for good efficiency the water needs to be given some swirl before entering the turbine runner. With good design, the swirl is absorbed by the runner and the water that emerges flows straight into the draft tube. Methods for adding inlet swirl include the use of a set of guide vanes mounted upstream of the runner with water spiralling into the runner through them.

Another method is to form "snail shell" housing for the runner in which the water enters tangentially and is forced to spiral in to the runner. When guide vanes are used, these are often adjustable so as to vary the flow admitted to the runner. In some cases the blades of the runner can also be adjusted, in which case the turbine is called *Kaplan* (Fig. 6.5-5). The mechanics for adjusting turbine blades and guide vanes can be costly and tend to be more affordable for large systems, but can greatly improve efficiency over a wide range of flows.

FIGURE 6.5-4 **PROPELLER TYPE TURBINE**

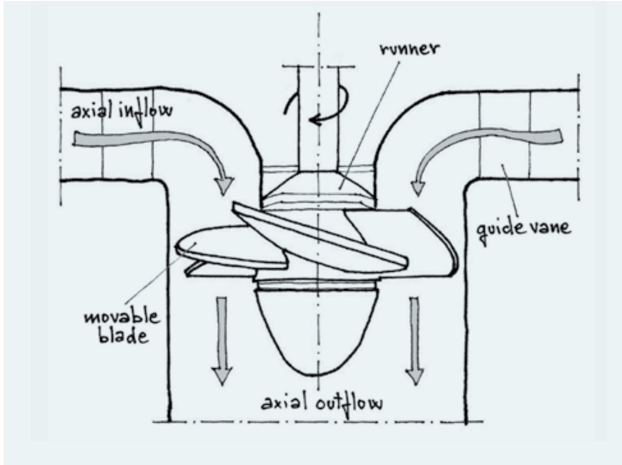
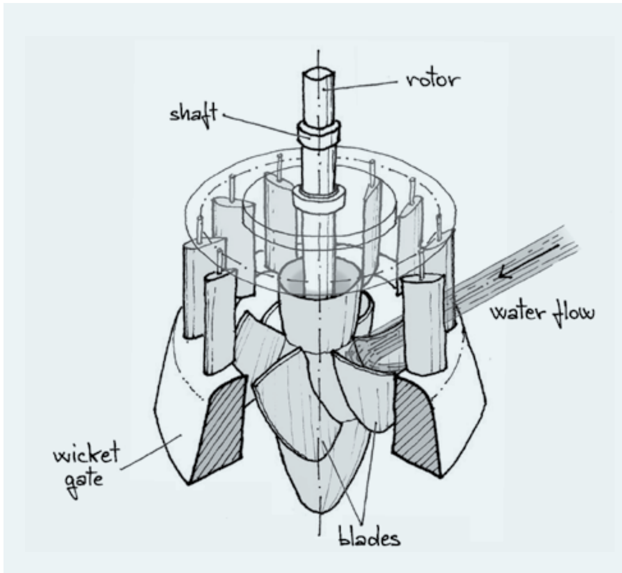


FIGURE 6.5-5 **KAPLAN TURBINE**



The Francis turbine (Fig. 6.5-6) is essentially a modified form of propeller turbine in which water flows radially inwards into runner and is turned to emerge axially. For medium-head schemes, runner is most commonly mounted in a spiral casing with internal adjustable guide vanes.

Although an efficient turbine, it is superseded by the propeller turbine which is more compact and faster-running for the same head and flow conditions.

The *Archimedean screw* is so called because Archimedes is widely acknowledged as the inventor of the screw back in 250 BC. Historically the screws were used in irrigation to lift water to a higher level (Fig. 6.5-7).

When used as a hydro turbine the water enters the screw at the top and the weight of the water pushes on the helical flights, allowing the water to fall to the lower level and causing the screw to rotate (Fig. 6.5-8).

FIGURE 6.5-6 **FRANCIS TURBINE**

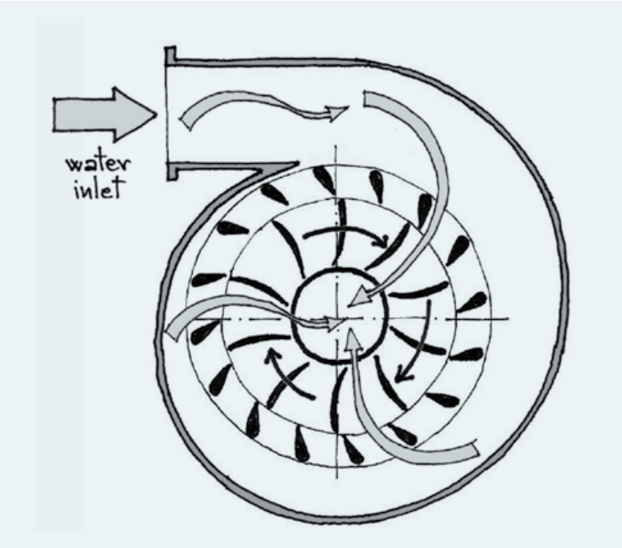


FIGURE 6.5-7 **ARCHIMEDEAN SCREW USED AS A PUMP TO LIFT WATER**

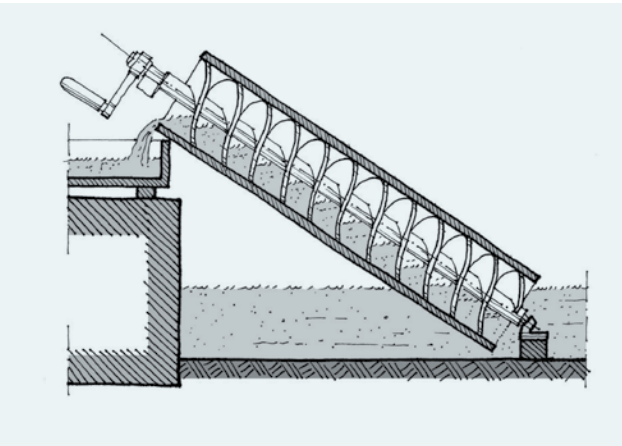
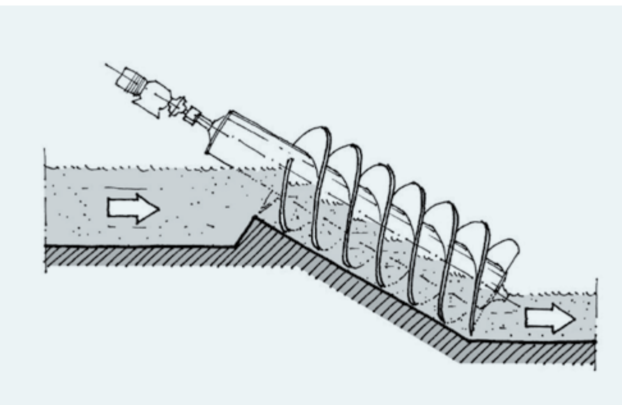


FIGURE 6.5-8 **ARCHIMEDEAN SCREW USED AS A TURBINE**



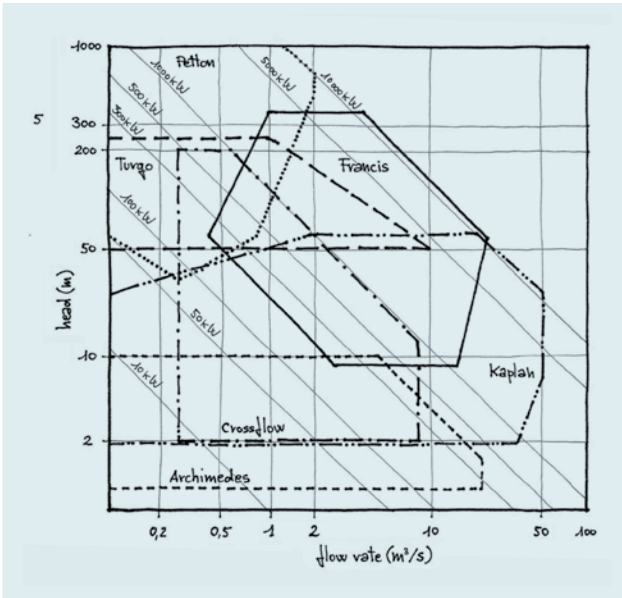
Archimedean screws for hydropower are used on low head / high flow sites. They can work efficiently on heads as low as 1 metre, though are not generally used on heads less than 1.5 m (more for economic reasons than technical ones). Single screws can work on heads up to 8 metres, but above this multiple screws are generally used, though in many cases for heads above 8 metres there may be more appropriate turbines available with much smaller footprints.

The maximum flow rate through an Archimedean screw is determined by the screw diameter. The smallest screws are just 1 m diameter and can pass 250 litres/second; in terms of power output, the very smallest Archimedean screws can produce as little as 5 kW, and the largest 400-500 kW[93].

6.5.3 TURBINE OPERATING REGIONS

Each type of turbine works best within defined operating regions, in terms of head and flow rate, as shown in figure 6.5-9.

FIGURE 6.5-9 **OPERATING REGIONS OF DIFFERENT TYPES TURBINES**



Adapted from: *S. Sangal, A. Garg, D. Kumar, Review of Optimal Selection of Turbines for Hydroelectric Projects, International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 3, March 2013*

93 *Renewables First, http://www.renewablesfirst.co.uk/hydro-learning-centre/archimedean-screw/*

07 NET ZERO ENERGY BUILDINGS AND COMMUNITIES

7.1 NET ZERO ENERGY BUILDINGS

According to the IPCC (Intergovernmental Panel on Climate Change), to limit the rise in the temperature of the earth's surface to 2 °C by the year 2050, by that time the amount of CO_2 emissions must be 85% lower than in the year 2000. This is a tremendous challenge that must be faced in all energy consuming sectors. In the building sector, since the energy consumption of the existing stock can be reduced only to a certain extent, it is necessary to take vigorous action on new constructions, not least because there is very fast growth going on in emerging and developing countries. In this context, the only answer consistent with the target of reducing emissions is to start to move towards zero energy buildings. This is going to happen in the EU where, according to a Directive[94] on Energy performance of Buildings[95], member States shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings and that after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings.

The same Directive states that a 'nearly zero-energy building' is a building that has a very high energy performance, and that the nearly zero or very low amount of energy required should be supplied to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

"Energy performance" is defined as the calculated or measured amount of energy needed to meet the energy demands associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting. This definition implies (or should imply, it is a little ambiguous) that the electricity consumed by all the electric and electronic appliances of a building should also be provided from renewable sources, not only heating, cooling, hot water and lighting. The energy performance of a ZEB (Zero Energy Building), or – better – NZEB, where N stands for "Net", nor for "Nearly", can be defined in several ways. Different definitions may be appropriate, depending on the accounting method used, namely: net-zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions:

- **Net-Zero Site Energy:** a site NZEB produces at least as much Renewable Energy (RE) as it uses in a year, when accounted for at the site;

- **Net-Zero Source Energy:** a source NZEB produces at least as much RE as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to extract, process, generate, and deliver the energy to the site;

- **Net-Zero Energy Costs:** in a cost NZEB, the amount of money the utility pays the building owner for the RE the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year;

- **Net-Zero Emissions:** a net-zero emissions building produces (or purchases) enough emissions-free RE to offset emissions from all energy used in the building annually. Carbon, nitrogen oxides, and sulphur oxides are common emissions that NZEBs offset.

These definitions, however, are incomplete if they are not accompanied by a choice between RE supply on-site or off-site (the EU Directive favours on-site) and, if the on-site option is chosen, it should be specified whether on-site means within the building footprint or it includes the area pertaining to the building. There are also two options for RE produced off-site: RE sources are produced off-site, but the energy conversion takes place on-site (as for biomass, wood pellets, ethanol, or biodiesel), or RE sources are produced and converted into useful energy off-site (as for "green purchase" of electricity produced in a distant wind or solar park).

Whatever the definition, creating a zero energy building involves tremendous changes at technical, economic and cultural levels. Technical because it demands a new way to design and construct buildings; economic because it means that the operational costs, not only the investment,

94 A directive is a legislative act of the European Union, which requires member states to achieve a particular result without dictating the means of achieving that result.

95 Directive 2010/31/EU of The European Parliament And Of The Council of 19 May 2010 on the energy performance of buildings (recast).

must be looked at; cultural because it is unavoidable that the language of architecture has to change.

The design process is already subject to analysis and revision as a consequence of the energy certification of buildings, but the real turning point comes when a zero energy building has to be designed: new experts and new design tools have roles to play in this.

The zero energy goal also challenges the concept of flexibility in the use of a building: a modification of the internal layout, or of the functions of the spaces, involves a shift from the production-consumption balance of energy in the original project. If the functions of a building and the way it is used are changed, it will be necessary to redesign the entire system, or at least to adapt it.

In zero energy buildings, the occupants' behaviour becomes a crucial factor; the relationship between occupant and building is closer than in the recent past, and is more like that in more distant times, when the only available energy was renewable energy. In this relationship, electric and electronic appliances play a crucial role, because of their energy efficiency and the way they are used.

A zero energy building is no longer the passive terminal of an electric grid, but actively interacts with it, injecting or withdrawing energy. The grid and the building have, in general, different needs, and a dialogue has to take place to find a reasonable equilibrium. It is not a problem only for electric engineers; buildings must be designed and operated in such a way as to take this issue into account from the beginning.

With a zero energy building, unless the energy source is biomass, and the technology used is cogeneration, or wind, the largest part of the energy consumed (or all of it) will have to be produced with a PV system, integrated in the roof or in the façades or "nearby". Thus, there is a physical, spatial limit for the production of renewable energy (i.e. the available area for the collection of solar energy), which imposes a maximum consumption limit. This limit, in turn, has a great impact on urban planning, not only because of the constraint on density (cubic meters built per square meter of land), but also on the shape and the orientation of buildings.

Embodied energy in components and systems is another issue that will become more and more important in the characterisation of zero energy buildings. For zero energy buildings, embodied energy will be the only energy consumed, and future regulations will have to take it into account. Embodied energy will have to be balanced in the building's lifespan. Thus the choice of materials will become an extremely critical factor, and new expertise will have to be included in the design team, to add to the others.

7.1.1 ZEB BALANCE CONCEPT

Building codes focus on a single building and the energy services that are metered. Therefore, it is possible to distinguish between a physical boundary and a balance boundary.

FIGURE 7.1-1 **SKETCH OF THE CONNECTION BETWEEN BUILDINGS AND ENERGY GRIDS SHOWING THE RELEVANT TERMINOLOGY**

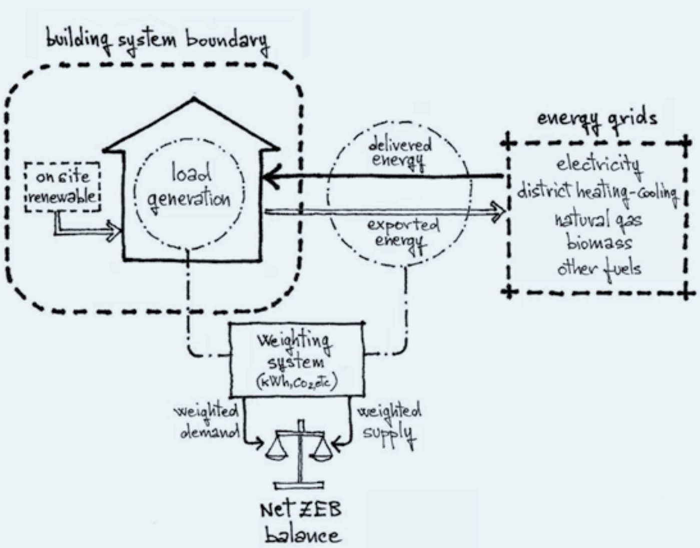
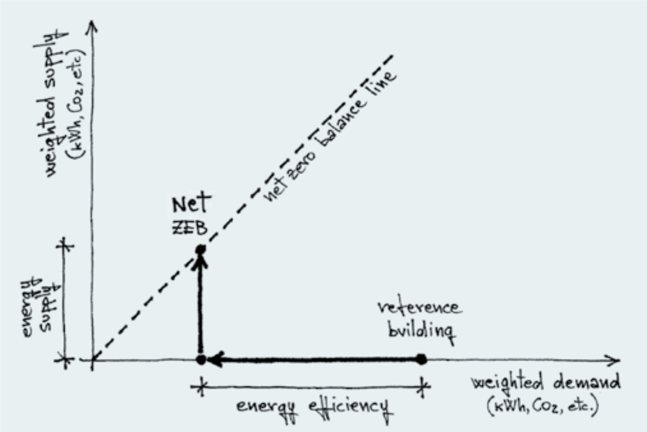


FIGURE 7.1- 2 **GRAPH REPRESENTING THE NET ZEB BALANCE CONCEPT**



Adapted from: *K. Voss, I. Sartori, E. Lollini, Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions, REHVA Journal – December 2012*

The definitions of the terms are:

The physical boundary identifies the building (as opposed to a cluster of buildings or a neighbourhood). The energy analysis addresses energy flows at the connection point to supply grids (power, heating, cooling, gas, fuel delivery chain). Consequently the physical boundary is the interface between the building and the grids. The physical boundary therefore includes everything up to the meters (or delivery points). The physical boundary is also useful for identifying so-called "on-site generation" systems; if a system is within the physical boundary (within the building distribution grid before the meter) it is considered to be on-site, otherwise it is off-site. Typical on-site generation systems are PV and micro CHP, which allow energy to be exported beyond the physical boundary. The yield of solar thermal systems is typically consumed entirely on-site due to technical limitations at the connection point to district heating systems. Therefore solar thermal systems are mostly treated as demand-reduction technology (efficiency path, x-axis in figure 7.1-2). A typical off-site option is a share in a wind energy turbine that is financed by the building budget. This option would allow economically feasible options to balance the building energy consumption, but should be considered within the primary energy factor for the imported electricity to avoid double counting.

The balance boundary identifies which energy services are considered (heating, cooling, ventilation and domestic hot water, plug loads, charging of electric vehicles on-site, etc. Although some of these loads are not related to the building performance, a holistic balance should include them.

Other forms of energy consumption that do not appear in the annual operational phase but belong to the life cycle of a building may be considered within the balance boundary, such as embodied energy/emissions related to construction materials and installations.

7.1.2 LOAD MATCHING

The challenge that NZEBs have to face is not limited to reaching a balance between the building's energy consumption and renewable energy production, on a yearly basis. The problem of load matching, i.e. of the time coincidence between demand-supply, also needs to be considered. Nowadays this is a minor problem; it will not be so when – as we hope – the number of zero energy buildings will be so high as to have a significant effect on the national energy system, especially on the electric grid and the gas network.

For electricity, it is necessary to try to minimise the energy exchanges between the building and the grid, i.e. to minimise the load match index f, expressed as[96]:

$$f_i = \min\left[1, \frac{\text{electricity production from renewable energy source}}{\text{electricity consumption}}\right] \cdot 100\ [\%] \qquad (7.1\text{-}1)$$

i = time interval (hour, day, month)

When the time interval (yearly, monthly, daily, hourly) is diminished, the index becomes smaller, down to values lower than 30% when the hourly time interval is chosen.

There is also another type of coincidence to consider, regarding the value (economical or environmental) of electricity that is supplied to or received from the grid, instant by instant (its economic value is higher in peak hours

96 *Voss K. et al., Load Matching and Grid Interaction of Net Zero Energy Buildings, in Proceedings "Eurosun 2010", Graz, Austria - http://repositorio.lneg.pt/bitstream/10400.9/963/1/EUROSUN2010_HGoncalves2.pdf*

and its environmental value is low when it is produced by a fuel mix that – at that moment – is generating more CO_2 per kWh than the average). The ideal is that a ZEB should not only minimise the load match index, but should also supply energy to or absorb it from the grid at the time that is most convenient (economically or environmentally).

In a ZEB some form of electricity storage (physical or virtual) has to be provided. Physical storage could be thermal, which is already used for both heating and cooling. Or it could be the storage of the energy that can be obtained by the integration of non-predictable energy production systems, like solar and wind, with systems that can be modulated according to the needs, such as gas or biomass CHP. In the case of gas, the fossil primary energy consumed can be balanced with the surplus production from the renewable energy system.

Virtual storage is that obtainable by means of sophisticated control systems, enabling the operation (on/off) of the electrical appliances and of the HVAC system, according to the weather, the needs of the grid, instantaneous kWh cost, etc., minimising the supply-demand mismatch as much as possible.

TABLE 7.1-1 **GIVES AN OVERVIEW OF RELEVANT TERMINOLOGY ADDRESSING ENERGY USE IN BUILDINGS AND THE CONNECTION BETWEEN BUILDINGS AND ENERGY GRIDS.**

Building system boundary	The boundary at which to compare energy flows flowing in and out the system. It includes: • Physical boundary: can encompass a single building or a group of buildings; determines whether renewable resources are 'on-site' or 'off-site'; • Balance boundary: determines which energy uses (e.g. heating, cooling, ventilation, hot water, lighting, appliances) are included in the balance.
Energy grids (or simply 'grids')	The supply system of energy carriers such as electricity, natural gas, thermal networks for district cooling, biomass and other fuels. A grid may be a two-way grid, delivering energy to a building and occasionally receiving energy back from it. This is normally the case for electricity grid and thermal networks.
Delivered energy	Energy flowing from the grids to buildings, specified per each energy carrier in [kWh/y] or [kWh/m^{2}y]. This is the energy imported by the building. However, it is established practice in many countries to name this quantity 'delivered energy'.
Exported energy	Energy flowing from buildings to the grid, specified per each energy carrier in [kWh/y] or [kWh/m^{2}y].
Load	Building's energy demand, specified per each energy carrier in [kWh/y] or [kWh/m^2 y]. The load may not coincide with delivered energy due to self-consumption of energy generated on-site.
Generation	Building's energy generation, specified per each energy carrier in [kWh/y] or [kWh/m^2 y]. The generation may not coincide with exported energy due to self-consumption of energy generated on site.
Weighting system	A weighting system converts the physical units into other metrics, for example accounting for the energy used (or emissions released) to extract, generate, and deliver the energy. Weighting factors may also reflect political preferences rather than purely scientific or engineering considerations.
Weighted demand	The sum of all delivered energy (or load), obtained by adding together all energy carriers each multiplied by its respective weighting factor.
Weighted supply	The sum of all exported energy (or generation), obtained by adding together all energy carriers each multiplied by its respective weighting factor.
Net ZEB balance	A condition that is satisfied when weighted supply meets or exceeds weighted demand over a period of time, nominally a year. The net zero energy balance can be determined either from the balance between delivered and exported energy or between load and generation. The former is called import/export balance and the latter load/generation balance. A third option is possible, using monthly net values of load and generation and it is called monthly net balance. The Net ZEB balance is calculated as: NetZEB balance : $\lvert$weighted supply$\rvert - \lvert$weighted demand$\rvert = 0$ where absolute values are used simply to avoid confusion over whether supply or demand is considered as positive. The Net ZEB balance can be represented graphically as in figure 7.1-2, plotting the weighted demand on the x-axis and the weighted supply on the y-axis.

Adapted from: *K. Voss, I. Sartori, E. Lollini, Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions, REHVA Journal – December 2012*

Building design (and construction and operation), then, requires that new expertise, dealing with TLC and AI, is integrated into the design team, to interact with the architect, the mechanical engineer and the energy expert.

No doubt, the design team is going to be more and more crowded.

On the other hand, it has to be clear that it is most important not to limit the design to the building scale, but to move towards the district scale. At district scale it is easier to modulate the demand and supply profile by means of different forms of virtual or physical storage, by using technologies that scale economy makes more economically viable. The necessary step to follow the zero energy building is the zero energy district, prelude to the zero energy city.

7.1.3 ZERO ENERGY BUILDINGS IN THE TROPICS: EARLY EXPERIENCES

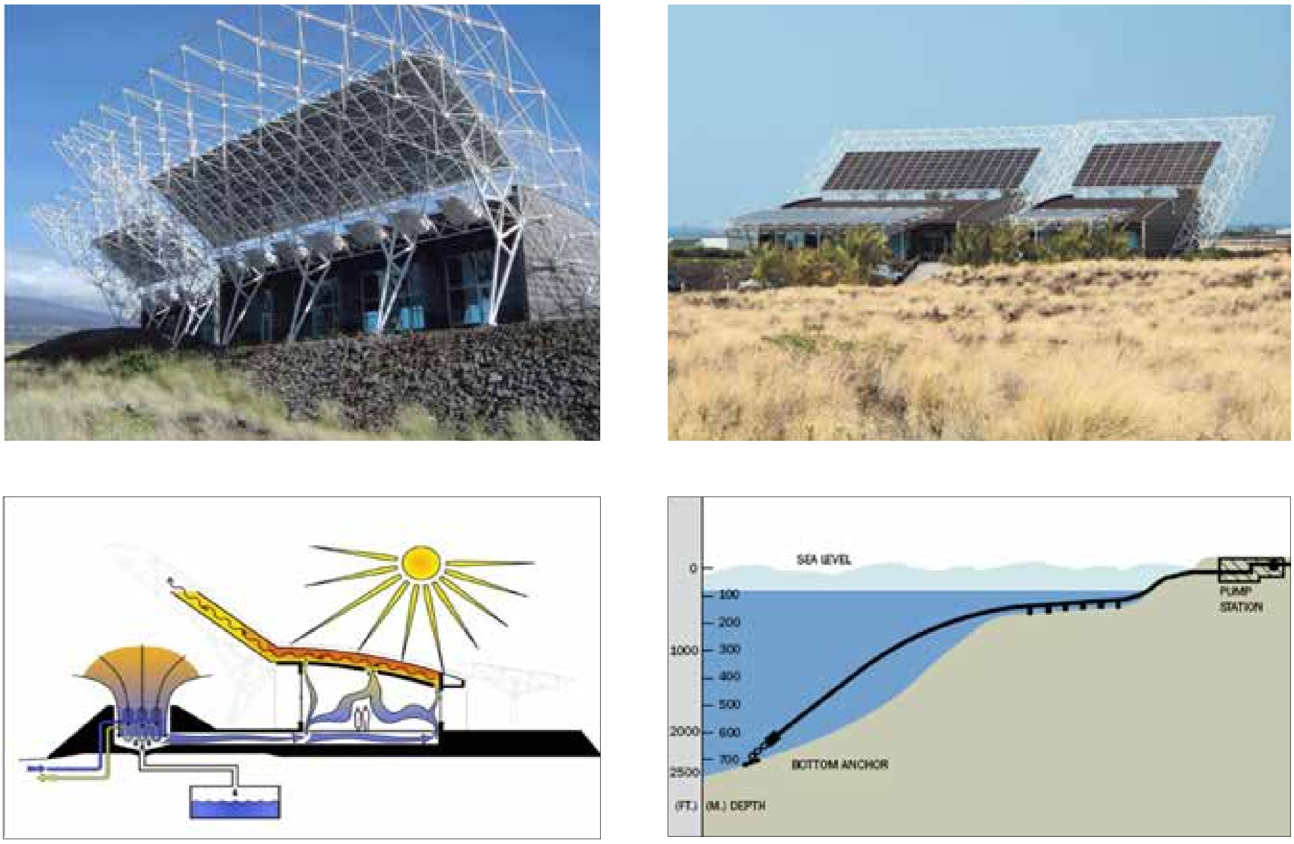
If the design and construction of a zero energy residential building is a challenge, requiring high level integrated design, the challenge with commercial buildings is even bigger, due to the greater complexity of their architecture and mechanical systems. For this reason the number of monitored commercial buildings is very low, lower than residential buildings. Compared with a growing number of buildings presented as ZEB, whose simulated performances are described in detail, the number of those for which measured data are available is very low, and not only because they were built only a few years ago. The main reason lies in the fact that the ways in which a residential building is used are fairly limited; this is not so for commercial buildings, where changes in the originally intended use (a software house instead of an office, for example) and in the occupants' behaviour may be far greater.

In the following some significant cases for which measured data were available are presented.

7.1.3.1 HAWAII GATEWAY ENERGY CENTRE (HGEC)

The Hawaii Gateway Energy Centre (HGEC)[97] complex is situated on the south coast of Kona on the Big Island of Hawaii (lat. 20° N, tropical climate). It serves the Natural Energy Laboratory of Hawaii (Fig. 7.1-3). The complex houses administrative office space, rest rooms, support areas, and a large multi-purpose space used for displays, outreach, conferencing, and education. It has a total floor area of about 335 m².

FIGURE 7.1-3 **HAWAII GATEWAY ENERGY CENTER**



97 http://www2.aiatopten.org/hpb/searchby.cfm?search=Location

The long axis of the building is oriented east-west for ideal shading and daylighting. There is no need for electric ambient lighting during daytime business hours (8:00 to 18:00 hrs) because the building is entirely daylit. When electric lighting is needed, occupancy sensors and photosensors control fixtures. The quality of HGEC's indoor environment stems from excellent daylighting, views, ventilation, and thermal comfort.

All of the occupied spaces offer substantial views, as virtually all the south and north elevations feature glass, shaded from direct sun. A translucent window treatment provides room darkening or privacy when desired. Windows are fixed, as operable windows would interfere with the chimney effect. The ventilation design is based on stack ventilation; cross ventilation was considered undesirable, as it would have introduced noise, wind, and dust.

Passive thermal chimneys move air without mechanical equipment, allowing conventional air conditioning to be eliminated. The copper roof collects heat, which is radiated into an insulated ceiling plenum. The hot air rises up and out through actual chimneys, drawing cool replacement air into occupied space through an underfloor plenum connected to a fresh-air inlet. The building maintains temperatures between 22 °C and 24.5 °C without mechanical controls. Ventilation rates range from 8 to 15 air changes per hour (ACH), exceeding health code requirements of 3 to 4 ACH. Indoor humidity is maintained at between 55% and 65%.

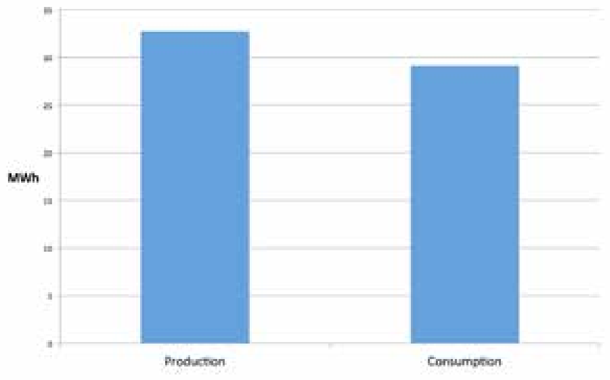
The cooling system uses seawater to reduce energy consumption. Cold, deep seawater, pumped from 900 m below sea level, passively cools the building. The water, which arrives at about 7 °C, is distributed through cooling coils located in a dedicated air inlet structure. The cooled air then passes through a plenum beneath the buildings before rising through the buildings to exit at a high level, moved by the stack effect. The only energy consumed for cooling is that used to run the seawater pump.

The building is well insulated for its climate. The U-value for the mass walls is 0.158 W/m²K while for the windows is 1.1 W/m²K.

With its energy efficiency design strategies and the 20 kW photovoltaic (PV) system, HGEC is a zero energy building that actually exports electricity (Fig. 7.1- 3); the photovoltaic system produces more energy than the building uses (Fig. 7.1- 4).

The contractor implemented an indoor air quality management plan during construction, and materials were selected for their low emissions of volatile organic compounds (VOCs).

FIGURE 7.1-4 **HAWAII GATEWAY ENERGY CENTER ENERGY BALANCE; 2007 DATA**



Locally manufactured construction materials used for HGEC include lava rock, concrete, and concrete masonry units. Although these materials did not meet LEED credit criteria for local materials, the production plants are located within 25 miles of the project, significantly reducing the energy embedded in their transportation. These materials are also inherently durable and should require no regular maintenance. Construction materials with post-industrial or post-consumer recycled content include steel, thermoplastic olefin (TPO) roofing, copper roofing, thermal and acoustic insulation, gypsum board, carpet, resilient flooring, and counter tops. Indoor finishes emit low or no volatile organic compounds (VOCs). Carpet tile was used in lieu of glue-down carpet in the multi-purpose space, and gravity-laid resilient flooring was used in the administrative areas.

A glass, paper, plastic, and metal recycling programme is followed in the building.

7.1.3.2 **ENERPOS, REUNION ISLANDS**

ENERPOS[98] (French acronym for POSitive ENERgy), on the island of La Reunion (lat. 21° S, tropical climate) is a two-storey university building split into two parallel wings separated by a vegetated patio, underneath which there is a car park (figures from 7.1-5 to 7.1-8). The building is composed of an administration zone, with 7 offices and a meeting room, 2 computer rooms and 5 classrooms and has a total gross floor area of 739 m².

98 *Sources of information: M. Franco, G. Baird, F. Garde, A. Lenoir, Environmental design and performance of the ENERPOS building, Reunion island, France. (http://archive.iea-shc.org/publications/downloads/DC-TP12-Garde-2011-06.pdf)*
A. Lenoir, S. Cory, M. Donn and F. Garde, USERS' BEHAVIOR AND ENERGY PERFORMANCES OF NET ZERO ENERGY BUILDINGS,.Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November. http://www.sustainabledesign.info/hpb/overview.cfm?ProjectID=1592
A. Lenoir, G. Baird and F.Garde, Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate.. Architectural Science Review. Vol. 55, No. 3, August 2012, 156–168
A. Lenoir, F. Garde, Tropical NZEB, High performance buildings – Summer 2012 - http://www.hpbmagazine.org/case-studies/educational/university-of-la-reunions-enerpos-saint-pierre-la-reunion-france

FIGURE 7.1-5 **ENERPOS BUILDING, REUNION ISLANDS**

Picture credits: *Jerome Balleydier*

FIGURE 7.1-6 **ENERPOS BUILDING; AERIAL VIEW**

Picture credits: *Jerome Balleydier*

FIGURE 7.1-7 **VIEW OF THE GREEN PATIO COMPOSED WITH NATIVE AND EXOTIC SPECIES**

Picture credits: *Aurélie Lenoir*

FIGURE 7.1-8 **NATURALLY VENTILATED CLASSROOM IN ENERPOS. THE CROSS-VENTILATION IS ADJUSTABLE, THANKS TO MANUALLY OPERATED LOUVRES ON BOTH SIDE OF THE CLASSROOM. EFFICIENT CEILING FANS PROVIDE THE REQUIRED AIR VELOCITY OF 1M/S TO ENSURE THERMAL COMFORT DURING WINDLESS DAYS**

Picture credits: *Jerome Balleydier*

The main feature of the building is the use of passive means and natural resources such as sun and wind to achieve thermal and visual comfort. Active energy consuming systems such as air-conditioning and artificial lighting should be used as a last resort.

A band of vegetation at least 3 m wide surrounds the building. The vegetation creates a pleasant climate around the building by the shade it provides, and lowers the temperature by absorbing solar radiation. Further, the north and south orientation of the main façades limits the amount of sunlight falling on the easterly and westerly gables. Moreover, they are perpendicular to the thermal breezes which blow during the hot season.

The building is naturally ventilated with a window to wall ratio (WWR) of 30%. Interior glass louvres have been installed in the building to control cross-ventilation. High-performance ceiling fans were installed for better air circulation inside the rooms and therefore a better cooling effect. External solar shading made of wooden strips was installed on the north and south façades of the building to prevent direct glare inside the rooms and to reduce the temperature of these walls. The roof was insulated with a 10 cm layer of polystyrene (less than 0.5% of the solar radiation comes through the roof).

Particular attention was given to the design for daylight. The use of artificial lights was optimized with a lighting load of 3.7 W/m^2 in the office spaces and 7 W/m^2 in the classrooms.

Low energy T-5 luminaires provide indirect ambiance lighting, while LED desk lamps in the offices provide additional lighting as needed. Timers in the classrooms turn the lights off automatically after two hours.

In two classrooms, artificial lighting was not installed because the simulations pointed out that during working hours i.e. from 8 am to 5 pm, the level of natural lighting was good enough to avoid artificial lighting.

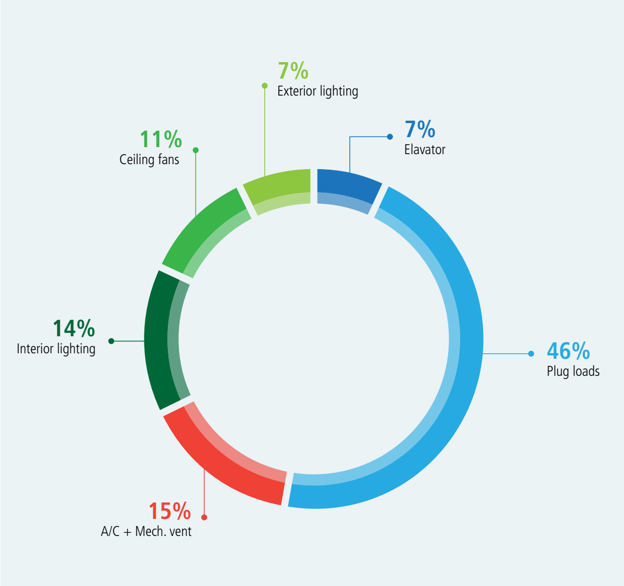
It is a positive energy building: that means that through different active and passive systems, the building consumes very little energy and it is able to produce more electricity than it consumes over the year, thanks to a PV roof, which is also used for shading.

Overall, the first simulation results lead to an energy index below 50 kWh/m^2.year and a PV supply of 78 kWh/m^2.year.

As an accurate energy monitoring system has been set up, there has been real scale feedback . In fact, it appears that the building is much more comfortable than was first indicated by the simulations.

The annual final energy use index, from May 2010 to April 2011 was 14.4 kWh/m^2.yr (final consumption), about ten times less than the consumption of a standard university building in La Reunion. Nearly 50% of the electricity consumption is due to the plug loads (Fig. 7.1-9). Air conditioning consumption is due to the split air conditioner used to cool the two technical rooms (air conditioning for offices was switched on on only 2 days during the hot season).

FIGURE 7.1-9 **THE DISTRIBUTION OF ENERGY CONSUMPTION**



The building integrated photovoltaic roof covers an area of 350 m^2 and enabled, in the same period the production of 104 kWh of electricity per square meter of the building's floor area, with a net surplus of 90 kWh/m^2. The building thus produces about seven times more electricity than its own consumption.

The performance of both the building and the PV systems are far better than estimated in the design phase.

7.1.3.3 **ZERO-ENERGY-OFFICE (ZEO), MALAYSIA**

A good example of a zero net energy building is the PTM (Pusat Tenaga Malaysia, Malaysian Energy Centre) Zero Energy Office[99], which is located approximately 40 km south of the centre of Kuala Lumpur and was completed in October 2007 (Fig. 7.1-10). The ZEO building is a pilot project and a research laboratory for tomorrow's sustainable office building for tropical climates.

99 *http://www.ecogreen4us.com/stories/green-technology-stories/green-building-zeo-research-lab/*
http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Pusat_Tenaga_Malaysia_Zero_Energy_Office_Building___Zero_Net_Energy_Building_Case_Study.html
http://www.ien.dk/Projects/geo.html

FIGURE 7.1-10 **ZERO ENERGY OFFICE (ZEO) PROJECT**

The Malaysia Energy Centre (Pusat Tenaga Malaysia) was established to fulfil the need for a national energy research centre that can co-ordinate various activities, specifically energy planning and research, energy efficiency, and technological research, development and demonstration.

The ZEO building uses integrated design concepts where active energy and passive energy systems are interwoven into the office building. Several building elements also serve as the energy systems of the building. These methods help to mitigate the extra costs of construction (its cost was 20% to 30% more than conventional Malaysian office buildings).

The other energy efficient features of ZEO are: the orientation of the building, so that windows face only towards the north and south in order to reduce solar heat gains; a staggered section for self-shadowing; light shelves (Fig. 7.1-11); heavily insulated walls and the roofs; and windows with double low-e glazing.

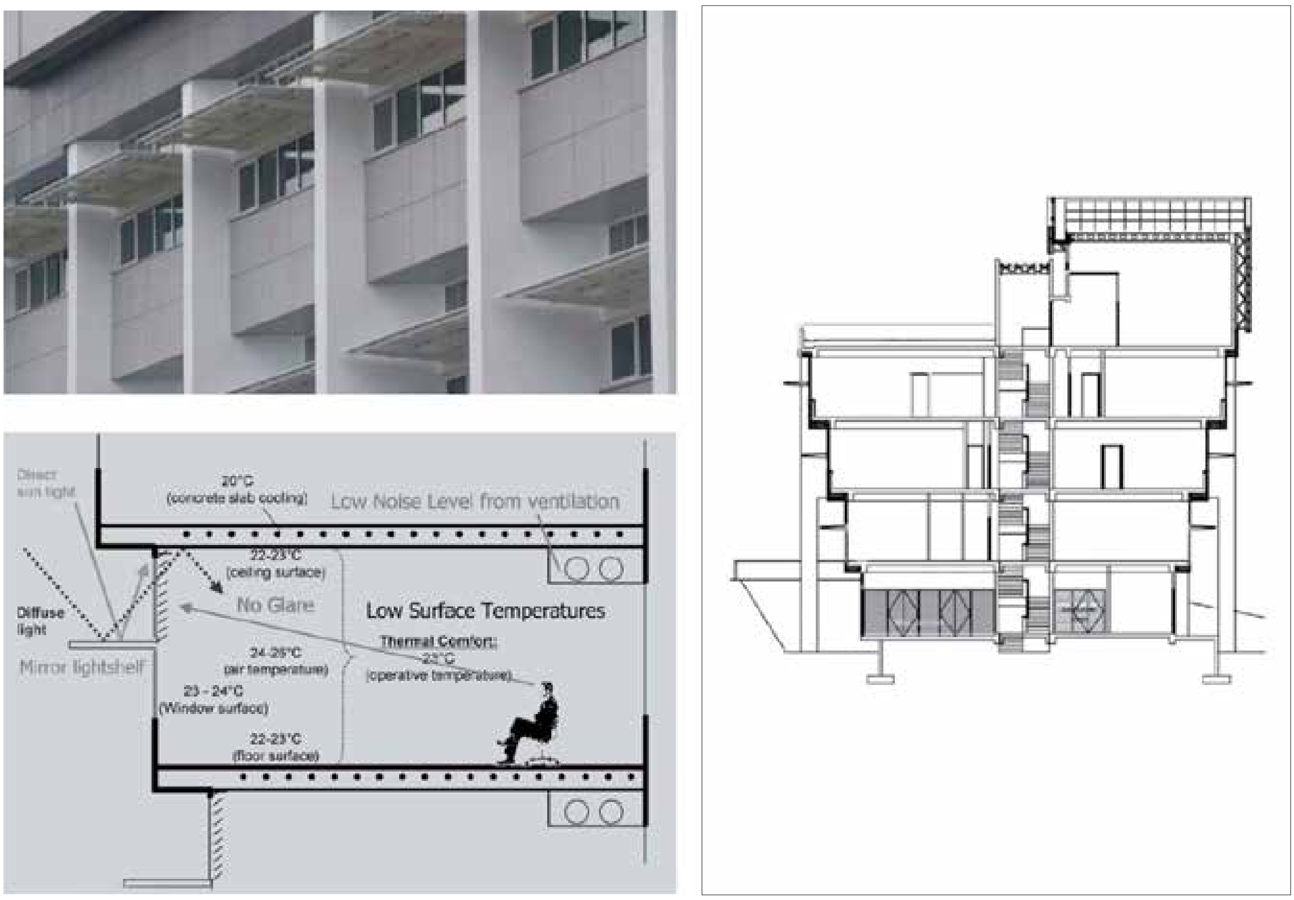
In a tropical climate strong sunlight can heat up the interior of any building if it is allowed to penetrate directly. In order to avoid, this high performance glazing and sealed double glazing are used in the building.

Furthermore, in the ZEO building, an enthalpy wheel is used, allowing the air conditioning load to be reduced, since most of it derives from air dehumidification.

The ZEO is lit primarily by daylight and only assisted by electric lighting at night and during very dark overcast periods.

The thermal and daylighting optimization of the building was carried out using computer simulations.

FIGURE 7.1-11 **SHADING AND DAYLIGHTING FEATURES**



The daylight autonomy is 95% during working hours. With the optimization of the lighting system with daylighting simulation, energy efficient lighting and lighting control is possible, with an installed lighting load about of 5 W/m^2 only.

Cooling is stored from night time to daytime in the building's concrete floor slabs and in the building's phase change thermal storage tank. Tubes embedded tubes within the concrete floor slabs release cooling effect to the rooms above and below them the use of air conditioning systems for the building is minimised.

The facility also incorporates sustainable design features such as the use harvested rainwater to provide 2/3 of its water needs.

Extensive active energy efficiency measures are implemented in the building to reduce the need for electricity. High efficiency pumps, fans and energy efficient office equipment are used in the building as part of the energy efficiency measures.

The ZEO is powered by its own BIPV or Building Integrated Photovoltaic system. The building's PV system is connected to the grid. Solar electricity is fed into the grid during the day, and bought back during the night, to run the building's chiller.

Four different PV systems/technologies are installed in this building. The first and biggest comprises 47.28 kWp polycrystalline modules on the main roof, followed by 6.08 kWp amorphous silicon modules on the second main roof. The building atrium uses 11.64 kWp glass-glass semi-transparent PV modules. The car park roof is integrated with 27 kWp monocrystalline PV modules.

Since October 2007, when the Malaysian Energy Centre moved to the building, the performance data of the building and its energy systems have been monitored continuously.

The building design focussed on energy efficiency (100% day-lit, efficient lightings, floor slab cooling, double-glazed windows, etc.). The building is self-sufficient with enough power from BIPV systems for the targeted building energy index of between 35 to 40 kWh/m^2/year (4200 m^2 floor area, to accommodate up to 111 staff. It has achieved an 85% reduction in energy use compared to conventional Malaysian office buildings).

7.2 NET ZERO ENERGY COMMUNITIES

According to the UN[100], rapid urbanisation is taking place, especially in developing countries, with the world population expected to reach 9 billion in 2050 (medium forecast). It has been estimated that, to accommodate the urban population, in the next 45 years the equivalent of a new town of one million inhabitants will be built every week. The world's energy consumption is mostly concentrated in settlements (for heating and cooling buildings, for lighting, for electric and electronic appliances, for transport), accounting for more than 70% of the total. Thus, more than two thirds of the total energy consumption is needed for urban metabolism, and more than two thirds of the CO_2 emissions are due to it.

Putting together all these data, it is evident that there is an urgent need for drastic action to curb fossil energy consumption in cities, where most of the energy is consumed. It is necessary, in other words, to develop a new approach to urban design based on a new urban energy system, to avoid the catastrophic effects of global warming on the one hand, and to cope with the unavoidable and constant increase in the cost of oil on the other.

By combining the technical and technological means that are available today in a way that is appropriate for the local climate and resources, it is possible to design an energy system for a settlement that will achieve the aim of zero CO_2 emissions. From the beginning the energy system must be conceived according to a new energy paradigm. This implies not only that the architectural design process for the individual buildings has to change, but also – and mainly – that the planning rules of the community have to change: no longer should it be a linear, fossil fuel based, energy economy, but a circular, renewable resource based energy economy.

There are already examples of settlements that have reached complete (or almost complete) independence from fossil fuels. None of these examples are in countries with a tropical climate, however the principles underlying their implementation are easily adaptable to any climate, when the appropriate technical and technological solutions are introduced.

7.2.1 A CARBON NEUTRAL SETTLEMENT: BEDZED

BedZED [Beddington Zero (fossil) Energy Development][101] is a mixed development urban village, built by a private investor; on a brownfield wasteland site in the London Borough of Sutton it provides 82 dwellings in a mixture of flats, maisonettes and town houses, and approximately 2,500m² of workspace/office and community accommodation including a health centre, nursery, organic café/shop and sports club house. The community is designed to host about 240 residents and 200 workers. BedZED is Britain's first urban carbon-neutral development (Fig. 7.2-1).

100 *United Nations, Urban and rural areas 2003, New York, 2004*

101 *C. Twinn, BedZed, The Arup Journal, 1/2003, http://www.arup.com/DOWNLOADBANK/download68.pdf*

FIGURE 7.2-1 **BEDZED**

Source: *Courtesy Bill Dunster Architects*

7.2.1.1 **ENERGY CONCEPT**

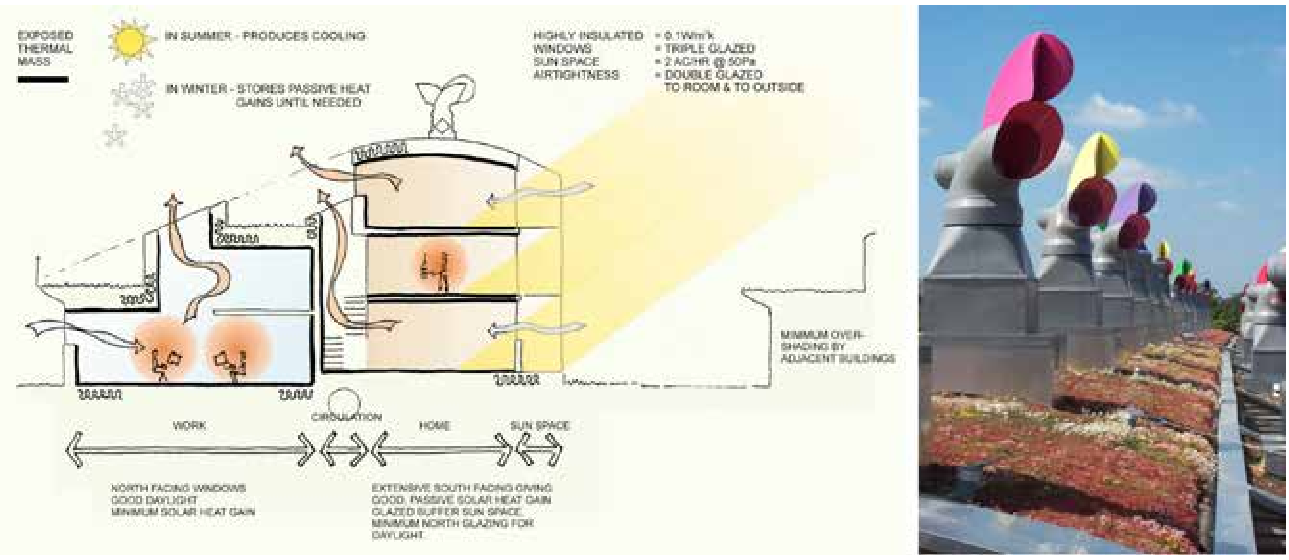
In order to minimise energy demand the houses face south to make the most of the heat from the sun, and are fitted with high levels of insulation, airtight triple-glazed windows and the latest energy saving appliances, including water saving devices. With the combination of super-insulation, heat recovery, passive solar gain stored within each flat by thermally massive floors and walls and internal gains, comfort temperature is obtained for most of the time without any need for backup heating (Fig. 7.2-2). In summer, workspaces placed in the shade zones of south facing housing terraces enable all flats to have outdoor garden areas, with good access to sunlight, at the same time as allowing cross ventilation.

Moreover, wherever possible building materials have been selected from natural, renewable or recycled sources and brought from within a 55 km radius of the site.

Primary energy consumption is minimised at two levels: individual building and community; in both cases renewable energy is used to power the energy efficient systems.

At individual building level, an innovative device was designed for ventilation heat recovery: the wind cowl. In well insulated buildings, the main energy demand is due to the need to heat the ventilation air. For this reason a current practice is to use mechanical ventilation combined with efficient heat exchangers for preheating fresh air with the heat of the exhaust one. Generally, a great deal of high-grade fan and pump electricity is consumed to deliver low-grade energy for room comfort temperature control and ventilation, and the energy consumption tends to be significant because these systems run for extended operating periods. The wind cowl system, instead, delivers preheated fresh air to each home and extracts its vitiated air, complete with heat recovery from the extracted ventilation air, using wind power, i.e. only renewable energy.

FIGURE 7.2-2 **BEDZED: BUILDING PHYSICS**



Source: *Courtesy Bill Dunster Architects*

At community level, a 135 kWe wood fuelled CHP plant meets all the energy requirements of the community, exchanging electricity with the grid. The CHP unit generates electricity, and distributes hot water around the site via a district heating system (Fig. 7.2-3), delivering constant heat to oversized domestic hot water cylinders. The cylinders have electric immersion heaters for emergency back-up. They are in cupboards within each home and office, positioned centrally so that they can be opened to work as a radiator in cold spells.

The CHP plant satisfies both the electrical and heat demand of the project due to three interrelated factors:

- average loads are reduced;
- the design evens out the normal fluctuations between summer/winter and daytime/evening space-heating demands;
- the domestic/commercial mix also evens out the daily electrical demand to more closely match the CHP output.

The generator engine is fuelled by gas produced from woodchips by an on-site gasifier. These come from tree pruning waste from nearby woodlands – waste that would otherwise go to landfill. The demand is 1,100 tonnes per year. London produces 51,000 tonnes of tree surgery waste per year (which could rise if local authorities develop plans for recycling park and garden waste).

It was calculated that, if the electricity is used to displace transport fossil fuel, with its high tax levels, the PV financial payback period was about 13 years. With EU/UK grants equating to 50% of capital cost, the theoretical payback period went down to just 6.5 years. On this basis, 107kWp of PV has been integrated into the south-facing BedZED façades, generating enough solar electricity to power 40 electric vehicles for approximately 8500 km/year. Charging points have been installed and occupants can have free parking and charging if they use electric cars.

Car pool and car hire services with electric cars are provided to reduce car ownership and journeys. The idea of the service is to create carbon neutral transport.

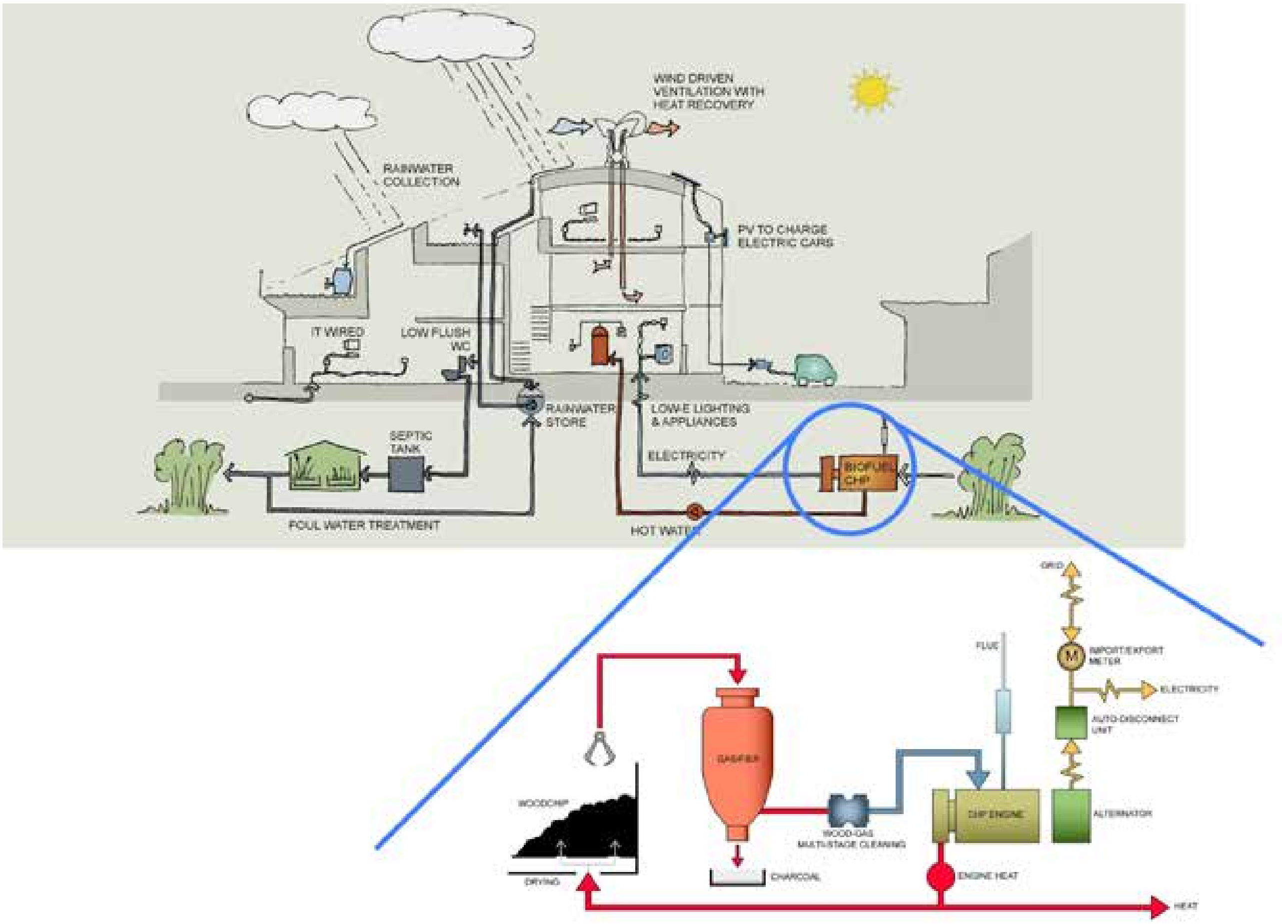
As a mixed-use development, BedZED offers the opportunity for residents to live and work on site, therefore eliminating the need to commute to work.

7.2.2 SAMSO: THE ENERGY SELF-SUFFICIENT ISLAND

Samsø, a Danish island in the North Sea, has become entirely energy self-sufficient, by using wind energy, solar and other renewables. In the nineties, the island of 4,300 people imported all their energy, mostly in oil tankers, and paid little attention to where it came from.

Then, quite deliberately, the residents of the island set about changing this. They formed energy cooperatives and organized seminars on wind power. They removed their furnaces and replaced them with heat pumps or connected to the CHP district heating. All the most suitable and appropriate means for using energy efficiently were adopted. By 2001, fossil-fuel use on Samsø had been cut in half. Since 2003, instead of importing electricity, the island exports it, and since 2005 it produces from renewable sources more energy than it uses.

FIGURE 7.2-3 **BEDZED: ENERGY SYSTEM**



Source: *ARUP*

7.2.2.3 GÜSSING: AN ENERGY SELF-SUFFICIENT COMMUNITY

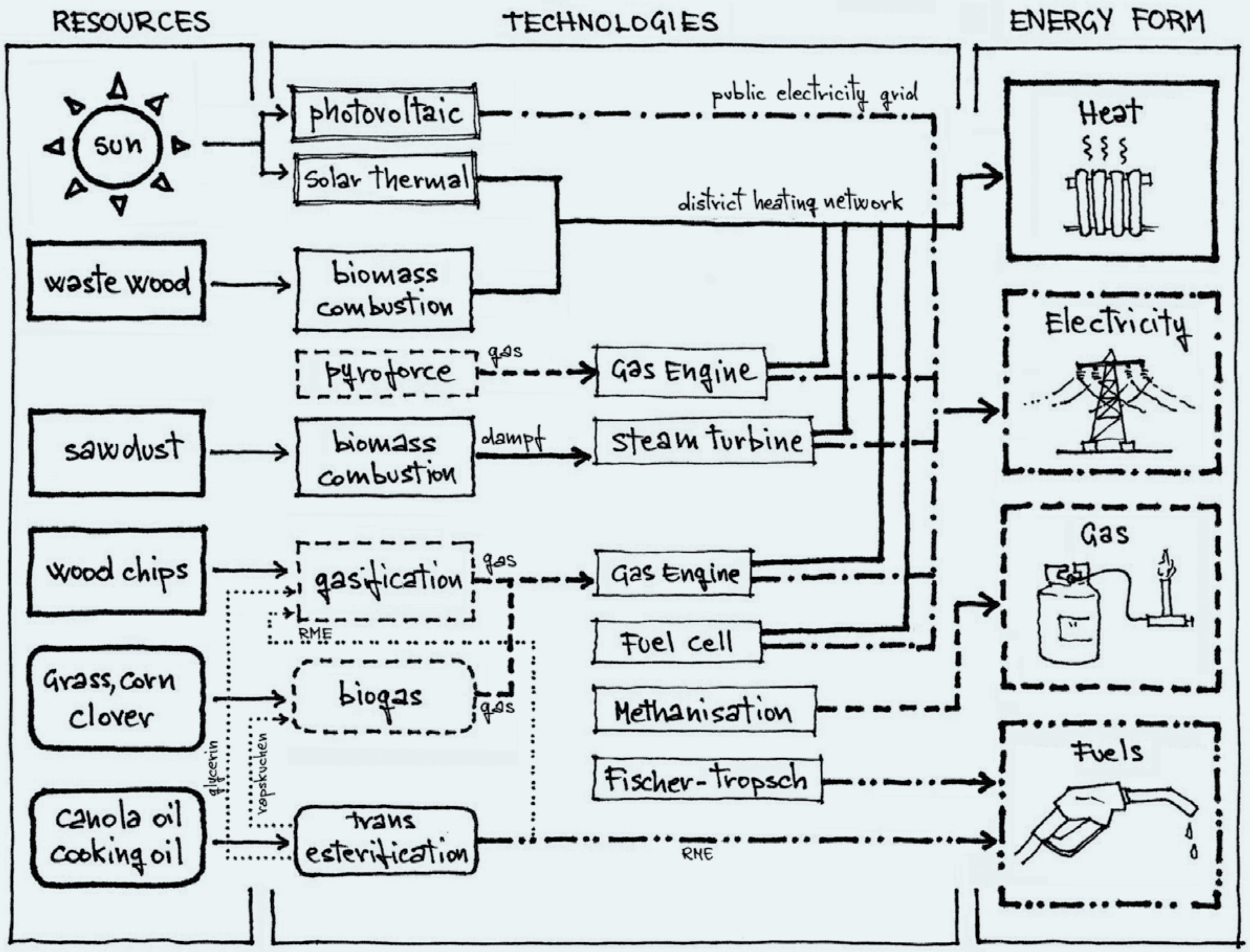
Güssing, a major town in south Burgenland (Austria), a district comprising around 27,000 inhabitants, is the first community in the European Union to produce its whole energy demand – electricity, heating/cooling, fuels – out of renewable resources, all resources from within the region.

In the early 1990s, a policy was proposed which called for a complete abandonment of fossil-fuel-based energy. The objective was to supply, in a first step, the town of Güssing and subsequently the whole district with regionally available renewable energy sources. The first step taken was to order that all public buildings in the town should stop using fossil fuels.

As a result of the energetic optimisation of buildings in the town, expenditure on energy was reduced by almost 50%. Then a wood burning plant that provided heating for 27 houses was built. Furthermore, a facility was constructed which turned rapeseed into car fuel.

In 1998 a pilot project was implemented for gasifying wood chips under high temperature conditions. Gas fuels an engine that produces electricity and the "by-product" heat is used to produce warm water for the district heating system.

The renewable-energy project expanded to other sources, as shown in figure 7.2-4.



RESOURCES
TECHNOLOGIES
ENERGY FORM
sun
waste wood
sawdust
wood chips
Grass, Corn clover
Canola oil cooking oil
photovoltaic
Solar thermal
biomass combustion
pyroforce
biomass combustion
gasification
biogas
trans esterification
gas
dampf
gas
gas
RME
glycerin
rapskuchen
Gas Engine
Steam turbine
Gas Engine
Fuel cell
Methanisation
Fischer-Tropsch
public electricity grid
district heating network
RME
Heat
Electricity
Gas
Fuels

A1 PRINCIPLES OF BUILDING PHYSICS

1. WHY ARCHITECTS SHOULD KNOW THE BASICS OF PHYSICS AND THE PHYSIOLOGICAL PRINCIPLES ON WHICH COMFORT IS BASED

For some time now many have claimed to design and build sustainable buildings. Unfortunately, in most cases these are claims that do not correspond to reality. There are many reasons for the gap between the intentions and the facts, but the main one is that architects have little knowledge of physics.

In fact, sustainable architecture is based on the ability to let the human product, the building, communicate with the natural environment. To establish this dialogue it is necessary to have a language in common. The language that man has developed to communicate with the natural environment is physics, of which the other sciences, chemistry, biology, ecology, are daughters.

Furthermore, we consume energy and exert an impact on the environment when we construct and operate our buildings because we want to create and maintain the conditions we need for thermal, visual and acoustic comfort. But comfort is a physiological phenomenon (as well as psychological) and physiology also uses the language of physics.

Finally, our buildings are now filled with more or less energy-consuming equipment, which provides a high quality of life but increases the environmental impact of the building. These technologies also work on the basis of the principles of physics.

Therefore, an architect cannot design sustainable buildings unless he understands at least the essential rudiments of physics, especially thermodynamics, and of the physiology of comfort. When he understands these basic principles the architect can engage in a real dialogue with the environment, and can exercise the necessary control over specialists, experts in energy systems and installers.

1.1 THE BUILDING AS A THERMODYNAMIC SYSTEM

Thermodynamics is the branch of physics closest to human sciences. It is not just a coincidence that the concept of entropy, which characterizes the second law of thermodynamics, is also used in information theory, and in economics, as well as in biology and ecology.

A building, seen as a thermodynamic system, is an open system, whose boundary (the envelope) is crossed by fluxes of energy and matter. These fluxes vary continuously over time, therefore the building is a dynamic system not just because the light illuminates it in a different way depending on the location, season and time, but also because there is not a single molecule of its structure that does not continuously change the thermodynamic parameters that affect comfort and energy demand.

Observing a building from this perspective, changes the way the architect has to look at the design process. The architect is used to drawing a component or system and seeing it realized. The hypothetical and actual functions are the same: the components perform in the way the designer has decided they should perform: the drawing of a wall becomes a real wall, so with a window, or a staircase. Not so with thermodynamics. A thermal flux through an opaque or glazed surface will not necessarily be the same as it was drawn: it is physics which decides what the heat flow will be in relation to the location, orientation, time and the material used. A common case, unfortunately, is that of natural ventilation: beautiful drawings with elegant red and blue arrows expressing the intention, or desire, of the architect about the flow and paths of air movements. Unfortunately - not so much for the architect, but for those who must live in the building - in many cases physics decides that things do not go as planned. Just as the architect has learned the law of gravity so that he can design structures capable of resisting every possible mechanical stress, he should - if he wants to take into account the constraints of environmental sustainability – also learn the laws of thermodynamics[102].

102 This implies that he has to know they exist and the basic principles. It is not required a deep knowledge: for that there are the experts, which have to be part of the design team.

The two best known laws of thermodynamics are the first and the second. The first concerns the conservation of energy, which is related to quantity and hence to the energy balance of the building (energy cannot be created or destroyed; it can only be changed from one form to another). The second is more sophisticated, and for this reason is less understood. It deals with the quality of energy. The same amount of energy can have a higher or lower value. To understand this concept, the hydraulic analogy is helpful. If there are no losses along the way, including evaporation, the principle of conservation is also valid for water flows: however much water I take from a higher reservoir, for example, I will find the same amount at the end of the piping, in a lower reservoir, at sea level. But the same amount of water does not have the same quality: some is worth more and some is worth less, depending on its altitude above sea level. One can wash, drink etc. with either the water of a mountain reservoir or that of a lake in the plain, but there is something that can be produced with the water at high level that cannot be produced with water at sea level: mechanical or electrical energy. This is due to the fact that the water in a mountain reservoir has an additional gift, high potential energy that the water at sea level does not have. So, water could and should be measured in terms of both quantity and quality. One million cubic meters in a plain is worth much less than a few thousand cubic meters at altitude. It is the same for heat: at high temperatures it is worth much more than at low temperatures, because in the first case it can produce, with appropriate technologies, mechanical energy, or electrical energy (which is the most valuable), while in the second it can produce little or nothing. What for water is called potential energy, for heat is what in thermodynamics is called exergy, i.e. the potential for converting heat into mechanical energy through an engine.

What applies to water, i.e. that moving it from the mountain to sea level loses its gravity energy forever, that is its quality, also applies to heat: after burning a certain quantity of gas, coal, oil, producing high temperature heat to convert into mechanical energy, the low temperature heat derived from the process cannot be reused to produce more mechanical energy: its exergy is lost and its quality is now irreversibly degraded.

The quantity is conserved, the quality is not: once used it is gone forever.

In a building, the required heat - the heat that has to be to supplied or subtracted - is at a low temperature and is therefore of little thermodynamic value (although it is high enough for us because it allows us a more comfortable life).

If a building is seen as a thermodynamic system, the high quality energy that comes into play is solar and electrical energy; for space heating and cooling and hot water production a low quality of energy is used.

The problem is that we need this energy, even if it is low quality, and it is not easily available; indeed in most cases high-quality energy is used to produce it, thus wasting value. In addition, as far as the air-conditioning is concerned, the second law of thermodynamics provides another constraint: as water cannot move spontaneously from a lower level to a higher one, it requires a technological system, the pump; similarly heat cannot pass spontaneously from a colder body to a warmer one and, for this to happen with continuity, we are obliged to use a technological system and high quality energy. Heating, thus, is easy – it accords with natural spontaneous processes – cooling is not. It is not surprising that heating has been used for millennia and cooling for only a little over one hundred years.

2. HEAT TRANSFER

Heat can be transferred in three forms:

- sensible heat, driven by temperature differences;
- radiant heat, which is transferred by electromagnetic waves;
- latent heat, which is the heat released or absorbed by a body when there is a phase change (water is transformed into vapour and vice versa, water into ice and vice versa, etc.).

2.1 SENSIBLE HEAT

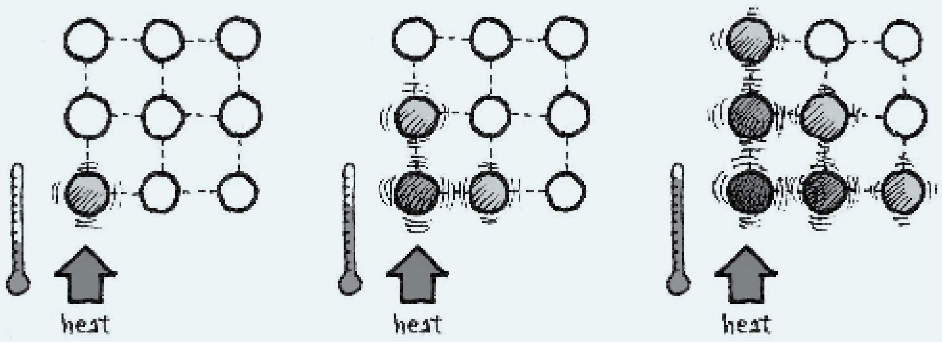
Sensible heat is the form of energy due to the random movement of molecules in a fluid, or to the vibration of the atoms in a solid body. These movements and vibrations are called thermal agitation. The higher the thermal agitation of a body, the higher the amount of heat that it contains and the higher its temperature. The temperature is, therefore, an indirect measure of the state of thermal agitation of a substance.

2.1.1 CONDUCTION

When a solid body is heated, the heat is transmitted from one end to the other: the atoms of the warmer part of the body transmit their greater thermal agitation to those adjacent to them, and the body progressively increases its temperature (Fig. A.1-1). This type of heat transfer is called conduction.

The higher or lesser ability to transmit the vibration of an atom to the adjacent ones (and then to "conduct" the heat inside from one point to another) is a specific property of each material and it is called thermal conductivity. Conduction also takes place between different bodies. When a solid body is put in contact with another, the atoms of the body at a higher temperature, which vibrate more, transmit energy to those of the body at a lower temperature, by increasing their thermal agitation; therefore the temperature of the body which was initially colder increases.

FIGURE A.1-1 **HEAT TRANSFER BY CONDUCTION**



Materials have different capacities to store heat; they are like sponges with different abilities to absorb water. The more they are able to accumulate heat, the more heat is needed to raise their temperature and, of course, the more they release as they cool down. This feature is named thermal capacity, and depends on a body's mass and specific heat, the latter being the amount of heat required to raise by one degree Celsius the temperature of one kilogram of material, and it is measured in J/kg K.

When heat starts to flow across a solid body (for example a homogeneous wall), initially a part of the heat goes to heat the body, and only when this is heated to a certain temperature does the incoming heat flow become equal to the outgoing one. When this occurs it is said that a steady state has been reached.

The heat required for heating the body remains stored in it, and it is partially or fully returned when there is a reduction or a stop in the incoming heat flow.

The higher or lower capacity of a body to accumulate and release heat and the speed with which this occurs is measured through its diffusivity:

$$\alpha = \lambda/\rho c \quad \text{(A.1-1)}$$

where:
λ = thermal conductivity [W/m K];
ρ = density [kg/m^3];
c = specific heat capacity, or specific heat [J/kg K].

In a sense, thermal diffusivity is the measure of thermal inertia. Heat moves rapidly through a substance with high thermal diffusivity, because the substance conducts heat quickly relative to its volumetric heat capacity.

To heat a body of volume *V* from initial temperature t_1 to final temperature t_2 it is necessary to provide the quantity of heat q_a that is given by:

$$q_a = c \cdot \rho \cdot V(t_2 - t_1) \quad \text{(A.1-2)}$$

where:
q_a = quantity of heat required to heat the body [J];
V = volume of the heated body [m^3].

The same amount q_a will be released by the body when it is cooled down to the temperature t_1.

When the body is heated continuously from one part, and has reached the steady state, the temperature gradient through it is linear, as in the case of the heat transfer along a metal bar heated at one end or through the two faces of a homogeneous wall (Fig. A.1-2). The thermal flux Q_c, i.e. the amount of heat transferred per unit of time by conduction through a flat plate (or a homogeneous wall) of area *S* and of thickness *s* is calculated by the expression:

$$Q_c = \frac{(t_{s1} - t_{s2})}{R_s} S = \frac{\lambda}{s}(t_{s1} - t_{s2})S \quad \text{(A.1-3)}$$

where:
Qc = thermal flux [W];
t_{s1} and t_{s2} are the temperatures of the faces 1 and 2 respectively [K, °C];
R_s = s/l is the thermal resistance of the material constituting the wall [m^{2}K/W];
S = area of the plate or wall [m^2];
l = thermal conductivity of the material [W/mK];
s = thickness of the plate or wall [m].

In case of a multi-layered slab (Fig. A.1-3), eqn. A.1-3 becomes:

$$Q_c = \frac{(t_{s1} - t_{s2})}{R_1 + R_2 + R_3 + \cdots R_n} S = \frac{(t_{s1} - t_{s2})}{\frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \frac{s_3}{\lambda_3} + \cdots \frac{s_n}{\lambda_n}} S \quad \text{(A.1-4)}$$

FIGURE A.1-2 **STEADY STATE CONDUCTION – SINGLE-LAYER SLAB**

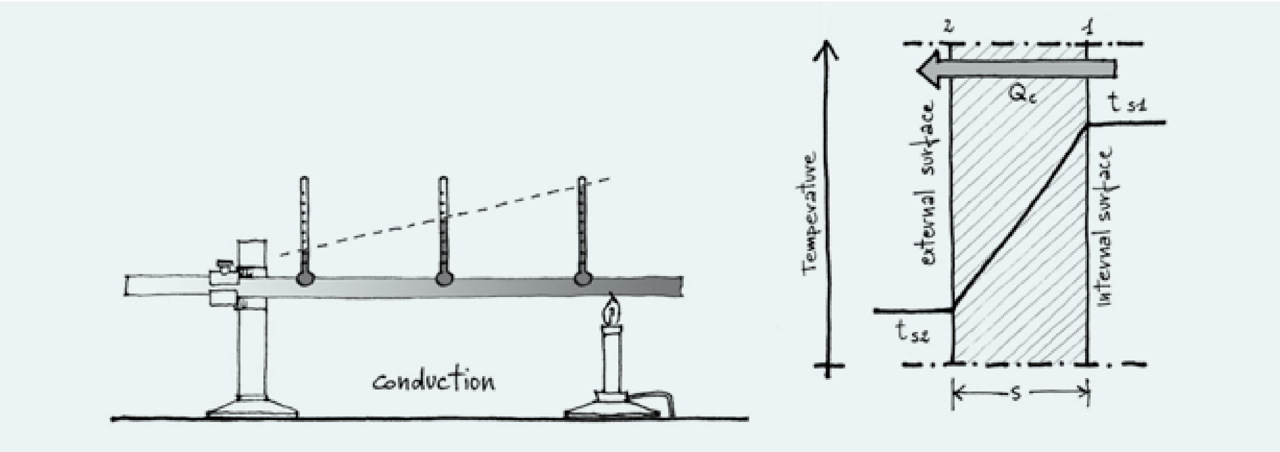
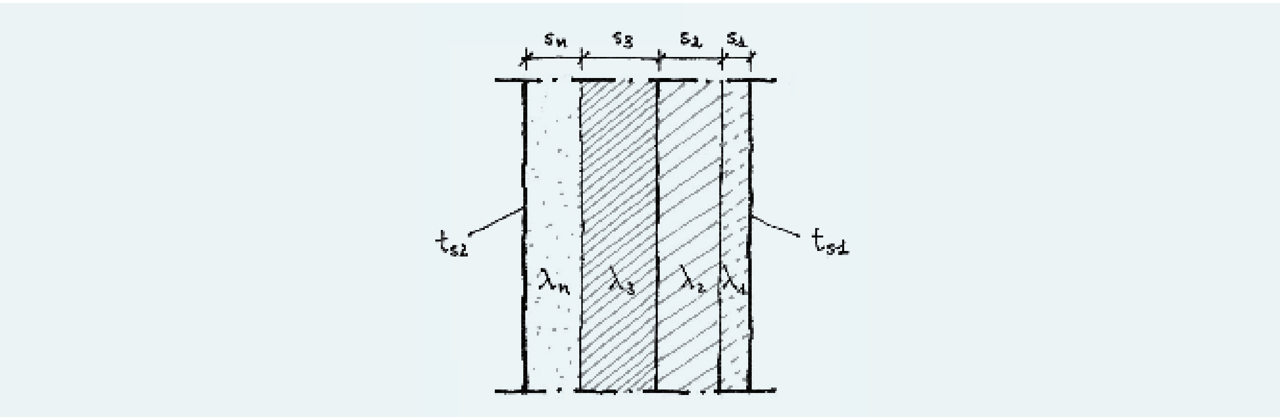


FIG. A.1-3 **STEADY STATE CONDUCTION; MULTI-LAYER SLAB**



If instead, as in a real situation, the heat flow across the wall is not constant because the outside air temperature changes in a cyclical pattern throughout the course of the day, the heat capacity also comes into play, and the heat flow through a wall varies over time in different ways depending on the resistance and the specific heat capacity of the material (Fig. A.1-4 and A.1-5).

It can be noted that the actual heat flow curve is delayed behind the zero-mass curve by some time. This delay of the peak is referred to as the time-lag, and is measured in hours.

The actual peak heat flow, when mass is taken into account, is also reduced by the effect of the mass, and this effect is added to that due to thermal resistance. The ratio of the real wall peak heat flow to that of the ideal wall with zero mass is referred to as the decrement factor**.**

For a homogeneous slab (for multi-layered slabs the calculation is more complex) the time-lag ϕ and the decrement factor ψ can be calculated as:

$$\varphi = 0.023 \cdot s\sqrt{\frac{1}{\alpha}} \qquad \text{(A.1-5)}$$

$$\psi = exp\left(-0.003 \cdot s\sqrt{\frac{1}{\alpha}}\right) \qquad \text{(A.1-6)}$$

where:
φ = time-lag [h];
s = thickness of the element [m];
α = diffusivity of the material = λ/ρc [m^2/s];
ψ = decrement factor, dimensionless.

Table A.1-1 reports data on thermal properties of most common building materials; Table A.1-2 on time-lag and decrement factor of some common building components.

FIGURE A.1-4 **THERMAL RESISTANCE REDUCES THE PEAK HEAT FLOW; THE HEAT CAPACITY REDUCES AND ALSO DELAYS IT**

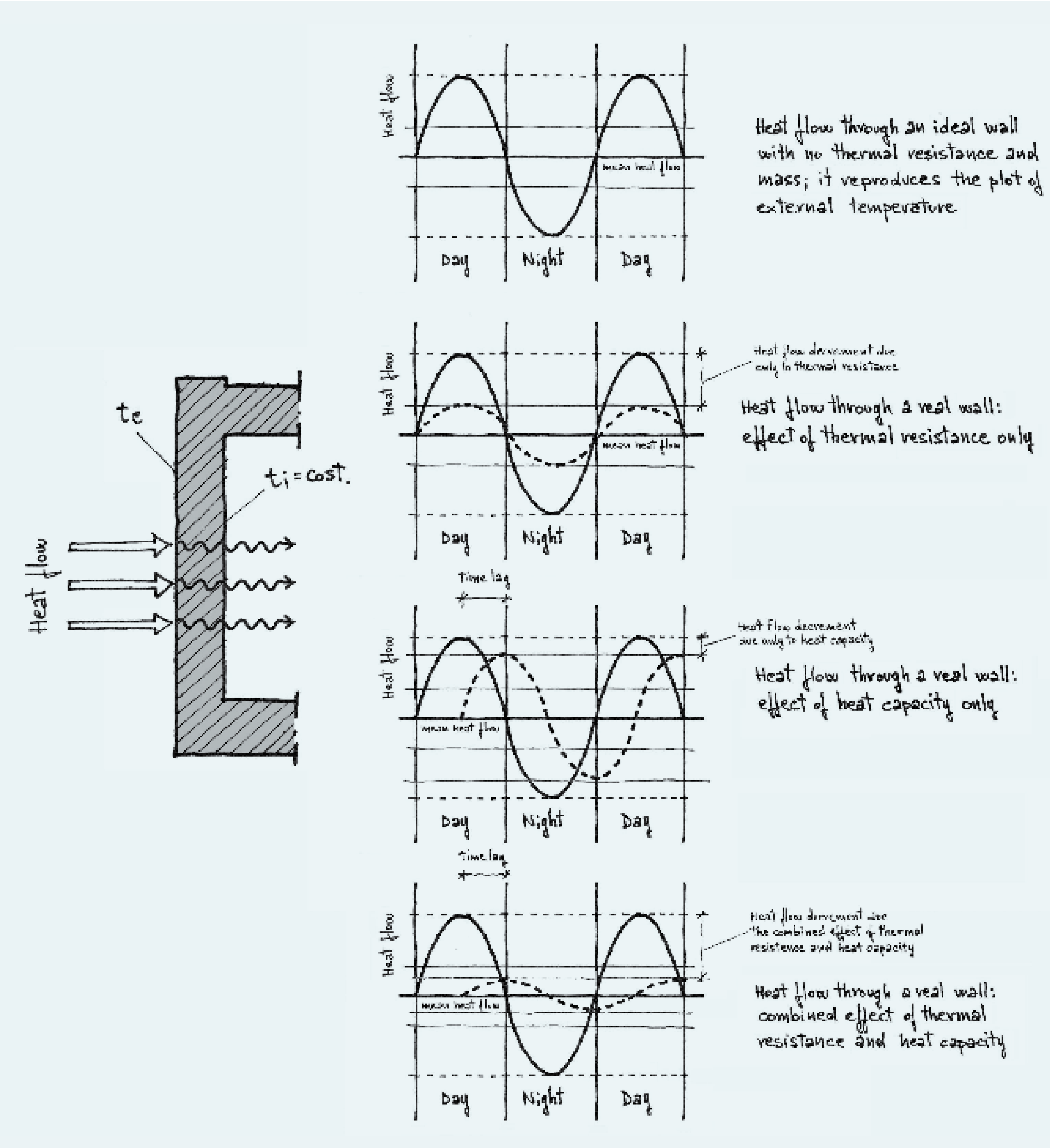
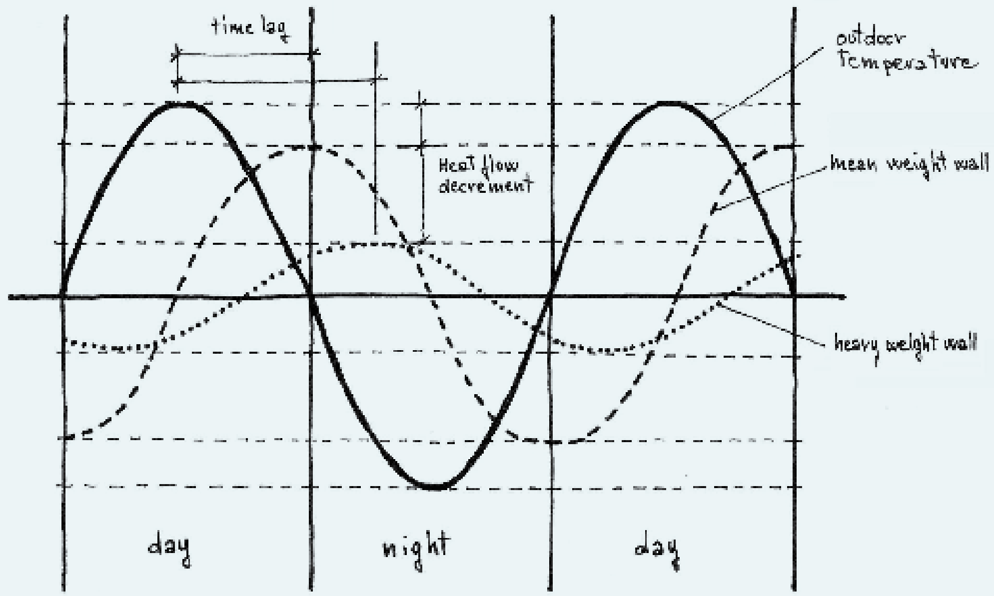


FIGURE A.1-5 **HEAT FLOW THROUGH THE WALLS OF DIFFERENT WEIGHT.**



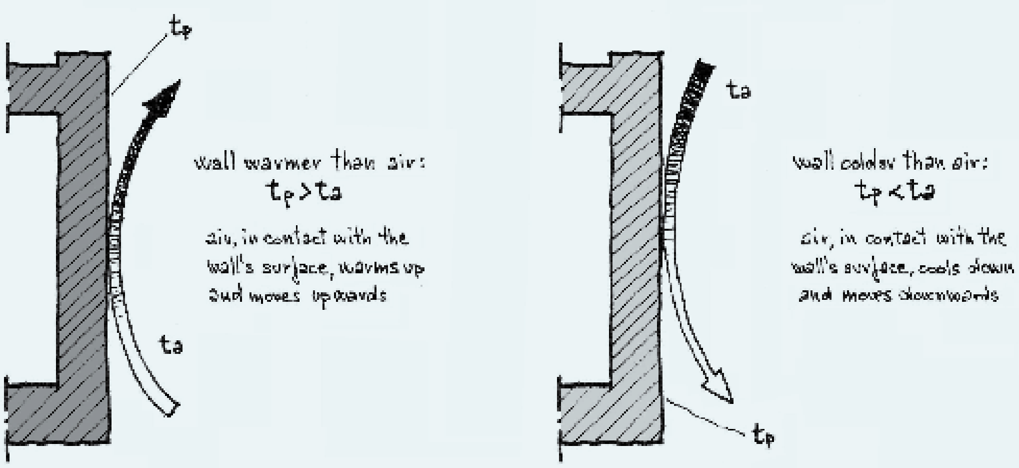
2.1 CONVECTION

With a fluid, the only change is that its molecules, instead of its atoms, move in a completely random way and without a binding position, and the heat transfer takes place through the collisions between them. The temperature of a fluid is a measure of the average velocity of the molecules that it is composed of.

The specific heat of fluids varies much more than that of solids. For example, with the amount of heat necessary to raise the temperature of one litre of water by 1 °C, we can raise by 1 °C the temperature of 3,000 litres of air.

When a fluid flows around a warmer solid body, the thermal agitation of the solid body is transmitted to the molecules of the fluid, which increase their speed, and the fluid is heated. In this case, however, the physical phenomenon becomes more complicated, because the portion of the warmer fluid that is in contact with the solid, has a lower density than that of the rest of the fluid and tends to "float" i.e. to move upwards (buoyancy effect). On the contrary, if the fluid is warmer than the solid body, the part in contact loses heat, and cools down; its density decreases compared to that of the rest of the fluid, and it tends to "sink" that is, to move downwards (Fig. A.1-6). This phenomenon is called natural convection; it involves - in contrast to conduction - the movement of mass and it is the way in which heat is transferred between a solid and a fluid.

FIGURE A.1-6 **HEAT TRANSFER WALL-AIR BY NATURAL CONVECTION**



Convection can also be forced. This occurs when a fluid is already moving when it touches a solid; if the fluid is air, this is the case where there is wind or when the air is moved by a fan. More heat is transferred with forced convection than with natural convection.

The thermal flow Q_c, i.e. the amount of heat which is transferred by convection per unit time by a solid body of area S to a fluid (or vice versa) depends on the surface temperature of the solid body t_s, that of the fluid t_f and on heat transfer coefficient h_c which – in turn - depends on the type of fluid and its temperature; it can be calculated by the expression[103]:

$$Q_c = h_c \cdot S \cdot (t_s - t_f) \qquad \text{(A.1-7)}$$

where:
Q_c = heat flux transferred by convection [W];
h_c = convection heat transfer coefficient [W/m^{2}K].

2.2 RADIANT HEAT

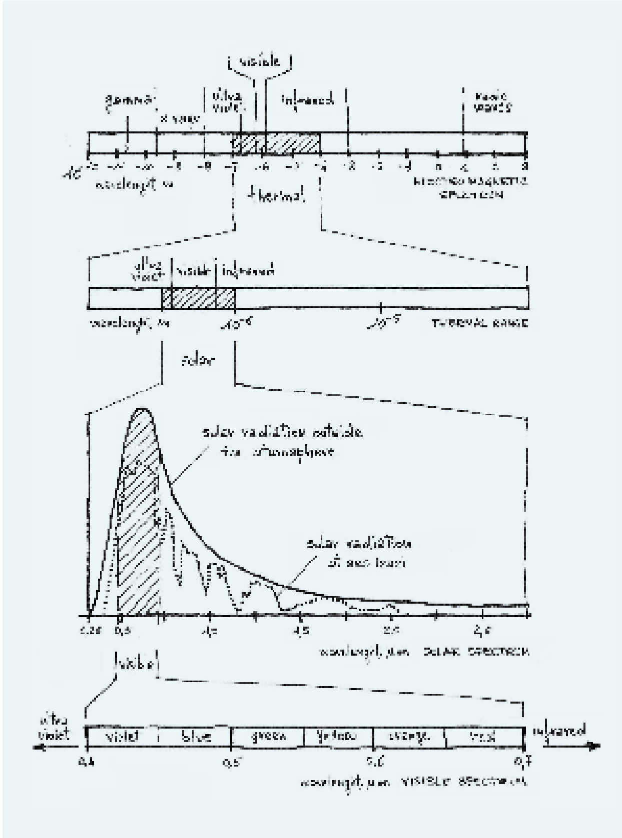
We are immersed in electromagnetic radiations, ranging from gamma rays to radio waves (Fig. A.1-7). The range of radiation wavelengths which is of interest in the energy performance of buildings is called the thermal range. Each radiation of a given wavelength can also be seen, according to the corpuscular theory, as a group of photons, whose associated energy is a function of the wavelength, travelling in the space.

When a photon associated with electromagnetic radiation hits an atom, the latter changes its state because of the energy transferred. This energy manifests itself as increased thermal agitation. On the other hand, the thermal agitation of the atoms and the transition of the electrons from one energy level to another give rise to the emission of electromagnetic radiation. So, all bodies emit electromagnetic radiation, and all bodies absorb it. A body able to completely absorb the electromagnetic radiation that hits it is called a black body. When the temperature of a body is increased, the amount of radiant energy Q_r that it emits per unit time increases very rapidly, in proportion to the fourth power of the absolute temperature (K), according to the Boltzmann law:

$$Q_r = \varepsilon \cdot \sigma \cdot S \cdot T^4 \qquad \text{(A.1-8)}$$

where:
Q_r = radiant heat flux [W];
ε = emissivity, or emittance, of the surface, which is equal to the ratio of the radiant flux emitted from the real body and that emitted from the blackbody at the same temperature (thus, for a blackbody ε = 1), dimensionless;
σ = Stefan-Boltzmann constant = 5.7 x 10-8 [W/m^2 K4];
S = area of emitting surface [m^2];
T = absolute temperature of emitting surface [K].

FIGURE A.1-7 **ELECTROMAGNETIC WAVES SPECTRUM**

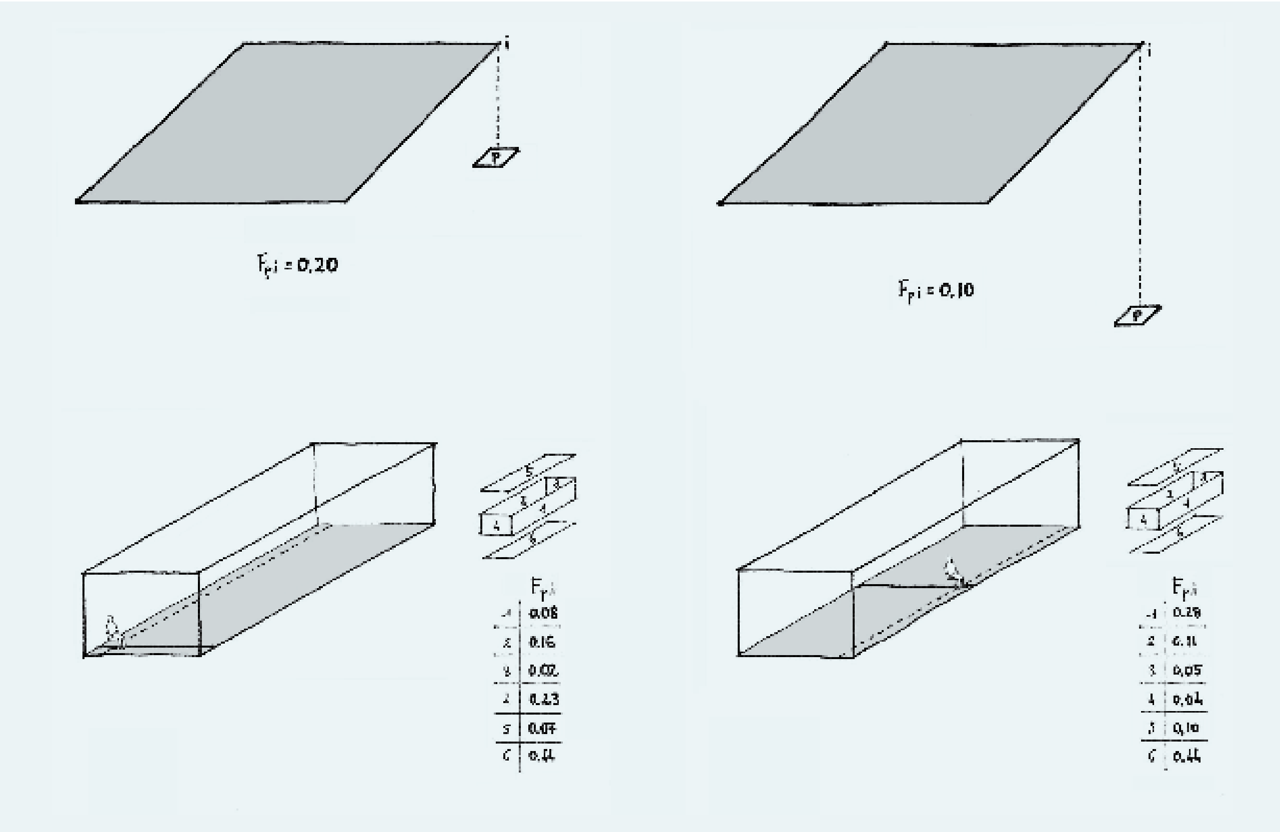


A body not only emits, but also receives radiant heat, being surrounded by other bodies that in turn emit it. What matters in the end, then, is the net balance of energy, i.e. the difference between the radiant heat emitted and the radiant heat received. This balance depends not only on the temperature and emissivity of the bodies but also on their positions, which determine the reciprocal apparent surfaces. For example, the electromagnetic radiation we receive from a fireplace is different depending on our distance from it, and if we are in front or to the side; this derives from the apparent surface of the fireplace: it is smaller if we are away from it or to the side. The greater the apparent surface, the greater the amount of radiant energy we receive. For this reason a fireplace warms us more if we are close to and in front of it.

To quantify phenomenon, the view factor $F_{p,i}$ (called also form or shape factor) is used, indicating the proportion of the radiation which leaves surface A that strikes surface B (Fig. A.1-8).

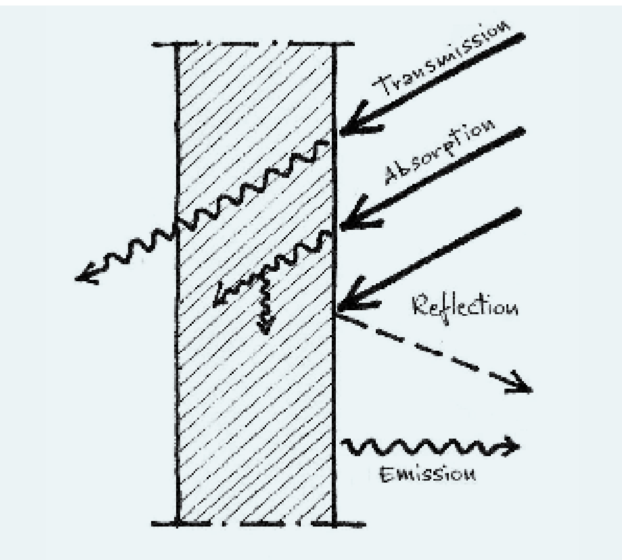
*103 h_c as a function of the wind speed **v** can be estimated by means of the following empirical formulas:*
$h_c = 5.62 + 3.9v$ if $v < 5\ m/s$
$h_c = 7.2v^{0.78}$ if $v < 5\ m/s$

FIGURE A.1-8 **EXAMPLES OF VIEW FACTOR CHANGING WITH THE POSITION OF A SURFACE P (TOP) AND OF A PERSON WITH RESPECT TO THE SURFACES OF AN ENCLOSURE**



There are four ways in which the electromagnetic radiation interacts with matter; they are (Fig. A.1-9): transmission, reflection, absorption and emission.

FIGURE A.1-9 **FOUR TYPES OF INTERACTION THAT CAN OCCUR BETWEEN RADIANT ENERGY AND MATTER**



Transmission takes place when radiation passes through a material; reflection when it is reflected by the surface; absorption when radiation is absorbed and converted into sensible heat; emission when the material emits radiation from its surface.

It always has the relationship:

$$\tau + \rho + \alpha = 1 \qquad \text{(A.1-9)}$$

where τ, ρ and α are, respectively the transmission through the material, the reflection and the absorption coefficients, dimensionless.

For most of the materials commonly used in construction and the operating temperatures range:

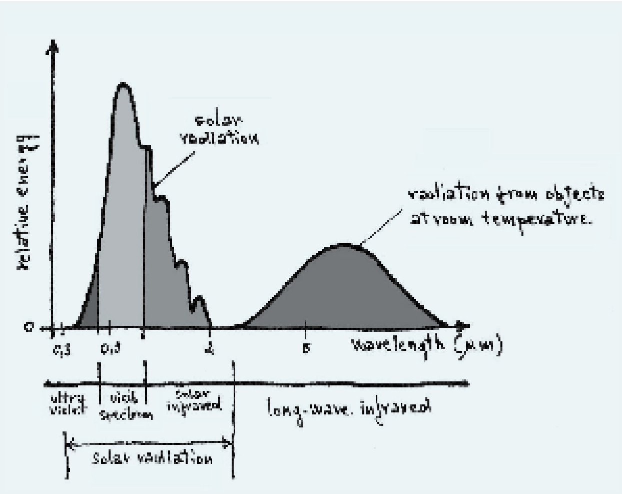
$$\varepsilon = \alpha \qquad \text{(A.1-10)}$$

Each material shows specific characteristics of transmission, reflection and absorption (Fig. A.1-11) in relation to the wavelength of the incident radiation (Fig. A.1-10). A glass pane, for example, has a high ability to transmit electromagnetic radiation whose wavelength lies in the visible range, while a copper plate blocks it completely; a polished metal surface has a low capacity for emission in the far infrared, but a high reflectivity in the visible.

These are precisely the selective properties of the materials, thanks to which the glass lets through the solar radiation but absorbs the long wave radiation coming from the objects that make possible the so-called greenhouse effect. Since solar radiation entering an enclosed space through glass is largely absorbed by the objects on which it falls, they are heated but their electromagnetic emission is blocked by the glass, which thus traps the energy in the space.

In Table A.1-3 are reported emissivity, reflection and absorption coefficient (also called emittance, reflectance and absorptance) at different wavelengths for most common materials used in buildings.

FIGURE A.1-10 **SOLAR RADIATION SPECTRUM AND EMISSION SPECTRUM OF RADIANT ENERGY IN THE FAR INFRARED OF OBJECTS AT ROOM TEMPERATURE**



2.2.1 LONGWAVE EMISSION TOWARDS THE SKY

The atmosphere also emits longwave radiation, and the net radiative energy balance Q_{rs} for a horizontal surface seeing the sky is given by:

$$Q_{rs} = Q_r - Q_{sky} = \sigma\varepsilon(T_s^4 - T_{sky}^4)S \qquad \text{(A.1-11)}$$

where:
Q_{rs} = net flux exchanged by the surfaces [W];
Q_r = radiant flux emitted by the surface [W];
Q_{sky} = radiant flux emitted by the sky [W];
T_s = absolute temperature of emitting surface [K];
T_{sky} = absolute temperature of sky [K].

The absolute temperature of clear sky can be evaluated with the expression[104]:

$$T_{sky} = 0.0553 T_a^{1.5} \qquad \text{(A.1-12)}$$

where T_a is the air temperature in K and the sky is supposed to have .

For cloudy sky, the following expression can be used:

$$T_{sky} = 0.0553\, T_a^{1.5} + 2.625\, cc \qquad \text{(A.1-13)}$$

where *cc* is the cloud cover expressed in Octas[105].

If the surface is not horizontal, Q_{rs} is given by:

$$Q_{rs} = \sigma\varepsilon\left[F_s(T_s^4 - T_{sky}^4) + F_g(T_s^4 - T_g^4)\right]S \qquad \text{(A.1-13a)}$$

where:
Q_{rs} = radiant flux emitted by the surface [W];
T_g = absolute temperature of ground [K];
F_s is the dimensionless view factor of the sky dome from the surface, function of the tilt angle of the surface ψ, given by:

$$F_s = \frac{1 + \cos(\psi)}{2} \qquad \text{(A.1-14)}$$

and F_g is the shape factor between the surface and the ground, given by

$$F_g = 1 - F_s \qquad \text{(A.1-15)}$$

2.2.2 RADIANT ENERGY EXCHANGES FOR BUILDING APPLICATIONS

The calculation of the radiant energy exchanges is rather complex, however for building applications, i.e. temperatures and materials involved, a simplified approach can be used.

The longwave radiant heat gain or loss Q_r at the walls, roofs and windows surfaces can be calculated with the expression:

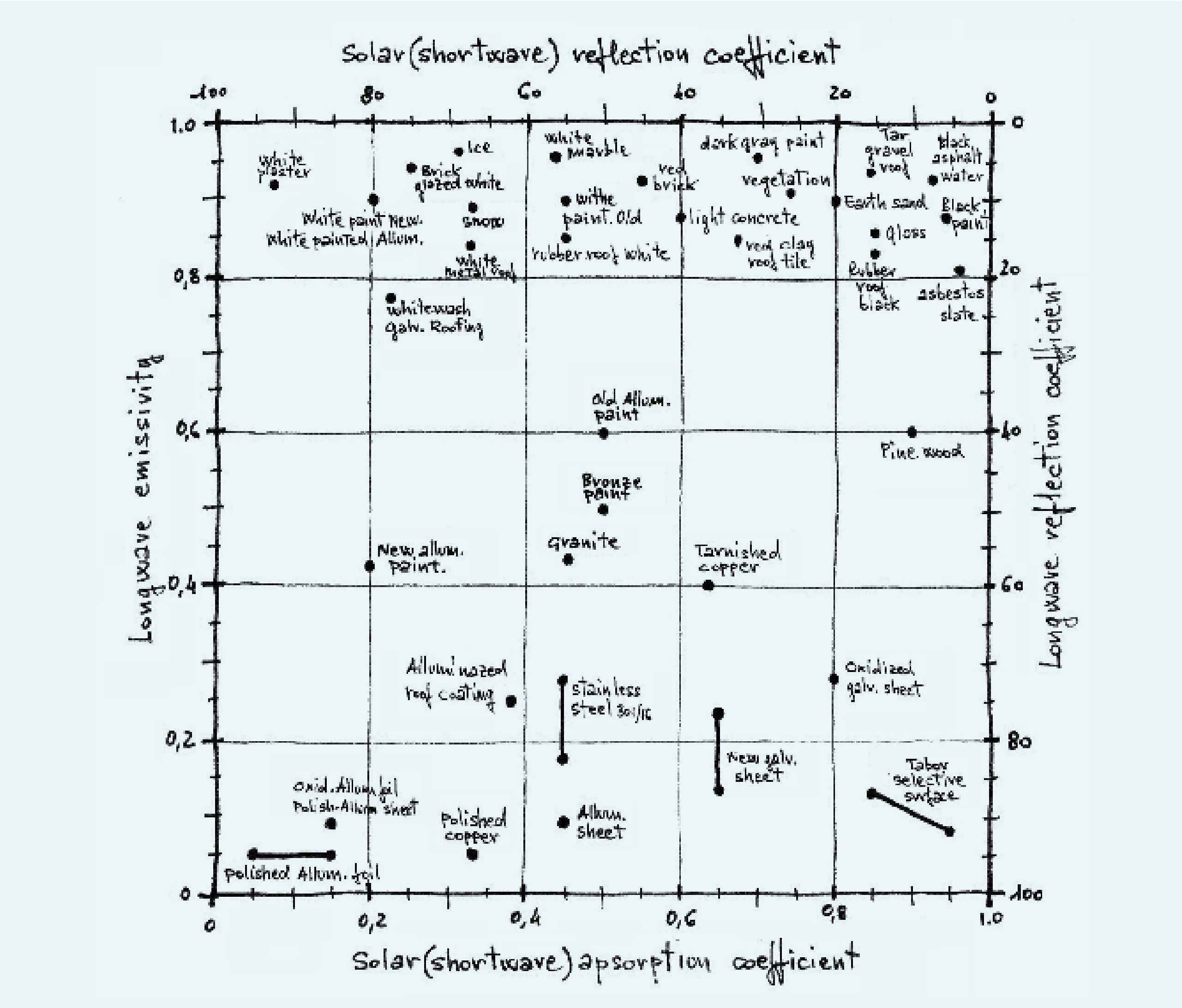
$$Q_r = h_r \cdot S \cdot (t_s - t_a) \qquad \text{(A.1-16)}$$

where:
Q_r = radiant heat flux [W];
h_r = radiation coefficient [W/m²K];
S = area of the surface [m²];
t_s = surface temperature [K,°C];
t_a = air temperature [K,°C].

104 R.J. Goldstein, Application of aerial infrared thermography to the measurement of building heat loss, ASHRAE Trans. N. 2482, 1978

105 It is an estimate of how much of the sky is covered by cloud. A clear sky is 0 Oktas, A summer's day sky with fluffy clouds but lots of sky could be 1-3 Oktas; An overcast sky with bits of blue showing 7 Oktas, and full overcast 8 Oktas.

FIGURE A.1-11 **ABSORPTION COEFFICIENT AND EMISSIVITY OF DIFFERENT MATERIALS FOR SOLAR RADIATION AND FAR-INFRARED RADIATION**



2.2.3 CONVECTIVE AND RADIATIVE HEAT EXCHANGES

The convective and radiative heat exchanges that take place at the surface of a wall, roof or window can be calculated together by combining them as:

$$Q_r = h_c \cdot S \cdot (t_s - t_a)$$

$$Q_r = h_r \cdot S \cdot (t_s - t_a)$$

$$Q_s = Q_c + Q_r = (h_c + h_r) \cdot S \cdot (t_s - t_a)$$

$$Q_c = h_c \cdot S \cdot (t_s - t_f) \quad \text{(A.1-17)}$$

where:
Q_s = total, radiative + convective, heat flux through the surface [W];
h = overall surface heat transfer coefficient [W/m²K].

The above equation can also be written as:

$$Q_s = \frac{t_s - t_a}{R_h} S \quad \text{(A.1-18)}$$

where R_h = *1/h* is the surface resistance to heat flux. Values of *h* are given in Table A.1-4.

2.2.4 OVERALL HEAT TRANSFER COEFFICIENT

In case of a homogeneous flat slab (for example a wall or a roof) dividing two air spaces at different temperature, combining eqns. (A.1-1) and (A.1-4), the heat flux *Q* through the slab is given by[106]:

106 By convention, the heat flux Q is considered positive when indoor temperature is higher than outdoor, i.e. the heat flows from inside to outside.

$$Q = \frac{t_o - t_i}{R_s + R_{hi} + R_{ho}} S = \frac{t_o - t_i}{R_t} S = U(t_o - t_i)S \quad (A.1\text{-}19)$$

where:
t_o = outdoor temperature [°C];
t_i = indoor temperature [°C];
$R_s = s/\lambda$ = thermal resistance of the material constituting the slab [m²K/W];
$R_{hi} = 1/h_i$ h_i = internal surface heat transfer coefficient [W/m² K];
$R_{ho} = 1/h_o$ h_o = external surface heat transfer coefficient [W/m² K];
$U = 1/R_t$ = overall heat transfer coefficient [W/m² K].

The overall heat transfer coefficient U (named also "U-value") characterises the thermal performance of a building component (wall, roof, glass, etc.), being the amount of heat which passes through it per unit area and for a temperature difference of 1 K (or 1 °C) between inside and outside air; the lower the value, the better the thermal performance.

In case of a multi-layered slab, eqn. (A.1-5) becomes:

$$Q = \frac{t_o - t_i}{R_{hi} + R_{l1} + R_{l2} + \cdots R_{ln} + R_{ho}} S = \frac{t_o - t_i}{R_t} S = U(t_o - t_i)S \quad (A.1\text{-}20)$$

where $R_{l1} = s_1/\lambda_1$, $R_{l2} = s_2/\lambda_2$, $R_{ln} = s_n/\lambda_n$ are the thermal resistances of layer 1, 2, ...n, and R_t is the thermal total resistance of the slab.

The most common and general way to calculate the overall heat transfer coefficient of a multi-layered wall is:

$$U = \frac{1}{\frac{1}{h_i} + \frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \cdots \frac{s_n}{\lambda_n} + \frac{1}{C} + \frac{1}{h_o}} \quad (A.1\text{-}21)$$

where:
U = overall heat transfer coefficient [W/m²K];
C = conductance of a cavity, or air space (see Table A.1-5).

To evaluate the instantaneous heat flow through a slab in non-steady state conditions, time-lag and decrement factor must be taken into account. Instantaneous heat flow $Q_{(t)}$ through a slab at time τ can be calculated as:

$$Q_{(t)} = Q_m + \Psi \times U \times S \times (t_{o(\tau-\varphi)} - t_{o(m)}) \quad (A.1\text{-}22)$$

where:
$Q_{(t)}$ = instantaneous heat flow [W];
$Q_m = U \times S\ (t_{o(m)} - t_{i(m)})$ is the mean heat flow of the day considered [W];
Ψ = decrement factor;
$t_{o(\tau-\varphi)}$ = external air temperature at time $\tau - \varphi$ [°C];
φ = time-lag;
$t_{o(m)}$ = mean external air temperature [°C];
$t_{i(m)}$ = mean internal air temperature [°C].

2.2.5 SOL-AIR TEMPERATURE

When the surfaces of a building are hit by solar radiation, a change in the heat flow is produced.

The change derives from the fact that the external surface warms up, and the temperature increase depends upon the incident solar radiation and the absorptance of the surface.

A similar change in heat flow could occur if there was no solar radiation but if the external air temperature was increased to an appropriate value. The increased air temperature which is producing the same heat flow change as was obtained with solar radiation acting in conjunction with the actual external air temperature is called the sol-air temperature (Fig. A.1-12). Hence:

$$Q_{sa} = Q + \alpha I_s \quad (A.1\text{-}23)$$

where:
$Q_{sa} = h(t_{sa} - t_p)$ = Rate of heat flow through the surface due to sol-air temperature [W];
$Q = h(t_o - t_p)$ = Rate of heat flow due to actual external air temperature [W];
αI_s = Rate of heat flow due to solar radiation [W];
h = surface heat transfer coefficient [W/m²K];
t_p = surface temperature [°C];
t_{sa} = sol-air temperature [°C];
t_o = external air temperature [°C];
α = absorption coefficient of the surface, dimensionless;
I_s = total solar radiation incident on the surface [W].

thus[107]:

$$h(t_{sa} - t_p) = h(t_o - t_p) + \alpha I_s \quad (A.1\text{-}24)$$

$$t_{sa} = t_o + \alpha I_s / h \quad (A.1\text{-}25)$$

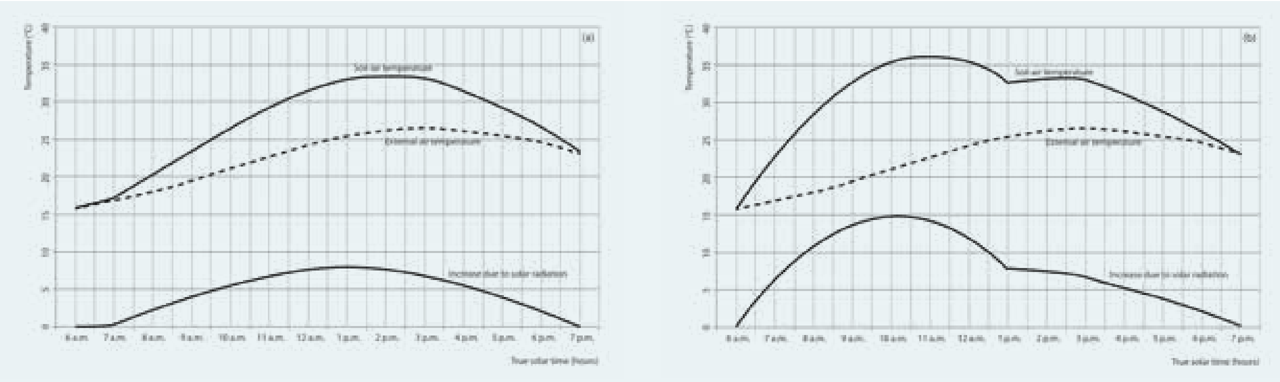
To calculate the instantaneous heat flow through a slab subject to solar radiation eqn. A.1-22 becomes:

$$Q_{(\tau)} = Q_{msa} + \Psi \times U \times S \times (t_{sa(\tau-\phi)} - t_{sa(m)}) \quad (A.1\text{-}26)$$

where:
$Q_{msa} = U \times S\ (t_{sa(m)} - t_{i(m)})$ is the mean heat flow of the day considered [W];
$t_{sa(m)}$ = mean sol-air temperature [°C];
$t_{sa(\tau-\phi)}$ = sol-air temperature at time $\tau - \phi$ [°C].

107 *Actually, there is some heat released by radiation in the far infrared. It has been ignored in the energy balance because is a very small amount, compared to solar radiation.*

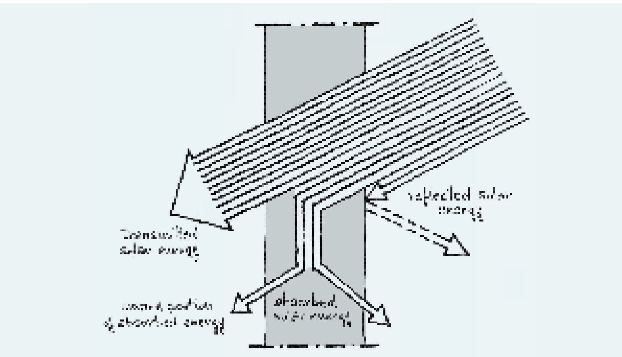
FIGURE A.1-12 **SOL-AIR TEMPERATURES FOR NAIROBI DURING THE HOTTEST MONTH (MARCH). R_{so}=0.05 M²K/W AND α =0.6; (A) SOUTH-FACING WALL; (B) EAST-FACING WALL**



2.2.6 GLASS AND SOLAR RADIATION

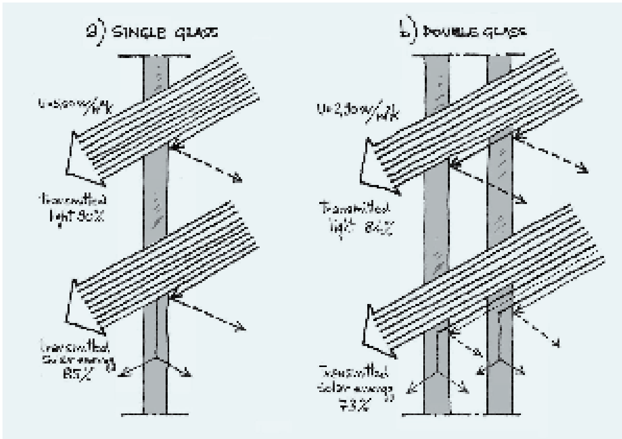
Solar radiation incident on a glass surface is partly reflected, partly absorbed and partly transmitted; of the absorbed energy, a part returns to the outside and a part is released inside, due to the heating of the glass (Fig. A.1-13). It should be noted that the fraction of solar energy transmitted does not correspond to the fraction of light transmitted (Fig. A.1-14). This is due to the fact that glass transmits all the wavelengths of the solar spectrum, not only the ones contained in the visible spectrum (Fig. A.1-15).

FIGURE A.1-13 **SOLAR ENERGY BALANCE OF A SINGLE GLASS**



Glass causes the so-called greenhouse effect, due to the selectivity of the glass to radiation: the glass transmits short and near infrared waves (radiation of wavelength less than 2.5 microns), but blocks the long waves. Short and near infrared waves pass through the glass and are absorbed by surfaces and objects inside. These objects warm up and re-radiate long waves, the thermal radiation, which, being of a wavelength greater than 2.5 microns, are blocked by the glass and retained in the indoor environment, thus generating a temperature increase.

FIGURE A.1-14 **ENERGY AND LIGHT TRANSMITTED IN A SINGLE AND DOUBLE GLASS**



The feature of transforming solar energy into thermal energy is an ambivalent factor; if, on the one hand, it allows the room to be heated with solar energy in cold climates, on the other hand it causes an energy gain that must be removed to avoid overheating in hot climates and seasons.

2.2.6.1 **ENERGY BALANCE OF WINDOWS**

The energy balance of a glass pane is given by (Fig. A.1-16):

$$Q_{gl} = (A + B + C) \times S_g \qquad (A.1\text{-}27)$$

where:
Q_{gl} = total energy flux through the glass [W];
A = solar radiation flux per square meter, transmitted through the glass [W/m²];
B = fraction of incident solar energy flux absorbed by the glass and transferred inside [W/m²];
C = thermal flux per square meter due to the difference in temperature between inside and outside[W/m²];
S_g = glass pane area [m²].

FIGURE A.1-15 **SOLAR SPECTRUM AND VISIBLE RANGE**

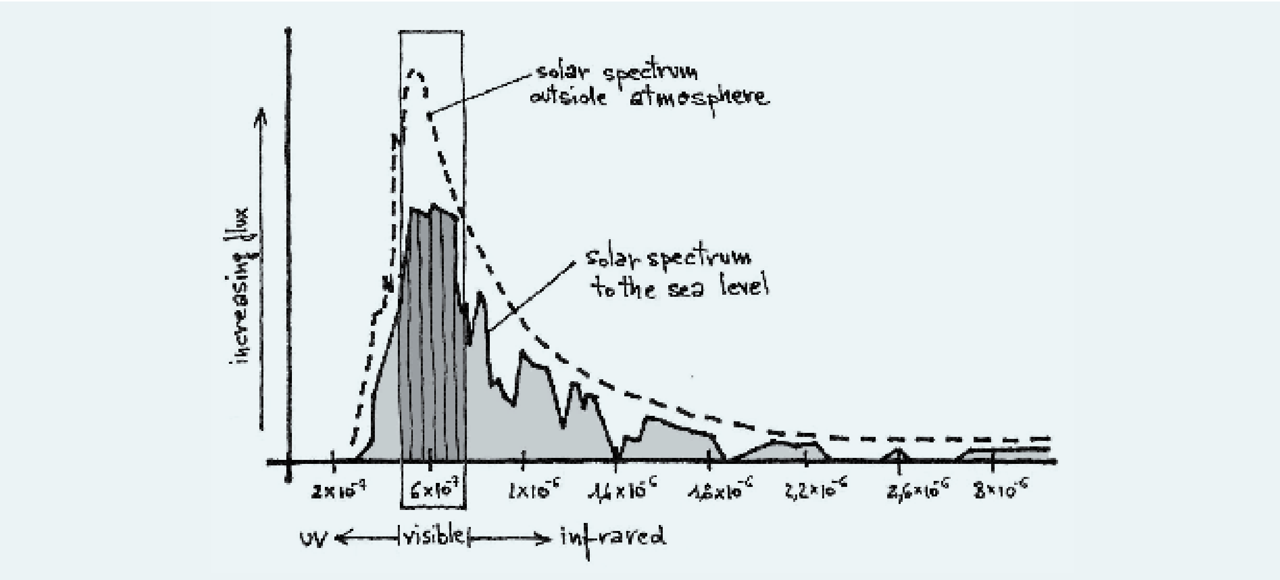
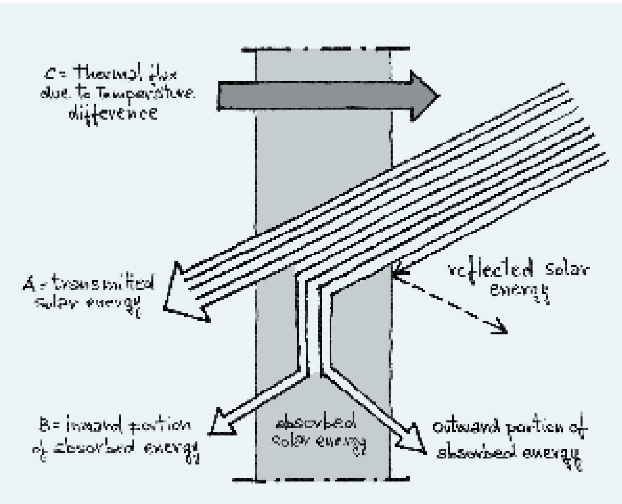


FIGURE A.1-16 **ENERGY BALANCE OF A GLASS PANE (INDOOR TEMPERATURE > OUTDOOR TEMPERATURE)**



The instantaneous energy balance can then be written as:

$$Q_{gl} = [\tau I_t + N_i \alpha I_t + U_{gl} (t_o - t_i)] \times S_g \quad \text{(A.1-28)}$$

Where the terms terms τI, $N_i \alpha I$ and $U_{gl}(t_o - t_i)$ correspond, respectively, to A, B and C and where:

τ = the solar transmission factor of glass, function of the incidence angle of solar beam radiation (Fig. A.1-17);
I_t = total solar irradiance incident on the glass [W/m^2];
N_i = represents the fraction of solar energy absorbed by the glass and released into the internal environment by radiation in the far infrared and convection[108], given by the ratio U_{gl}/h_o;

U_{gl} = overall heat transmission coefficient (or thermal transmittance) [W/m^{2}K] of the glass;
h_o = external surface heat transfer coefficient [W/m^{2}K];
α = absorption coefficient of glass;
t_o = temperature of external air [°C];
t_i = temperature of internal air [°C].

Since the terms A and B are linked to solar radiation, while C exists even in its absence, equation (A.1-28) can be written as:

$$Q_{gl} = [SHG + U_{gl} (t_o - t_i)] \times S_g = [SHGC \cdot I_t + U_{gl} (t_o - t_i)] \times S_g \quad \text{(A.1-29)}$$

where *SHG* is the solar heat gain through the fenestration and SHGC is the Solar Heat Gain Coefficient, the dimensionless ratio of solar heat gain to incident solar radiation:

$$SHG = SHGC \times I_t \quad \text{(A.1-30)}$$

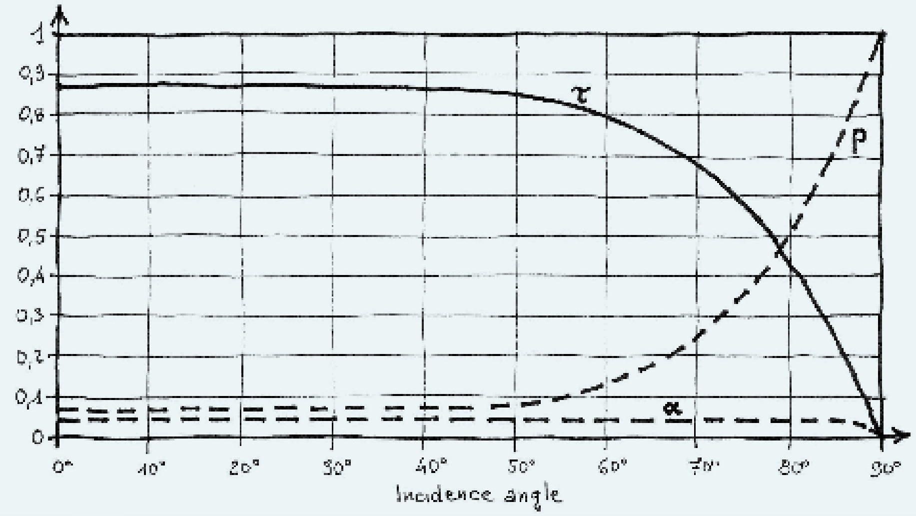
The solar heat gain coefficient SHGC is a characteristic of each type of fenestration and varies with the incident angle.

An alternative parameter used to characterise fenestrations is the Shading Coefficient or SC, the ratio of solar heat gain through the fenestration relative to that through 3 mm clear glass at normal incidence:

SC = SHG of fenestration/SHG of reference glass = SHGC of fenestration/0.87

108 For a 3 mm clear glass, N_i can be considered constant and equal to 0.26.

FIGURE A.1-17 **SOLAR TRANSMITTANCE, ABSORPTANCE AND REFLECTANCE THROUGH A 3 MM SINGLE CLEAR GLASS**



If a shading device (internal or external) is used to protect the window from sun, the corresponding shading coefficient can be calculated. In the case of curtains or blinds the manufacturer generally provides the value (see Table A.1-6, where an example of a manufacturer's data sheet is given). In Table A.1-7 some typical values of SHGC and SC at near normal solar radiation incidence are given.

2.3 LATENT HEAT

The air we breathe contains a certain amount of water vapour, and this has a not insignificant role in the energy balance of a building. In fact, to increase by 1 °C one kg of water, 4.18 kJ of heat are required, thus to bring one kg of water from a temperature of 10 °C to 100 °C, 376 kJ of heat are required. However, to transform this one kg of water into vapour, 2,270 kJ are required. The phase change always requires a higher amount of heat because of the modifications occurring in the molecular structure. As seen before, this amount is called latent heat.

From this it follows that, as far as ventilation is concerned, in order to transform hot and humid outdoor air into air with a comfortable temperature and humidity, most of the energy needed is due to the dehumidification process, which is obtained through the condensation of a part of the water vapour contained in the air. To condense the vapour, in fact, it is necessary to subtract the same amount of energy required for its vaporization: 2,270 kJ per kg of condensed water, while for cooling by 1 °C a cubic meter of dry air only 1.2 kJ are needed. The psychrometric chart is used to evaluate the effect of the transformations that the moist air can have.

2.3.1 AIR AND THE PSYCHROMETRIC CHART

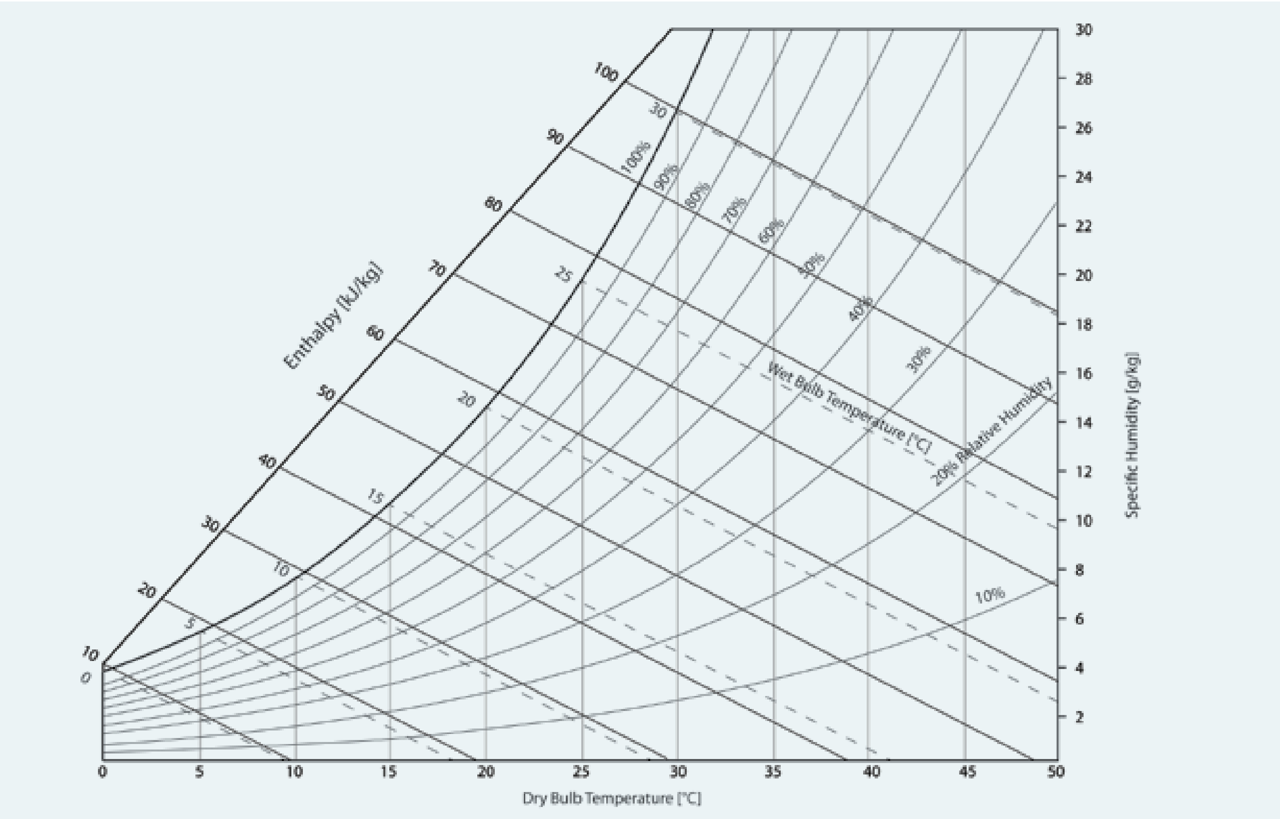
In buildings, latent heat comes into play because the cooling of air for air conditioning, and the need to maintain the relative humidity at values below 70% - the limit above which thermal comfort is not assured - necessarily involves the condensation of a certain amount of water vapour contained in the air.

The interconnections between air temperature and humidity are summarized in a diagram called the psychrometric chart[109] (Fig. A.1-18). On the X-axis the values of dry bulb temperature (the air temperature measured with a thermometer) are marked, and on the Y-axis the humidity ratio, i.e. the amount (grams) of moisture contained in a kg of dry air; the highest curve is of that of saturation, indicating the locus of points in which the values of dry bulb temperature and absolute humidity are such that the relative humidity is 100%, and the water vapour present in the air starts to condense (dew point). At that point dry bulb and wet bulb temperatures are equal, wet bulb temperature being defined as the temperature a parcel of air would have if it was cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel. For a given parcel of air at a known pressure and dry-bulb temperature, wet-bulb temperature corresponds to unique values of relative humidity, dew point temperature, and other properties.

The diagram allows the air properties inside a room or outdoors to be represented through a data pair, which can

109 The interconnection between air temperature and humidity also depends on the atmospheric pressure, i.e. on the altitude above sea level The chart reproduced in the figure, is for altitude above sea level = 0 m. Psychrometric charts for different altitudes above the sea level are given in figures A.1-27, A.1-28 and A.1-29 at the end of this chapter.

FIGURE A.1-18 **PSYCHROMETRIC CHART AT SEA LEVEL**

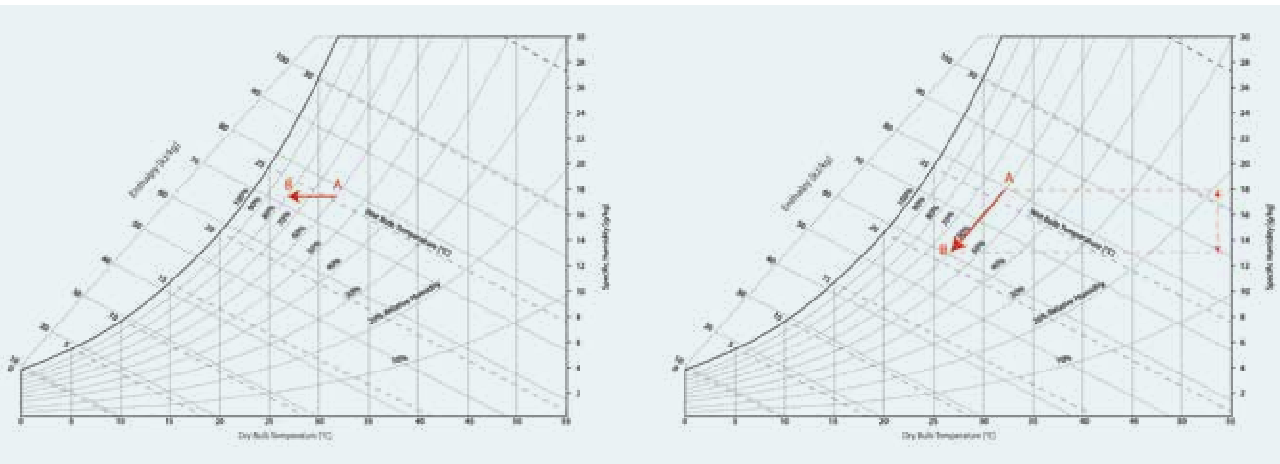


be: the dry bulb temperature and humidity ratio, or the dry bulb temperature and relative humidity or the dry bulb temperature and the wet bulb, etc. Given a pair of these values, it is possible to read all the others, including the specific enthalpy (the energy content per kg of air at given conditions, which corresponds to the sum of sensible and latent heat).

Therefore, a point marked in the diagram represents the conditions of the air at a given place and time.

If we cool the outdoor air, initially at 32 °C and 60% RH and bring it down to 26 °C, the resulting process is represented in figure A.1-19 (left). It is called sensible cooling. It can be seen that the resulting relative humidity is too high for comfort. To maintain the relative humidity at an acceptable value, water vapour must be subtracted from the air, as indicated in the transformation of figure A.1-19 (right), in which about 5 grams of water per kg of dry air are condensed.

FIGURE A.1-19 **SENSIBLE COOLING (LEFT); COOLING AND DEHUMIDIFICATION (RIGHT)**



The transformation actually occurring in air conditioning systems is not the one indicated in figure A.1-19 (right), but involves the cooling of air to reach the saturation curve, and moving along it to the point where the required amount of vapour is condensed to achieve the desired relative humidity (Fig. A.1-20, left).

If we evaluate the change in enthalpy required to perform the two transformations, i.e. the energy that has to be supplied for each kg of treated air, it can be seen that in air conditioning the subtraction of latent heat (i.e. the condensation of the water vapour) requires more energy than subtraction of sensible heat (Fig. A.1-20, right).

Finally, there is a last transformation, which allows heat to be subtracted from an environment, at the expense of increasing relative humidity; it is called adiabatic humidification and it occurs when water is sprayed into an air stream. The water evaporates and, in so doing, it absorbs heat from the air, which cools down, increasing its humidity (Fig. A.1-21). In very hot and dry climates this is an easy way to improve comfort conditions in an enclosed space.

FIGURE A.1-20 **SENSIBLE COOLING AND DEHUMIDIFICATION, REAL PROCESS (LEFT); ENERGY REQUIRED FOR SENSIBLE COOLING AND DEHUMIDIFICATION (RIGHT)**

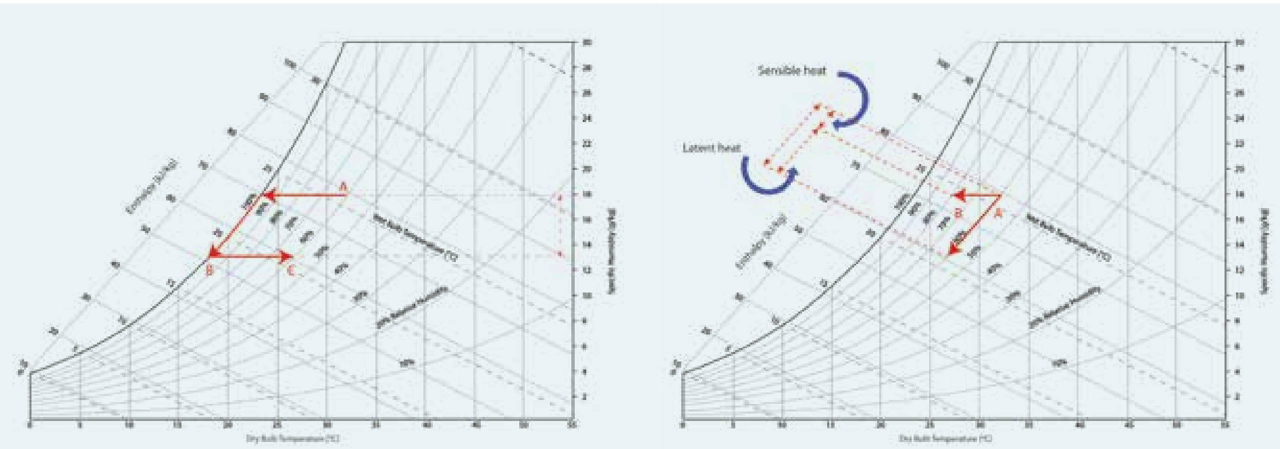
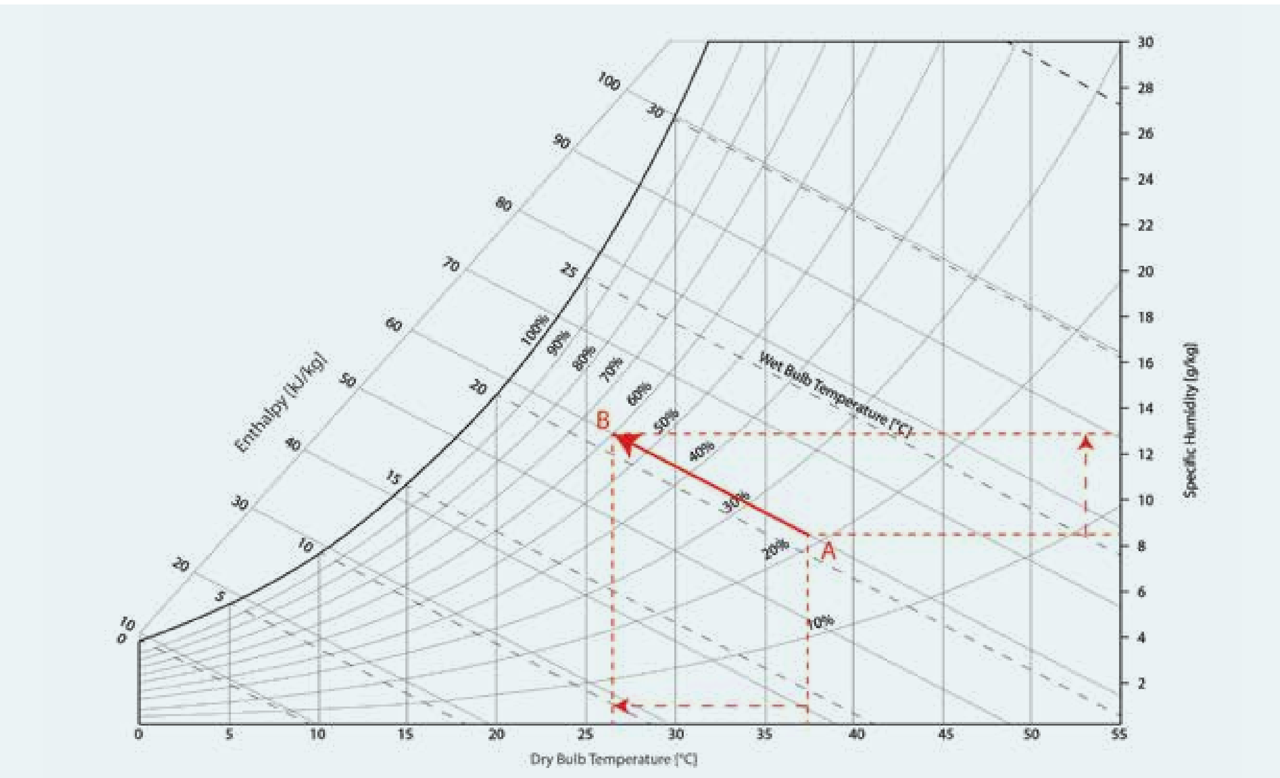


FIGURE A.1-21 **ADIABATIC HUMIDIFICATION**



3. ENERGY BALANCE OF THE BUILDING

In the second half of the nineteenth century it was still thought that heat was a fluid called caloric, and a warm body was seen as a tank full of this fluid. The analogy with the most common fluid, water, was complete. In fact, just as water flows from one reservoir to another if there is a difference in altitude, heat flows from one body to another if there is a temperature difference. It turned out, later, that the analogy holds up to a certain point, and the concept of caloric fluid was abandoned. The water analogy, however, is useful as it helps us to understand the energy balance of a building.

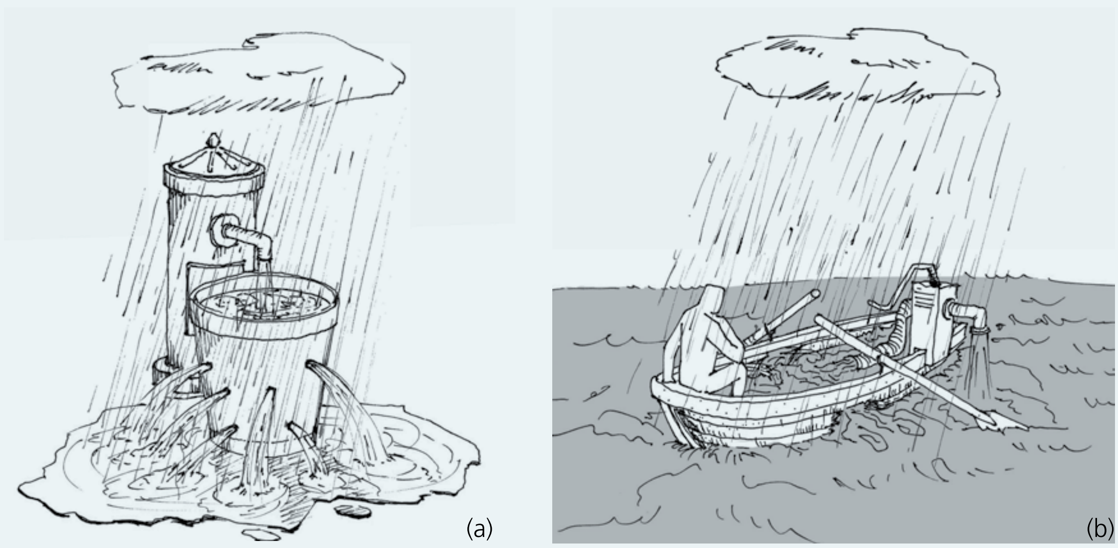
If we imagine a bucket with holes in the bottom and the sides (Fig. A.1-22a), we know that if we fill it with water and we want to maintain a certain level, we need to provide as much water as it loses. To maintain a certain temperature inside a building in a cool period, since there are heat losses (the holes in the bucket), we must provide as much heat as it loses, and this is done with the heating system, which provides the necessary heat to compensate for the losses (Fig. A.1-23a). The "holes" of a building, in winter, are the transmission heat losses through walls, windows, doors and roof, those due to air infiltration through doors and windows ,and those for ventilation to ensure clean air in the room. Actually, there are not only losses in the relationship between the building and the environment: there are also solar gains, as if – going on with the analogy - the bucket was placed outside, where the rain helps to fill it. To these gains, the internal gains (the heat produced by the occupants, lights, and equipment) must be added.

In summer things go in a similar, but opposite, way (Fig. A.1-22b), as in a boat with leaks in the hull. To keep the boat floating water must be pumped out. This corresponds to the building in the summer, when the heat penetrates and you have to pull it out with air conditioning (Fig. A.1-23b). The penetration takes place through walls, roof and windows and through infiltration and ventilation. In this case there are also solar gains, but they now do not help: on the contrary they tend to increase the temperature of the environment, in the same way that rain would fill the boat faster, raising the water level.

The analogy is also useful to help understand the need to change the cultural approach that has dominated the twentieth century. In this approach, instead of trying to plug the holes we have been trying to pour in more and more water or pump out more and more; i.e., instead of reducing losses in winter and heat gains in summer, we went in the direction of supplying and removing more and more energy. This is a path that has to be abandoned; the main road, consistent with sustainability, leads to the reduction or elimination of holes, i.e. heat losses in winter and gains in summer.

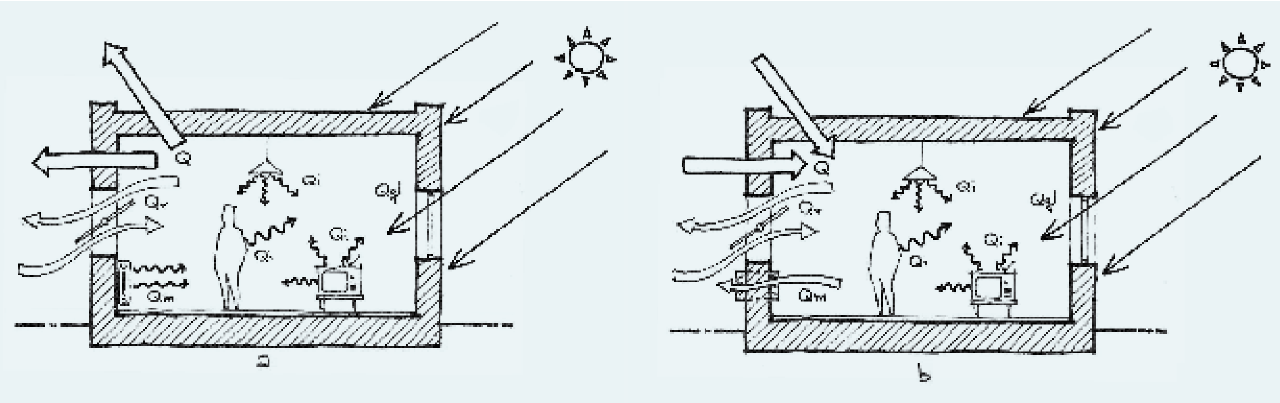
Of course, the analogy is useful, but greatly simplifies the problem that, to be addressed properly, must include a number of areas of knowledge, primarily thermodynamics and heat transfer.

FIGURE A.1-22 **WATER ANALOGY**



(a) (b)

FIGURE A.1-23 **ENERGY BALANCE THROUGH BUILDING ENVELOPE IN COOL (A) AND HOT (B) PERIOD**



3.1 BUILDING ENERGY BALANCE

The energy balance of a building (Fig. A.1-23) at time τ can be calculated as follows:

$$\Sigma\, Q_{(\tau)} + \Sigma\, Q_{gl\,(\tau)} + Q_{v\,(\tau)} + Q_{i\,(\tau)} + Q_{m(\tau)} = 0 \qquad \text{(A.1-31)}$$

where:
$\Sigma\, Q_{(\tau)}$ is the sum of the heat flows through the roof, each wall and the floor [W]; $Q_{(\tau)}$ is calculated with eqn. (A.1-26);
$\Sigma\, Q_{gl\,(\tau)}$ is the sum of the heat gains through each window [W]; Q_{gl} is calculated with eqn. (A.1-29);
$Q_{v\,(\tau)} = 1200 \cdot V \cdot (t_o - t_i)$ is the ventilation heat flow [W];
V is the ventilation rate [m^3/s], see Table A.1-8;
$Q_{i\,(\tau)}$ are the internal heat gains, due to people, domestic appliances and equipment [W], see Table A.1-9;
$Q_{m(\tau)}$ is the sensible heat demand compensated by the heating or cooling system [W].

To evaluate the building's monthly sensible heat demand Q_{mm} the same eqn. (A.1-12) can be used in the form:

$$Q_{mm} = \Sigma\, Q_m + \Sigma\, Q_{glm} + Q_{vm} + Q_{im} \qquad \text{(A.1-32)}$$

where:
Q_m = monthly heat flow through the opaque surfaces calculated using the monthly-mean daily temperature (air and sol-air) instead of the temperatures at time τ and the result multiplied by the number of hours of the month [MJ or kWh];
Q_{glm} = monthly solar gain through windows calculated using the monthly-mean daily solar irradiance incident on the glass and multiplying the result by the number of days of the month [MJ or kWh];
Q_{vm} = monthly ventilation heat flow calculated using the monthly-mean daily air temperature instead of the temperature at time τ and the result multiplied by the number of hours of the month [MJ or kWh];
Q_{im} = monthly internal loads calculated multiplying the monthly-mean daily internal loads by the number of days of the month [MJ or kWh].

If the space is air-conditioned, the psychometric chart can be used to evaluate the total (sensible + latent) heat demand due to ventilation, to be added to the latent heat deriving from the presence of people in the air-conditioned space.

4. PRIMARY ENERGY

The energy balance of the building envelope regards the thermal energy flows required to maintain the desired conditions of temperature and humidity in rooms. The architectural choices are crucial for the part of the balance that covers the sensible heat. The balance of the latent heat, in fact, depends only on internal sources (people, plants and kitchen) and on outdoor air conditions, thus the envelope characteristics have no influence on it.

The objective of energy-conscious design must be to ensure the best comfort conditions in the building, with a minimum of thermal energy to be supplied in cold climates/periods, and to be subtracted in hot climates/periods.

What counts, however, for the purposes of energy sustainability of a building is what is called "primary energy".

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be non-renewable or renewable. Primary energy sources are transformed in energy conversion processes to more convenient forms of energy (that can be directly used by society), such as electrical energy, refined fuels, etc.

The energy we use in a building is the so-called final energy: the energy available after the conversion processes.

The amount of primary energy consumed, thus, depends on the conversion processes[110].

Of course, the lower the thermal energy demand of the envelope, the lower the primary energy needed, but equally important is the technological system used to supply it. In the case of a boiler, for example, losses due to its performance must be taken into account. That is why using the heat pump to produce heat is much more convenient than using a boiler, in terms of primary energy consumption. But there is more. In fact, for distributing the hot or cold fluid in an air conditioning system, pumps and fans are required; they consume electricity and, as we have seen, the production of electricity requires a lot of primary energy. As pumps and fans (so-called auxiliary components of an air conditioning system) require more or less energy also in relation to the layout of the distribution system, which depends on the functions attributed to the different zones, and since this distribution of functions is an integral part of the architectural design, the architect indirectly affects energy consumption in this way also.

4.1 EMBODIED ENERGY OF BUILDING MATERIALS

The embodied energy or the energy content of a building material comprises all the energy consumed in acquiring and transforming the raw materials into finished products, and transporting them to the place of installation or the building site.

The material life cycle puts into sequence the various stages of a material and identifies where energy is consumed at each stage, from acquisition of raw materials, production, and installation, to use and operation, to disposal and ultimate reuse (Fig. A.1-24 and Table A.1-10).

This energy consumption is attributed, in official statistics, to the industrial sector but more properly should be included in the construction sector, which is the cause. In the case of a building, to this energy should be added the energy needed for the transportation of materials, for the construction and for the demolition.

It should be noted that the values shown in figure A.1-24 and Table A.1-10 are indicative: the energy content of a material depends on the process of extraction and transportation. For a component, we also need to add the diversity of manufacturing processes.

Another aspect is recycling. Aluminium, for example, which has the highest value of embodied energy, is recyclable (as is steel), and its energy content, in cases where it is recycled to 100% is reduced to slightly more than 10 % of the "virgin" aluminium. This is still a high value compared to other materials (slightly less than the embodied energy of "virgin" steel); aluminium is not a low energy material. Indeed, no aluminium component is made of 100% recycled material; in Italy, for example, only 45% of aluminium is recycled. Recycling depends on two factors: the first is the effectiveness of the collection system, and the second derives from the rate of economic growth, which is linked to the growth of aluminium consumption. For example, in countries such as China, India, Brazil and other countries whose economy is fast growing, the improvement of financial resources allows large numbers of people to have access to goods that were not there before. In this case, the recycling rate is almost insignificant compared to the amount of virgin material needed and the use of aluminium should be limited to cases where it is really impossible to replace it with another material. Glass can also be recycled, but the presence of layers of metal oxides used to improve its performance results in soil contamination; for the same reason, even when they are recycled and go to landfill, glass panes must be treated with great care to avoid contamination of the subsoil.

Wood, from the environmental point of view, appears to be the best building material and not only because it has a low energy content which derives only from cutting, transportation and processing, but also because its use results in a subtraction of CO_2 to the atmosphere, the energy absorbed during the growth of the tree and captured in the log. In fact, other factors should also be taken into account, such as the deforestation induced if the cycle cutting/growth is not followed correctly and the environmental impact of substances that are used for its treatment and processing.

Finally, we must consider the thermo-physical properties of wood: it provides fair thermal insulation, but it has a rather low thermal inertia. This makes it little recommended for climates with hot climates/periods and a large day-night temperature swing. In these climates the achievable thermal comfort is much lower than when using heavier materials, and this leads to an increase in consumption for air conditioning. To mitigate this effect, it is necessary to use partition walls and/or floors entirely or partly made of heavier materials, thus increasing the thermal inertia of the building.

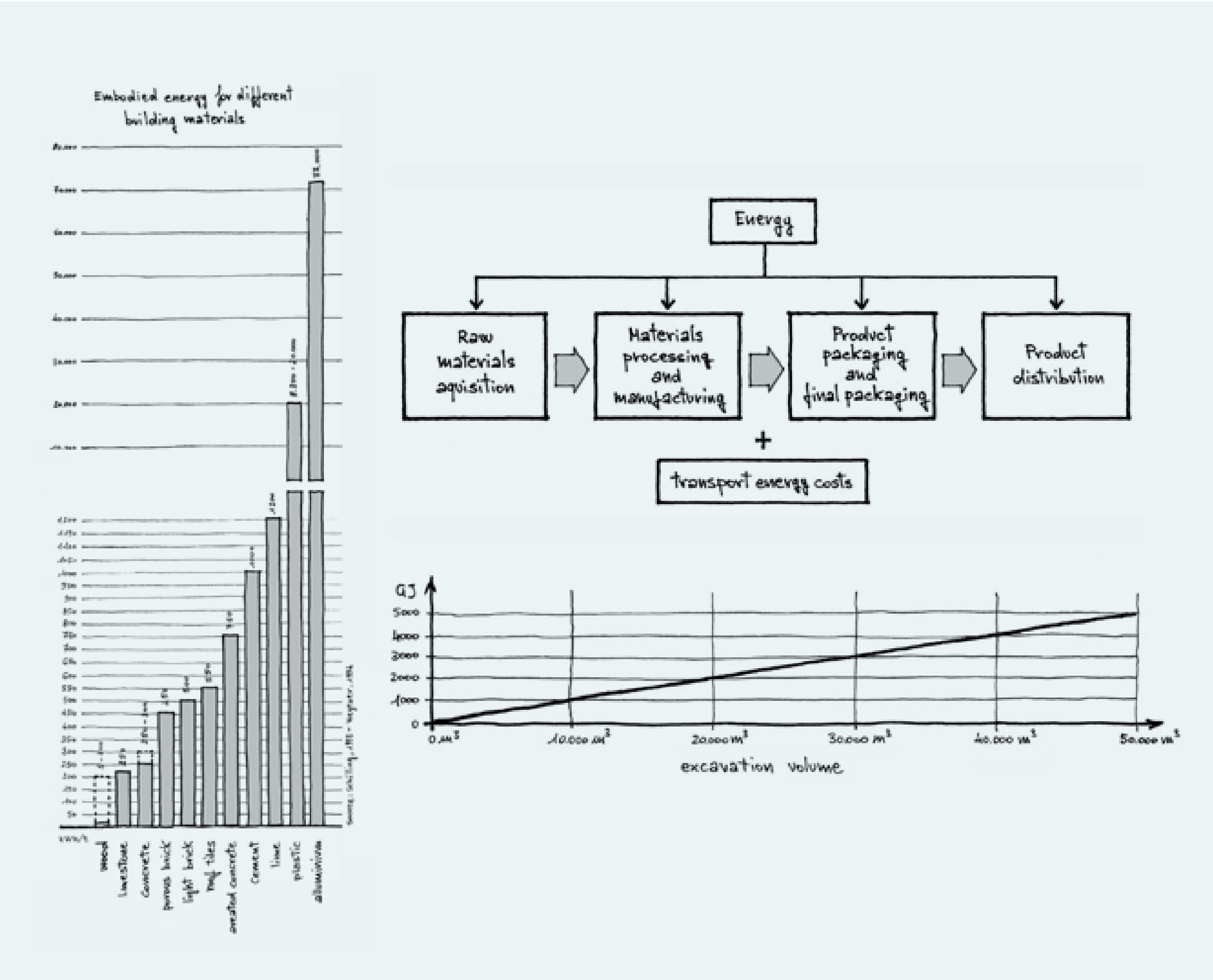
The energy consumption induced by a building constructed in Europe with techniques typical of the twentieth century, assuming a life cycle of 80 years, is derived 80% from its operation and 20% from the embodied energy of the construction materials, including maintenance and renovation (Fig. A.1-25).

110 For example, to make available 1 kWh of electricity at the plug about three kWh of primary energy must be used. If this electricity is used for heating water with a resistance water heater, about 3 kWh primary energy are needed to deliver 1 kWh to water. If, instead, a gas boiler is used, with 80% conversion efficiency, to deliver 1 kWh of energy to water about 1.25 kWh of primary energy are needed. If electricity is used to feed a heat pump water heater, whose efficiency (COP) is about 300%, to deliver 1 kWh energy to water about 1 kWh of primary energy is needed.

The energy consumption of new buildings and of those significantly renovated is much less when regulations on the energy performance of buildings are implemented. In these conditions, the share of the embodied energy increases because of the decrease in consumption for operation, until it ends up at 100% of the energy needed for the new construction in the case of Zero Energy Buildings.

The choice of materials and components therefore becomes increasingly important in energy-conscious design, and this has a great impact on the architectural choices related to the envelope, in particular due to the high embodied energy of glass that, per unit area, is much higher than that of an isolated masonry well (Fig. A.1-26).

FIGURE A.1-24 **EMBODIED ENERGY OF SOME CONSTRUCTION MATERIALS* AND ENERGY EXPENDITURE ON EXCAVATION AND FILLINGS****



** T. Herzog (ed.), Solar Energy in Architecture and Urban Planning, Munich, Prestel, 1996*

*** R. Sigg, U. Houzer, T. Rühle, S. Tanner, J. Schurke, Sustainable Building Design Guidebook, Munchen, Siemens Real Estate, 2006*

FIGURE A.1-25 **ENERGY USED IN THE BUILDING'S LIFE CYCLE IN EUROPE (MEAN OF THE BUILDING STOCK)**

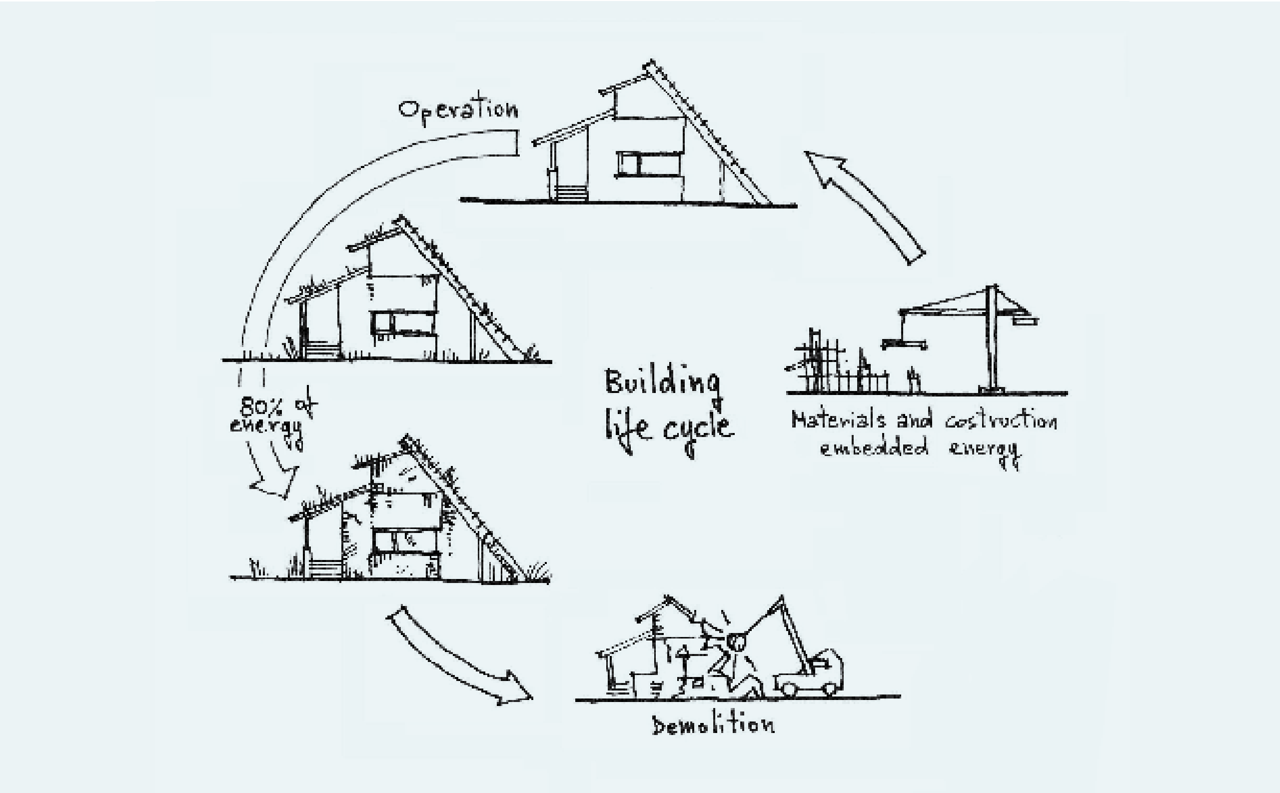


FIGURE A.1-26 **RELATIVE VALUES OF EMBODIED ENERGY IN SOME TYPES OF FACADE. FACADE WITH WOOD FRAME = 1 (RVT IS THE RATIO BETWEEN THE GLAZED SURFACE AND THE TOTAL OF THE FAÇADE) (ADAPTED FROM: IEA ECBCS ANNEX 44, EXPERT GUIDE - PART 2)**

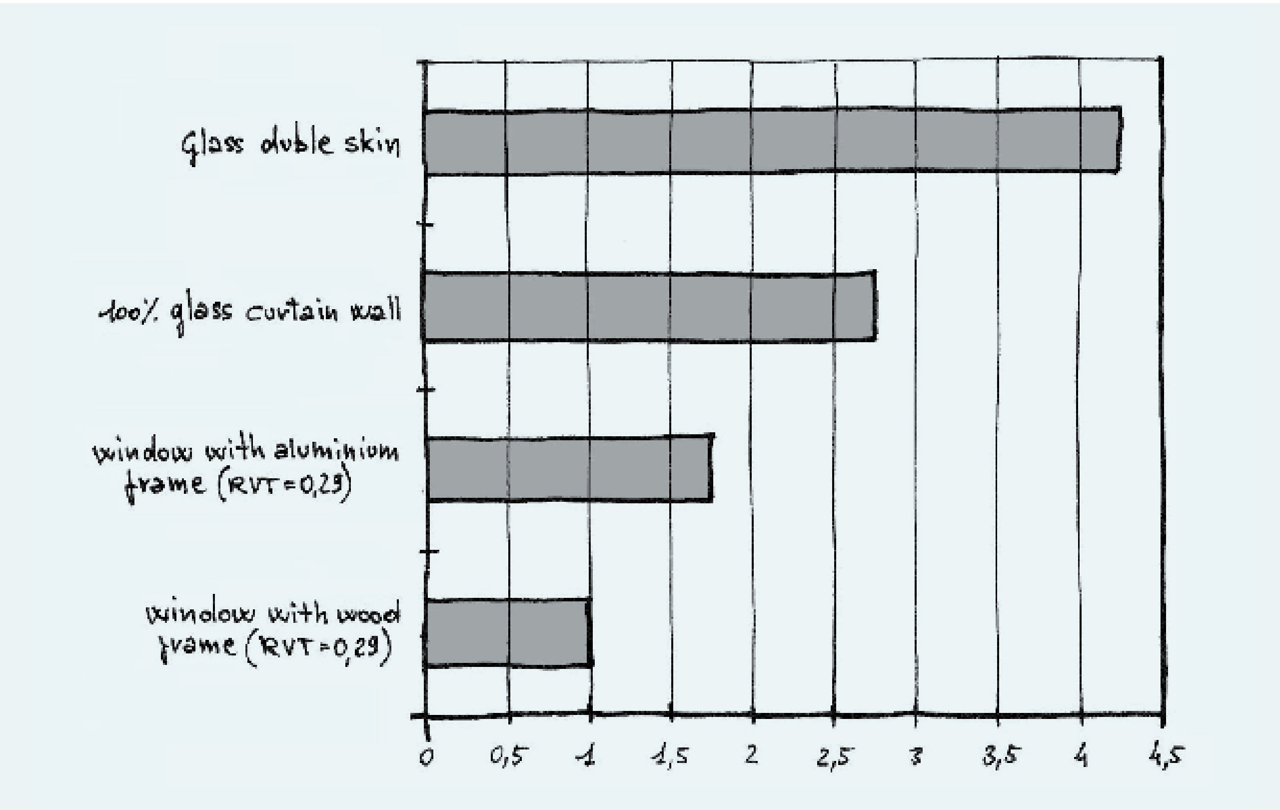


TABLE A.1-1 **THERMAL PROPERTIES OF BUILDING MATERIALS**

	Thermal conductivity [W/mK]	Density [kg/m³]	Specific heat capacity [J/kgK]
Masonry materials			
Adobe blocks	1.25	2050	1000
Autoclaved aerated concrete block	0.2	700	1000
Autoclaved aerated concrete block	0.15	500	1000
Brick, burnt	0.811	1820	880
Brick, fly ash	0.54-0.70	1570	800
Brick, mud	0.75	1731	880
Brick, sand-lime	1.08	1840	840
Brick, silica	0.89	2240	840
Brickwork, inner leaf	0.62	1700	800
Brickwork, outer leaf	0.84	1700	800
Cast concrete	1.4	2100	840
Cellular brick (Poroton 30cm)	0.23	860	840
Cinder concrete	0.68	1406	840
Concrete block , heavy	1.63	2300	1000
Concrete block medium	0.51	1400	1000
Concrete block, light	0.19	600	1000
Expanded clay block (PHONO 30cm)	0.262	1170	840
Expanded clay block 25cm	0.384	840	840
Fibreboard (softboard)	0.06	300	1000
Fibrous cement sheet	0.36	700	1050
Fibrous cement decking	0.58	1500	1050
Geobeton	0.7-0.8	1800-2310	960
Glass	1.1	2500	840
Hollow floor brick	0.7	600	840
Lightweight aggregate concrete block	0.2	600	1000
Lightweight concrete	0.38	1200	1000
Mud phuska	0.519	1622	880
No–fines concrete	1.33	2000	1000
Perforated brick	0.35	750	840
Plasterboard	0.16	950	840
Plywood	0.138	620	1300
Precast concrete (dense) (exposed)	1.56	2100	1000
Precast concrete (dense) (protected)	1.46	2100	1000
Reinforced concrete	1.5-2.04	1200-1700	840
Roller compacted concrete	1.58	2288	880
Sand (dry)	0.3	1500	800
Solid brick	0.78	1700	940
Tile hanging	0.84	1900	800
Timber (hardwood)	0.15	680	1200
Timber (softwood)	0.13	610	1420
Wood chipboard	0.108	660	1300
Stone			
Granite stone	2.3	2600	820
Limestone	1.05-2.2	1650-2580	920
Marble stone	2	2500	900
Sandstone	1.3	2000	800
Slate stone	1.53	2950	750
Terracotta	1.15	1800-2000	900
Slab materials			
Asbestos cement sheet	0.245	1520	840

Ballast (chips or paving slab)	1.1	1800	1000
Carpet/underlay	0.6	200	1300
Cement mortar	0.719	1646	920
Concrete screed	1.4	2000	1000
Galvanized iron sheet	61	7520	500
Reinforced concrete (pillar and beam)	1.8	2500	1000
Reinforced concrete (slab)	1.6	2300	1000
Screed	0.46	1200	1000
Surface materials			
Acquapanel	0.35	1250	837
Cement-lime plaster	0.87	2200	1050
External rendering	0.5	1300	1000
External rendering (lime, sand)	0.87	1600	940
Gauged plaster	0.54	1500	1000
Gypsum plaster	0.16-0.5	720-2100	960
Insulating plaster	0.09	720	840-1340
Plaster (dense)	0.5	1300	1000
Plaster (lightweight)	0.16	600	1000
Plasterboard	0.25	900	1000
Plasterboard (fire-resisting)	0.25	900	1000
Plasterboard (standard)	0.21	700	1000
Plastic tile	0.5	1050	1070
Insulation materials			
Blown fibre	0.04	12	1030
Coconut pith insulation board	0.06	520	1090
Cork	0.038	144	1800
EPS	0.036	35	1480
Expanded clay	0.13	400	950
Expanded perlite	0.052	110	1340
Expanded polystyrene (EPS)	0.035	25	1400
Expanded polyurethan	0.03	40	1670
Expanded vermiculite	0.07	100	1100
Extruded polystyrene	0.035	40	1400
Foam Glass	0.055	160	750
Glass fibre (batt)	0.035	25	1000
Glass fibre (quilt)	0.04	12	840
Glass fibre (strawboard-like)	0.085	300	2100
Granulated cork	0.05	70	1700
Hemp wool (Celenit LC/30)	0.04	30	1700
Mineral fibre (same, denser)	0.044	150	920
Mineral fibre (slab)	0.035	35	1000
Mineralized wood wool	0.065	400	2100
Phenolic foam	0.04	30	1400
Polyurethane foam	0.026	30	1570
Rock wool	0.052-0.074	120-220	800-840
Strawboard	0.037	250	1050
Strawboard and paper faced	0.081	320	1450
Sheep wool	0.038-0.049	135-136	1260
Wood wool slab	0.1	500	1000
Miscellaneous			
Chipboard	0.14	600	1700
Timber battens	0.13	500	1600
Timber decking	0.13	500	1600
Timber flooring	0.13	500	1600

Timber flooring (hardwood)	0.18	700	1600
Timber studding	0.13	500	1600
Roof coatings			
Asphalted cardboard	0.23	1100	1300
Waterproof roof covering	0.23	110	1000
Metals			
Aluminium	236	2700	877
Aluminium composite panels (Alucopan)	0.06	150	902
Copper	384	8900	380
Iron	78	7900	437
Lead	37	11300	126
Stainless, steel	24	7900	510
Steel, mild	47	7800	480
Zinc	112	7200	390
Loose fills			
Cellulose fibre (fireproofed)	0.039	42	\
Cellulose fibre (same, denser)	0.047	83	\
Gravel	1.5	1200	980
Perlite fill, loose	0.046	65	\
Vermiculite, exfoliated	0.069	128	\
Various			
Ceramic tile	1.3	2300	840
Acoustic tile	0.058	290	1340
Ash (dry)	0.29	900	750
Asphalt, bituminous, felt	0.5	1700	1000
Charcoal	0.041-0.065	185-215	\
Coir board	0.038	97	1000
Concrete slab, aerated	0.16	500	840
Concrete slab, dense	1.13	2000	1000
Cotton	0.06	80	1420
Feather	0.037	80	
Fibre reinforced plastic (FRO) sheet	0.26	1850	960
Floor joists	0.13	500	1600
Jute fibre	0.067	329	1090
Leather	0.174	1000	\
Linoleum	0.17	1200	1400
Metal deck	50	7800	480
Paper	0.14	\	\
Parquet floor	0.13	500	1600
Polycarbonate sheet	0.21	1350	1170
Polyvinyl chloride sheet	0.16	1350	1255
Risk husk	0.051	120	1000
Sand	1.74	2240	840
Sand/cement screed	0.41	1200	840
Saw dust	0.06-0.07	213	2510
Silk	0.052	100	\
Soil (pressed)	1.15	1800	900
Stainless steel	17	7900	460
Stone chippings	0.96	1800	1000
Thatch (reed)	0.09	270	1000
Thatch (straw)	0.07	240	1420
Tiles	0.84	1900	800
Timber boarding	0.14	640	1200
Vinyl floor covering	0.17	1390	900

Wood (fir)	0.12	450	2700
Wood blocks	0.14	600	1700

TABLE A.1-2 **U-VALUE, TIME-LAG AND DECREMENT FACTOR OF SOME BUILDING COMPONENTS**

	U-value [W/m²K]	Time-lag [hours]	Decrement
Brick			
Single skin, 105 mm	3.28	2.6	0.87
Single skin, 220 mm	2.26	6.1	0.54
Single skin, 335 mm	1.73	9.4	0.29
Single skin, 105 mm plastered	3.02	3	0.83
Single skin, 220 mm plastered	2.14	6.5	0.49
Single skin, 335 mm plastered	1.79	9.9	0.26
Cavity, 275 mm plastered	1.47	7.7	0.44
same, with 25 mm EPS in cavity	0.72	8.9	0.34
same, with 40 mm EPS in cavity	0.55	9.1	0.32
same, with 50 mm EPS in cavity	0.47	9.2	0.31
Brick 105, cavity, 100 low concrete block, Low plaster	0.92	7	0.55
same + 25 mm EPS	0.55	8	0.43
same but 50 mm EPS	0.4	9	0.41
Concrete block solid 200, plasterboard	1.83	6.8	0.35
same, but foil-backed plasterboard	1.4	7	0.32
same, but 25 cavity, 25 EPS, plasterboard	0.7	7.3	0.29
same, but lightweight concrete	0.69	7.4	0.46
same, but foil-backed plasterboard	0.61	7.7	0.42
same, but 25 cavity, 25 EPS, plasterboard	0.46	8.3	0.34
Concrete block, hollow, 200 mm, ins. plasterboard	2.42	3	0.83
Concrete, dense, cast, 150 mm	3.48	4	0.7
same + 50 mm woodwool slab, plastered	1.23	6	0.5
same, but lightweight plaster	1.15	6.3	0.49
Concrete, dense, cast, 200 mm	3.1	5.4	0.56
same + 50 mm woodwool slab, plastered	1.18	7.7	0.36
same, but lightweight plaster	1.11	7.6	0.35
Concrete, precast panel, 75 mm	4.28	1.9	0.91
same + 25 cavity + 25 EPS + plasterboard	0.84	3	0.82
Concrete, precast, 75 + 25 EPS + 150 Low concrete	0.58	8.7	0.41
same, but 50 mm EPS	0.41	9.2	0.35
Brick/block veneers			
Brick 105 + cavity (frame) + plasterboard	1.77	3.5	0.77
same, but foil-backed plasterboard	1.35	3.7	0.75
same with 25 mm EPS or glass fibre	0.78	4.1	0.71
same with 50 mm EPS or glass fibre	0.5	4.3	0.69
same, 25 EPS + foil-backed plasterboard	0.69	4.1	0.71
Block 100 + cavity (frame) + plasterboard	1.57	4.1	0.72
same, but foil-backed plasterboard	1.24	4.3	0.69
same with 25 mm EPS or glass fibre	0.74	4.7	0.65
same with 50 mm EPS or glass fibre	0.48	4.9	0.62
same, 25 EPS + foil-backed plasterboard	0.66	4.7	0.64
Framed, single fibrous cement or galvanised steel	5.16	0	1
same + cavity + plasterboard	2.2	0.3	1
same with 25 mm EPS or glass fibre	0.86	0.5	0.99
same with 50 mm EPS or glass fibre	0.53	0.7	0.99

Framed, 20 mm timber boarding	3	0.4	1
same + cavity + plasterboard	1.68	0.8	0.99
same with 25 mm EPS or glass fibre	0.76	1	0.99
same with 50 mm EPS or glass fibre	0.49	1.2	0.98
Framed, tile-hanging + paper + cavity + 50 EPS + plasterboard	0.54	1	0.99
same, but 100 EPS or glass fibre	0.32	1	0.99
Reverse brick veneer: 5 mm fibrous cement + cavity + 105 brick	1.89	3.7	0.97
same + 25 mm EPS in cavity	0.7	4.5	0.68
same but 50 mm EPS	0.47	4.8	0.61
same but only aluminium foil in cavity	1.14	3.9	0.99
same but both foil and 25 mm EPS	0.63	4.5	0.7
Reverse block veneer: 5 fibrous cement + cavity + 100 hollow block	1.41	2.2	1
same but 100 mm solid concrete block	1.63	4.4	0.79
same but 50 EPS in cavity + 100 hollow block	0.47	3.2	0.85
same but 50 EPS in cavity + 100 solid block	0.49	5.2	0.46
same but 50 EPS in cavity + 200 solid block	0.48	7.7	0.21
Floors			
Suspended timber, bare or lino			
3 x 3m	1.05	0.7	0.99
7.5 x 7.5 m	0.68	0.8	0.98
15 x 7.5m	0.61	0.8	0.98
15 x 15 m	0.45	0.9	0.97
30 x 15 m	0.39	0.9	0.97
60 x 15 m	0.37	1	0.97
Concrete slab on ground, 2 edges exposed			
3 x 3m	1.07	\	0.01
6 x 6 m	0.57	\	0
7.5 x 7.5 m	0.45	\	0
15 x 7.5 m	0.36	\	0
15 x 15 m	0.26	\	0
30 x 15 m	0.21	\	0
60 x 15 m	0.18	\	0
100 x 40 m	0.09	\	0
Concrete slab on ground, 4 edges exposed			
3 x 3m	1.47	\	0.02
6 x 6 m	0.96	\	0.01
7.5 x 7.5 m	0.76	\	0.01
15 x 7.5 m	0.62	\	0
15 x 15 m	0.45	\	0
30 x 15 m	0.36	\	0
60 x 15 m	0.32	\	0
100 x 40 m	0.16	\	0
Windows			
Wood frame, single 6 mm glass	5	0	1
Wood frame, double glazing	2.9	0	1
Metal frame, single 6mm glass	6	0	1
same, but discontinuous frame	5.7	0	1
Metal frame, double glazing	3.6	0	1
same, but discontinuous frame	3.3	0	1
Vinyl frame, double (clear + clear) glazing	2.8	0	1
same, but bronze + clear glass	2.8	0	1
same, but argon filled clear + clear glazing	1.9	0	1
same, but argon filled low-e clear + clear	1.7	0	1

Insulated vinyl frame, krypton fill, triple clear glass	1.9	0	1
Insulated vinyl frame, krypton fill, triple (2 low-e) glass	0.8	0	1
Roof glazing single 6 mm glass	6.6	0	1
Roof glazing double glazing	4.6	0	1
Horizontal daylight + skylight, ventilated	3.8	0	1
same but unventilated	3	0	1
Flat roofs			
150 concr. slab, plastered, 75 screed + asphalt	1.8	8	0.33
same, but lightweight concrete	0.84	5	0.77
25 timber deck, bit. felt, plasterboard ceiling	1.81	0.9	0.99
same + 50mm EPS	0.51	1.3	0.98
10 fibrous cement deck, 13 fibreboard, asphalt, fibrous cement ceiling	1.5	2	0.96
50 ww, 13 screed, 20 asph, plasterboard ceiling	1	3	0.93
13 fibreboard, 20 asph, 10 foil-back plasterboard	1.2	1	0.99
Metal deck, 25 EPS, bitumenous felt	1.1	1	0.99
same + 13 fibreboard + plasterboard ceiling	0.73	1	0.99
same, but 50 mm EPS	0.48	1	0.98
Pitched roofs			
Corrugated fibrous cement sheet	4.9	0	1
same + attic + plasterboard ceiling	2.58	0.3	1
same + 50 mm EPS or glass fibre	0.55	0.7	0.99
Tiles, sarking + attic + plasterboard ceiling	2.59	0.5	1
same + 50 mm EPS or glass fibre	0.54	1.5	0.97
Tiles, sarking, 25 timber ceiling (sloping)	1.91	1	0.99
same + 50 mm EPS or glass fibre	0.51	1.4	0.97
Metal sheet (corrugated or profiled)	7.14	0	1

TABLE A.1-3 **EMITTANCE, ABSORPTANCE AND REFLECTANCE AT DIFFERENT WAVELENGTH FOR SOME MATERIALS USED IN BUILDINGS**

	Absorptance/Emittance (solar)	Reflectance	Absorptance/Emittance (far infrared)
Brick			
white, glazed	0.25	0.75	0.95
light colours	0.4	0.6	0.9
dark colours	0.8	0.2	0.9
Roofs			
asphalt or bitumen	0.9	0.1	0.96
red tiles	0.65	0.35	0.85
white tiles	0.4	0.6	0.5
aluminium, oxidised	0.3	0.8	0.11
bright aluminium, chrome, nickel	0.1	0.9	0.03
bright (new) aluminium foil	0.05	\	\
fiber cement (new)	0.35-0.50	\	\
fiber cement	0.60-0.85	\	\
Weathered building surfaces			
light	0.5	0.5	0.6
medium	0.8	0.2	0.95
Paint			
white	0.3	0.7	0.92
matt black	0.96	0.04	0.96
aluminium paint	0.4-0.5	\	\

TABLE A.1-4 **SURFACE HEAT TRANSFER COEFFICIENT W/M²K**

	Normal Surface	Low emittance surface
Inside		
walls	8.3	3.3
ceiling, floor		
heat flow up	10.0	4.5
heat flow down	7.1	1.8
45° ceiling		
heat flow up	9.1	4.2
heat flow down	7.7	2.6
Outside		
walls		
sheltered	16.7	9.1
normal exposure	16.7	14.3
severe exposure	33.3	33.3
roofs		
sheltered	14.3	11.1
normal exposure	25.0	20.0
severe exposure	50.0	50.0
Moving air (12 km/h) for any position	22.7	
Moving air (24 km/h) for any position	34.5	

TABLE A.1-5 **CONDUCTANCE OF A CAVITY OR AIR SPACE [W/M² K]**

	Normal Surface	Low emittance surface
Unventilated		
5mm cavity, any position	10	5.5
>25 mm cavity		
heat flow horizontal	5.5	2.8
heat flow up	5.8	2.8
heat flew down	4.5	0.9
45°, heat flow up	5.3	2.5
45°, heat flow down	5.0	1.0
Multiple foil		
heat flow horizontal or up	\	1.6
heat flow down	\	0.6
Ventilated		
Between fibrous cement sheet ceiling & dark metal roof	6.25	3.3
Between fibrous cement sheet ceiling & fribrous cement roof	7.14	4.0
Between fibrous cement sheet ceiling & tiled roof	5.56	3.6
Between tiles and sarking	8.33	\
Air space behind tile hanging (incl. the tile)	8.33	\
In ordinary cavity walls	5.56	\

TABLE A.1-6 **EXAMPLE OF A MANUFACTURER'S DATA SHEET (PILKINGTON)**

			Visible Light			**Solar energy**						
		Glass thickness [mm]	Transmit-tance [%]	Reflectance (outside) [%]	Reflectance (inside) [%]	Transmit-tance [%]	Reflec-tance [%]	UV Trans-mittance	U-Value air	U-Value argon	SHGC	SC
Single glass	Clear	2.5	90	8	8	86	8	75	5.9	\	0.87	1
		3	90	8	8	84	8	72	5.8	\	0.86	0.99
		4	89	8	8	81	7	68	5.8	\	0.84	0.97
		6	88	8	8	77	7	63	5.7	\	0.82	0.94
		10	86	8	8	70	7	54	5.6	\	0.77	0.88
		12	84	8	8	64	6	49	5.5	\	0.73	0.84
	Grey	3.2	61	6	6	59	6	35	5.8	\	0.69	0.8
		5	50	6	6	48	5	26	5.8	\	0.62	0.71
		6	44	5	5	41	5	21	5.7	\	0.57	0.66
		10	28	5	5	26	5	11	5.6	\	0.47	0.55
		12	19	4	4	17	4	7	5.5	\	0.42	0.49
	Bronze	3.2	68	6	6	65	6	37	5.8	\	0.73	0.84
		5	59	6	6	55	6	28	5.8	\	0.67	0.77
		6	51	6	6	48	5	22	5.7	\	0.62	0.72
		10	39	5	5	34	5	13	5.6	\	0.53	0.61
		12	29	5	5	25	4	8	5.5	\	0.47	0.55
	Blue-Green	6	75	7	7	48	6	32	5.7	\	0.62	0.72
		8	70	7	7	40	5	25	5.7	\	0.57	0.66
		10	67	6	6	36	5	21	5.6	\	0.54	0.63
	Low iron	3	91	8	8	90	8	87	5.8	\	0.91	1.04
		6	91	8	8	89	8	84	5.7	\	0.9	1.03
		10	90	8	8	86	8	81	5.6	\	0.89	1.02
		12	90	8	8	86	8	79	5.5	\	0.88	1.01

Insulating units constructed of equal glass thicknesses and 12.7mm airspace

			Visible Light			Solar energy						
		Glass thickness [mm]	Transmit-tance [%]	Reflectance (outside) [%]	Reflectance (inside) [%]	Transmit-tance [%]	Reflec-tance [%]	UV Transmit-tance	U-Value (air)	U-Value (argon)	SHGC	SC
Double glass: uncoated float glass outer and clear float glass inner	Clear	2.5	82	15	15	74	14	61	2.8	\	0.78	0.9
		3	81	15	15	71	13	57	2.8	\	0.76	0.88
		6	78	15	15	61	12	47	2.8	\	0.7	0.81
	Grey	3.2	55	9	13	50	9	29	2.8	\	0.58	0.67
		6	39	7	12	32	6	17	2.8	\	0.45	0.52
	Bronze	3.2	62	10	13	55	9	31	2.8	\	0.63	0.72
		6	45	8	12	38	7	18	2.8	\	0.5	0.58
	Blue-green	6	67	12	14	39	8	26	2.8	\	0.5	0.58
Double glass: Low-E glass outer and clear float glass inner	Clear	6	60	29	31	46	21	24	1.9	1.7	0.55	0.63
	Grey	6	29	10	29	23	9	8	1.9	1.7	0.33	0.39
	Bronze	6	34	13	29	28	11	9	1.9	1.7	0.38	0.44
	Blue-green	6	51	21	29	29	12	13	1.9	1.7	0.38	0.44

Double glass: uncoated float glass outer and Low-E glass inner	Clear	2.5	76	18	17	62	17	48	1.9	1.6	0.73	0.84
		3	75	18	17	59	16	45	1.9	1.6	0.71	0.82
		6	73	17	16	52	14	37	1.8	1.5	0.67	0.77
		10	69	16	15	43	12	29	1.8	1.5	0.6	0.7
	Grey	3.2	50	10	15	41	11	24	1.9	1.6	0.53	0.61
		6	36	7	14	27	7	13	1.8	1.6	0.4	0.46
	Bronze	3.2	57	12	15	45	12	25	1.9	1.6	0.57	0.66
		6	42	8	14	32	8	14	1.8	1.5	0.45	0.52
	Blue-green	6	62	13	15	34	9	21	1.8	1.6	0.45	0.52
Double glass: Low-E glass outer and Low-E glass inner	Clear	6	56	30	30	41	22	19	1.7	1.4	0.53	0.61
	Grey	6	27	11	29	20	9	7	1.7	1.4	0.31	0.36
	Bronze	6	32	13	29	24	11	7	1.7	1.4	0.36	0.41
	Blue-green	6	48	22	29	26	13	10	1.7	1.4	0.36	0.41

TABLE A.1-7 **TYPICAL VALUES OF SHGC AND SC**

	SC	SHGC
Single glazing		
clear glass, 1/8 in (3 mm) thick	1.0	0.86
Clear glass, 1/4 in (6 mm) thick	0.94	0.81
Heat absorbing or tinted	0.6-0.8	0.5-0.7
Reflective	0.2-0,5	0.2-0.4
Double glazing		
Clear	0.84	0.73
Bronze	0.5-0.7	0.4-0.6
Low-e clear	0.6-0.8	0.5-0.7
Spectrally selective	0.4-0.5	0.3-0.4
Triple-clear	0.7-0.8	0.6-0.7
Glass block	0.1-0.7	\
Interior shading		
Venetian blinds	0.4-0.7	\
Roller shades	0.2-0.6	\
Curtains	0.4-0.8	\
External shading		
Egg-crate	0.1-0.3	\
Horizontal overhang	0.1-0.6	\
Vertical fins	0.1-0.6	\
Trees	0.2-0.6	\

Single glass 4 mm

	Colour	[g/m²]	SHGC
External roller blinds	White	460	0.24
	Dark grey	460	0.25
	White	535	0.19
	Dark grey	535	0.21

Internal roller blinds	White	460	0.37
	Dark grey	460	0.63
	White	535	0.34
	Dark grey	535	0.63

Double glass 4,22,4 (g 0.75, U 2.9)

	Colour	[g/m²]	SHGC
External roller blinds	White	460	0.21
	Dark grey	460	0.20
	White	535	0.17
	Dark grey	535	0.17
Internal roller blinds	White	460	0.38
	Dark grey	460	0.61
	White	535	0.36
	Dark grey	535	0.62

TABLE A.1-8 **VENTILATION RATE**

Type of building or space	Category	Floor area	q_P	q_B	q_{tot}	q_B	q_{tot}	q_B	q_{tot}	Add when smoking
		[m²/person]	[l/s,m²]		[l/s,m²]		[l/s,m²]		[l/s,m²]	[l/s,m²]
			For occupancy	for very low-polluted building		for low-polluted building		for non low-polluted building		
Single office	I	10	1	0.5	1.5	1	2	2	3	0.7
	II	10	0.7	0.3	1	0.7	1.4	2.1	0.5	0.5
	III	10	0.4	0.2	0.6	0.4	0.8	0.8	1.2	0.3
Landscape office	I	15	0.7	0.5	1.2	1	1.7	2	2.7	0.7
	II	15	0.5	0.3	0.8	0.7	1.2	1.4	1.9	0.5
	III	15	0.3	0.2	0.5	0.4	0.7	0,8	1.1	0.3
Conference room	I	2	5	0.5	5.5	1	6	2	7	5
	II	2	3.5	0.3	3.8	0.7	4.2	1.4	4.9	3.6
	III	2	2	0.2	2.2	0.4	2.4	0.8	2.8	2
Auditorium	I	0.75	15	0.5	15.5	1	16	2	17	\
	II	0.75	10.5	0.3	10.8	0.7	11.2	1.4	11.9	\
	III	0.75	6	0.2	0.8	0.4	6.4	0.8	6.8	\
Restaurant	I	1.5	7	0.5	7.5	1	8	2	9	\
	II	1.5	4.9	0.3	5.2	0.7	5.6	1.4	6.3	5
	III	1.5	2.8	0.2	3	0.4	3.2	0.8	3.6	2.8
Class room	I	2	5	0.5	5.5	1	6	2	7	\
	II	2	3.5	0.3	3.8	0.7	4.2	1.4	4.9	\
	III	2	2	0.2	2.2	0.4	2.4	0.8	2.8	\
Kindergarten	I	2	6	0.5	6.5	1	7	2	8	\
	II	2	4.2	0.3	4.5	0.7	4.9	1.4	5.8	\

I – Expected dissatisfaction 15%

II – Expected dissatisfaction 20%

III – Expected dissatisfaction 30%

TABLE A.1-9 **INTERNAL HEAT GAINS**

		(at 20 °C)		(at 26 °C)	
	Total	**Sensible**	**Latent**	**Sensible**	**Latent**
Heat output of human bodies in Watt					
Seated at rest	115	90	25	65	50
Sedentary work	140	100	40	70	70
Seated. eating	150	85	65	70	80
Slow walking	160	110	50	75	85
Light bench type work	235	130	105	80	55
Medium work	265	140	125	90	175
Heavy work	440	190	250	105	335
Very heavy work (gymnasium)	585	205	380	175	420

Electric lighting load	**[W/m² lux]**
Incandescent	
open enamelled reflector	0.125-0.160
general diffusing	0.160-0.225
Fluorescent	
white, open trough	0.037
enclosed, diffusing	0.05
louvred. recessed	0.055
de luxe warm white, enclosed, diffusing	0.075-0.100
louvred. recessed	0.085-0.110
Mercury MBF, industrial reflector	0.050-0.075

Electrical appliances	**Sensible [W]**	**Latent [W]**
Hair dryer (blower)	700	100
Hair dryer (helmet type)	600	100
Coffee urn		
14L	800	500
23L	1000	700
Computer (PC)		
main unit	200-300	\
VDU (CRT). VGA	150-300	\
printer	30-300	\
Electric kitchen and washing machine (3000 W)	1450	1550
Fax	62	\
Food warmer per m² top surface	1000	1000
Frying pot (300x350 mm)	1100	1700
Grill, meat (250 x 300 cooking area)	1200	600
Grill. sandwich (300 x 300 cooking area)	800	200
Iron (500W)	230	270
Jug or Kettle	1800	500
Microwave oven	1300	\
Photocopier	750	\
Refrigerator		
1 door, manual	150-250	\
2 door, auto defrost	350-400	\
2 door, frost-free	500-600	\
Stereo (40W)	40	\
Sterilizer, bulk (600 x 600 x 900)	10000	6500
Sterilizer, water, 45 L	1200	4600

Sterilizer, water, 70 L	1600	7200
Sterilizer, instrument		
(150 x 100 x 450)	800	700
(250 x 300 x 900)	3000	2700
Toaster, pop-up (2 slices)	700	200
Toaster, continuous (2 slices)	1500	400
Toaster, continuous (4 slices)	1800	800
TV (1000W)	175	\
Vacuum cleaner	600-1200	
Waffles Iron	400	200
Water heater (domestic)	2400-3600	\

Gas appliances	Sensible [W]	Latent [W]
Coffee urn		
14 L	900	900
23 L	1200	1200
Food warmer per m^2 top surface	2700	1600
Frying pot 280 x 410 mm	2100	1400
Grill, top burner 0.13 m^2 surface	4400	1100
Toaster, continuous (2 slices)	2200	1000
Laboratory burners (bunsen) 10 mm dia. (natural gas)	500	100
Stove, short order, closed top per m^2 top surface	11000	11000
Same open top	13500	13500

TABLE A.1-10 **EMBODIED ENERGY IN MATERIALS**

	Embodied energy [MJ/kg]	[MJ/m^3]	[MJ/m^2]
Aggregate, general	0.1	150	\
virgin rock	0.04	63	\
river	0.02	36	\
Aluminium, virgin	191	515 700	\
extruded	201	542 700	\
extruded, anodised	227	612 900	\
extruded, factory painted	218	588 600	\
foil	204	550 800	\
sheet	199	537 300	\
Aluminium, recycled	8.1	21 870	\
extruded	17.3	46 710	\
extruded, anodised	42.9	115 830	\
extruded, factory painted	34.3	92 610	\
foil	20.1	54 270	\
sheet	14.8	39 960	\
Asphalt (paving)	3.4	7 140	\
Bitumen	44.1	45 420	\
Brass	62	519 560	\
Carpet	72.4	\	\
felt underlay	18.6	\	\
nylon	148	\	\
polyester	53.7	\	\
Polyethylene terephthalate (PET)	107	\	\
polypropylene	95.4	\	\
wool	106	\	\
Cement	7.8	15 210	\

cement mortar	2	3 200	\
fibre cement board	9.5	13 550	102/7.5mm
soil-cement	0.42	819	\
Ceramic			
brick	2.5	5 170	\
brick, glazed	7.2	14 760	\
pipe	6.3	\	\
tile	2.5	5 250	\
Concrete			
block	0.94	\	\
brick	0.97	\	\
GRC	7.6	14 820	\
paver	1.2	\	\
pre-cast	2 .0	\	\
ready mix, 17.5 MPa	1	2 350	\
ready mix, 30 MPa	1.3	3 180	\
ready mix, 40 MPa	1.6	3 890	\
roofing tile	0.81	\	\
Copper	70.6	631 160	\
Earth, raw			
adobe block, straw stabilised	0.47	750	\
adobe, bitumen stabilised	0.29	\	\
adobe, cement stabilised	0.42	\	\
rammed soil cement	0.8	\	\
pressed block	0.42	\	\
Fabric			
cotton	143	\	\
polyester	53.7	\	\
Glass			
float	15.9	40 060	240/6mm
toughened	26.2	66 020	396/6mm
laminated	16.3	41 080	246/6mm
tinted	14.9	375 450	\
Insulation			
cellulose	3.3	112	\
fibreglass	30.3	970	\
polyester	53.7	430	\
polystyrene	117	2 340	\
wool (recycled)	14.6	139	\
Lead	35.1	398 030	\
Linoleum	116	150 930	337
Paint	90.4	118/l	6.5
solvent based	98.1	128/l	6.1
water based	88.5	115/l	7.4
Paper	36.4	33 670	\
building	25.5	\	4.97
kraft	12.6	\	\
recycled	23.4	\	\
wall	36.4	\	\
Plaster, gypsum	4.5	6 460	\
Plaster board	6.1	5 890	33/9.5mm
Plastics			
ABS	111	\	\
high density polyethylene (HDPE)	103	97 340	\

low density polyethylene (LDPE)	103	91 800	\
polyester	53.7	7 710	\
polypropylene	64	57 600	\
polystyrene, expanded	117	2 340	\
polyurethane	74	44 400	\
PVC	70	93 620	\
Rubber			
natural latex	67.5	62 100	\
synthetic	110	\	\
Sand	0.1	232	\
Sealants and adhesives			
phenol formaldehyde	87	\	\
urea formaldehyde	78.2	\	\
Steel, recycled	10.1	37 210	\
reinforcing, sections	8.9	\	\
wire rod	12.5	\	\
Steel, virgin, general	32	251 200	\
galvanised	34.8	273 180	\
imported, structure	35	274 570	\
Stone, dimension			
local	0.79	1 890	\
imported	6.8	1 890	\
Straw, baled	0.24	30.5	15.2
Timber, softwood			
air dried, rough sawn	0.3	165	\
kiln dried, roughs awn	1.6	880	\
air dried, dressed	1.16	638	\
kiln dried, dressed	2.5	1 380	\
mouldings, etc.	3.1	1 710	\
hardboard	24.2	13 310	\
MDF	11.9	8 330	\
glulam	4.6	2 530	\
particle bd	8	\	\
plywood	10.4	\	\
shingles	9	\	\
Timber, hardwood			
air dried, rough sawn	0.5	388	\
kiln dried, rough sawn	2	1 550	\
Vinyl flooring	79.1	105 990	\
Zinc	51	364 140	\
galvanising, per kg steel	2.8	\	\

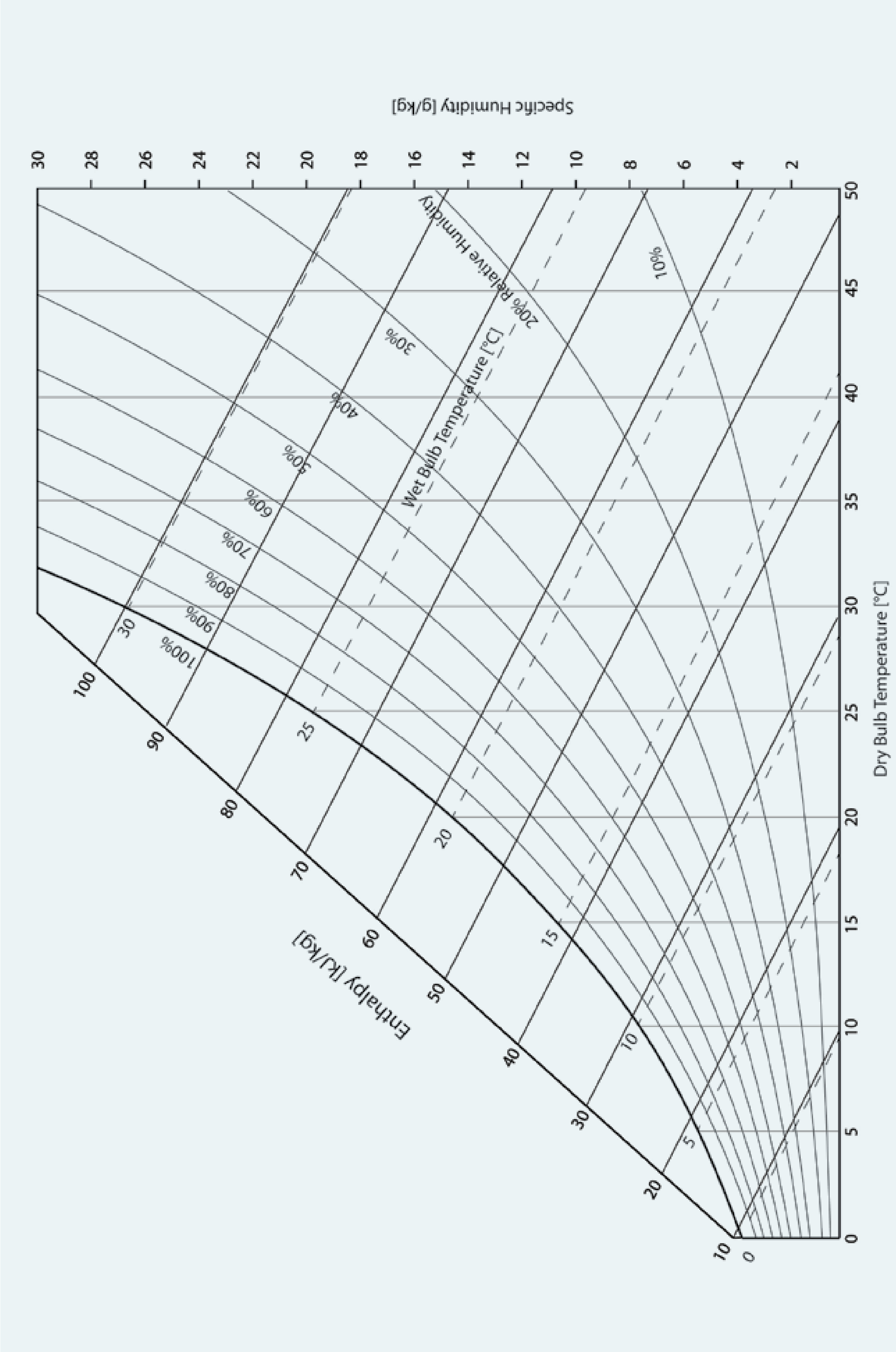


FIGURE A.1-27 **PSYCHROMETRIC CHART AT SEA LEVEL**

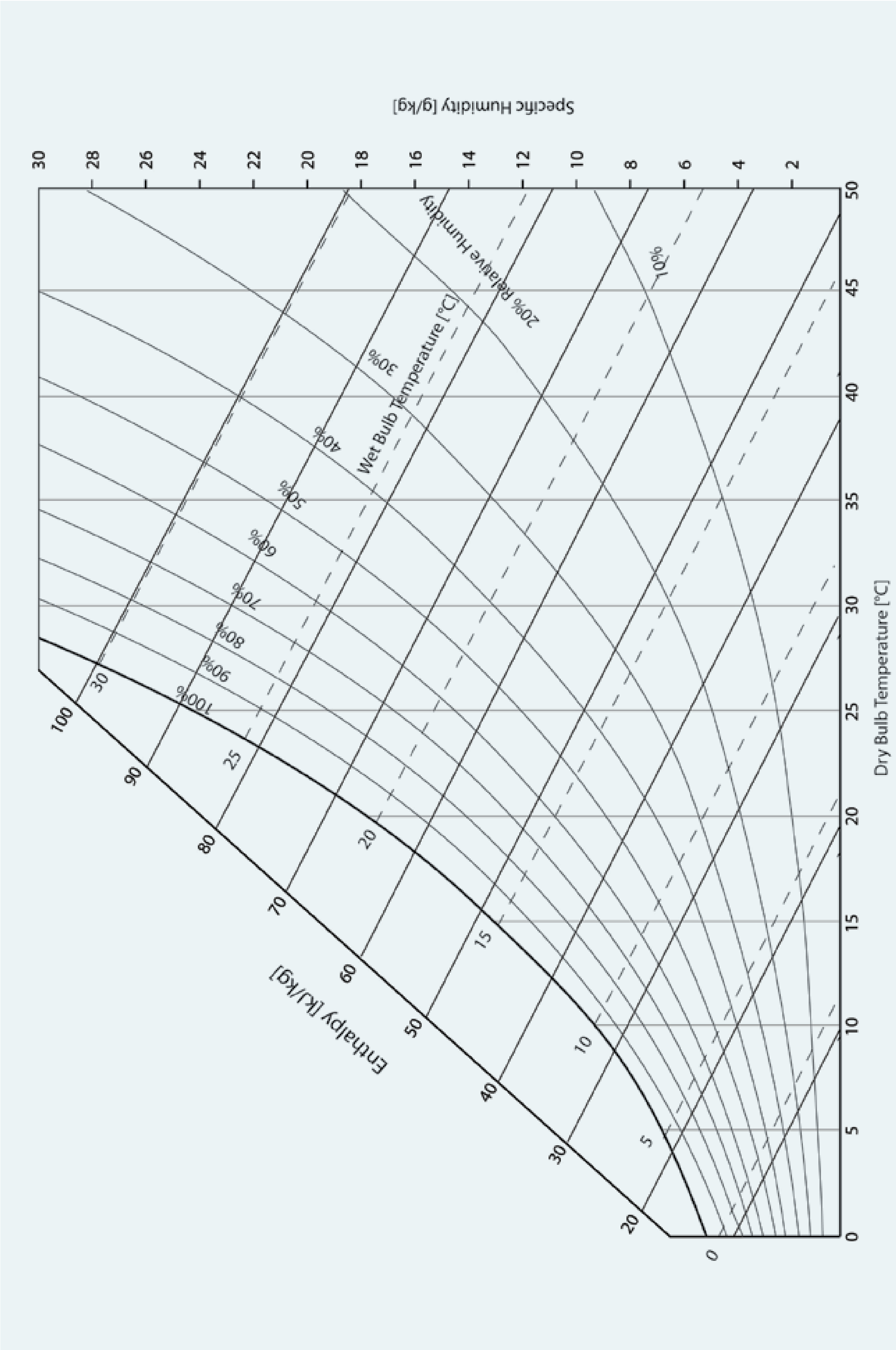


FIGURE A.1 -28 **PSYCHROMETRIC CHART AT 1500 M ALTITUDE ABOVE SEA LEVEL**

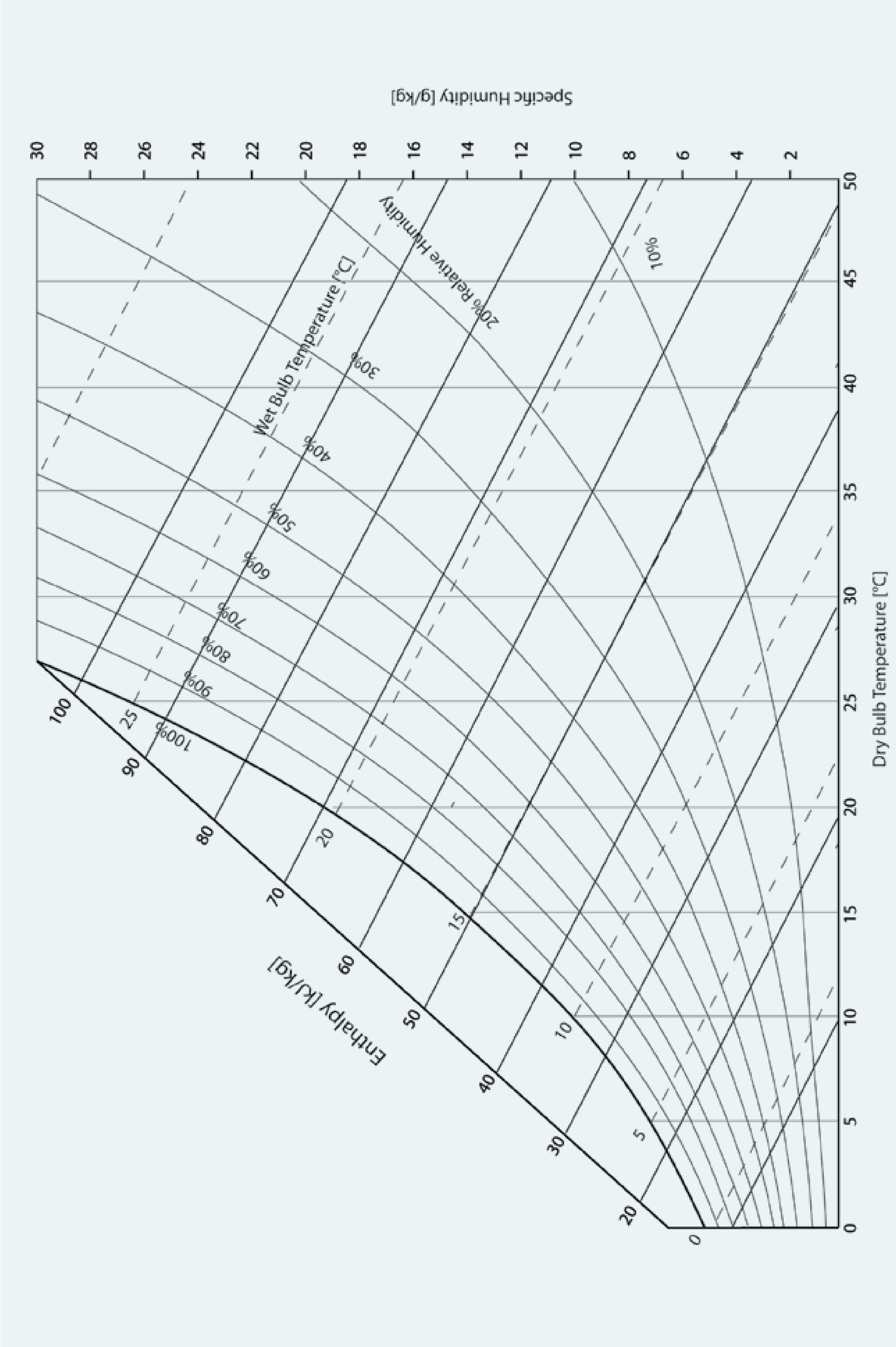


FIGURE A.1-29 **PSYCHROMETRIC CHART AT 2250 M ALTITUDE ABOVE SEA LEVEL**

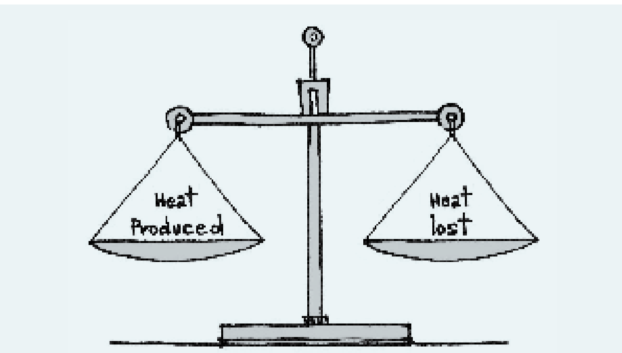
A2 PRINCIPLES OF THERMAL AND VISUAL COMFORT

1. PRINCIPLES OF THERMAL COMFORT

The perception of thermal comfort of a person in an environment is basically influenced by six parameters: physical activity, clothing, air temperature and humidity, relative air speed and temperatures of surfaces enclosing the space (walls, ceilings, floors, windows); also time spent in that environment and seasonal average temperature are influential.

The dependence on these parameters is derived from the primary need to keep the temperature of the innermost parts of the body in the range 36-38 °C; if this temperature is maintained for a long time outside the range, irreversible damages and finally death of the organism take place. In other words, thermal equilibrium between the heat produced because of our metabolism and our activity and the heat that is released into the environment must be satisfied (Fig. A.2-1).

FIGURE A.2-1 **THERMAL COMFORT CAN BE MAINTAINED WHEN HEAT PRODUCED BY METABOLISM EQUALS THE HEAT LOST FROM BODY**



The perception of lack of thermal comfort (i.e. feeling hot or cold) is a warning that our body sends us to tell us that thermal equilibrium is not satisfied, and for this reason is under stress. When we are cold it means that we are dissipating in the environment more heat than we are producing: our internal temperature tends to decrease. When we are hot it means that we are dissipating less heat than we are producing: our internal temperature tends to increase.

The amount of heat exchanged between a body and the surrounding environment depend on the physical activity being carrying out: a person seated comfortably produces much less heat than one that is running. Human body exchanges heat with the environment through (Fig. A.2-2):

- convection (the air in contact with the skin is heated, and so extracts heat), which depends on the skin temperature, the air temperature and its speed;
- transpiration (which can turn into sweating) and respiration, which result into the evaporation of water, with consequent removal of heat from the skin or lungs; it depends on the relative humidity of the air;
- conduction; if a part of the body is in contact with a solid object, through the contact surface it transfers heat, whose amount depends on the temperature of the skin and of the object, as well as on the thermo-physical characteristics of the latter;
- radiative heat exchanges, which depend on the temperature of the skin and on the temperatures of the surfaces enclosing the space.

Clothing highly influences heat transfer, through the additional thermal resistance it generates, the modification of the surface temperature and the transpiration process.

FIGURE A.2-2 **FACTORS DETERMINING THERMAL COMFORT**

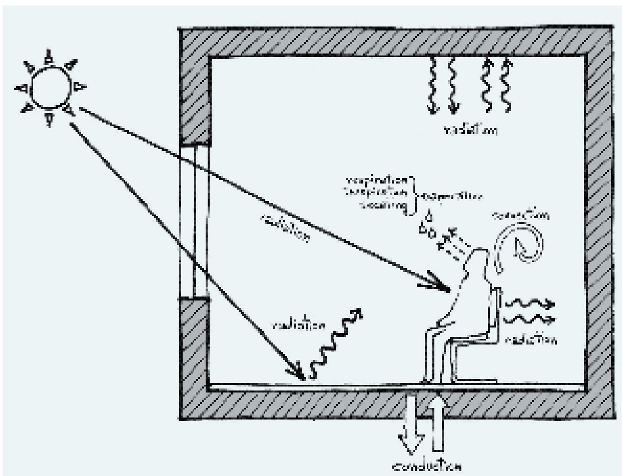
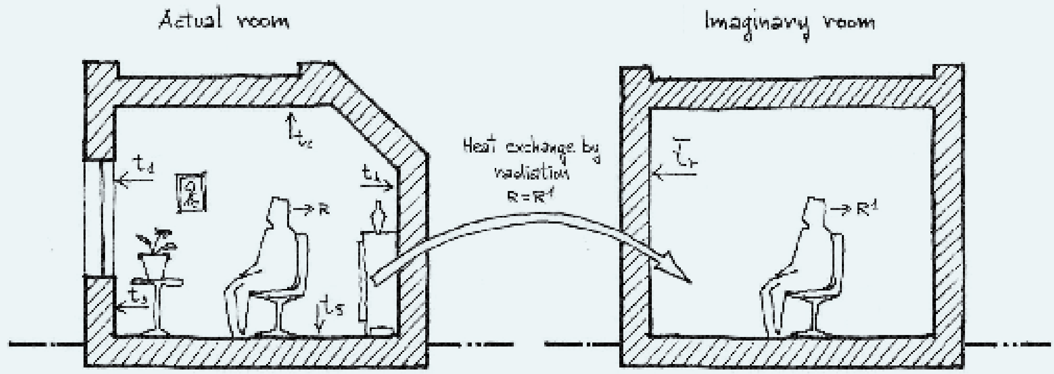


FIGURE A.2-3 **MEAN RADIANT TEMPERATURE**



To determine if a body is a net gainer or loser of radiant energy the apparent size of each radiating surface must be taken into account, not only the surface temperature, i.e, the view factor $F_{p,i}$ (see Appendix 1).

In order to take into account in a synthetic way this phenomenon, a specific index, the mean radiant temperature t_{mr}, was introduced. The mean radiant temperature is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (Fig. A.2-3), and it is calculated with:

$$t_{mr} = \Sigma\, t_i\, F_{p,i} \qquad \text{(A.2-1)}$$

where the sum is extended to all the surfaces seen by the subject. The mean radiant temperature in a point P situated at the barycentre of a parallelepiped room is given by:

$$t_{mr} = \frac{t_1 A_1 + t_2 A_2 + \cdots + t_n A_n}{A_{tot}} \qquad \text{(A.2-2)}$$

where t_1, t_2, ...t_n are the temperatures of the surfaces enveloping the point (including windows) and A_1, A_2, ... A_n are the respective areas, and $A_{tot} = A_1 + A_2 + ...A_n$ is the total area of the envelope seen from the point P.

Because of the important contribution of the temperature of the surfaces enclosing a space on heat exchanges and thus on thermal comfort, another index has been introduced, the operative temperature t_{op}, which, in normal conditions [still air and ($t_{rm} - t_{air}$) < 4 °C], is the average of the air temperature t_a and the mean radiant temperature t_{rm}. The operative temperature represents the perceived temperature better than air temperature, because it takes into account both the convective and the radiative exchanges of the body with the environment.

For example, in a room with 26 °C air temperature, a person seated right next to a large glass surface is not comfortable - he is hot - because the glass, absorbing solar radiation (direct or diffuse), heats up and its temperature reaches easily 40 °C or more. The mean radiant temperature is higher than if he was sitting in the extreme corner of the room (Fig. A.2-4).This implies that also the operative temperature is higher. Since thermal comfort depends on the operative temperature, the person sitting by the glass will be hot, while one sitting far from it is comfortable. In order to make the person near the glass comfortable, it is necessary to decrease the operative temperature. Mean radiant temperature and, thus, operative temperature is of paramount importance in largely glazed buildings; for keeping operative temperature at comfortable values, air temperature must be lowered, with consequent increase of energy consumption.

FIGURE A.2-4 **EFFECT OF POSITION AND SURFACE TEMPERATURES ON MEAN RADIANT TEMPERATURE (T_{RM}) AND OPERATIVE TEMPERATURE (T_{OP})**

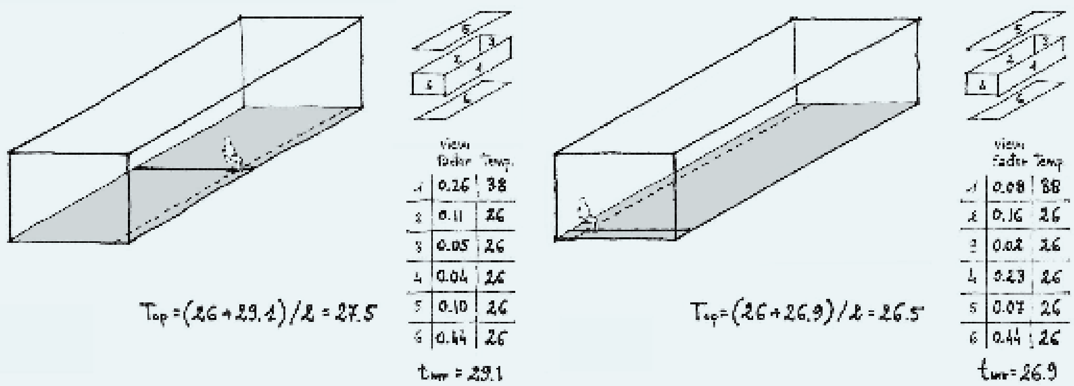


FIGURE A.2-5 **METABOLIC RATE FOR DIFFERENT ACTIVITIES, IN MET**

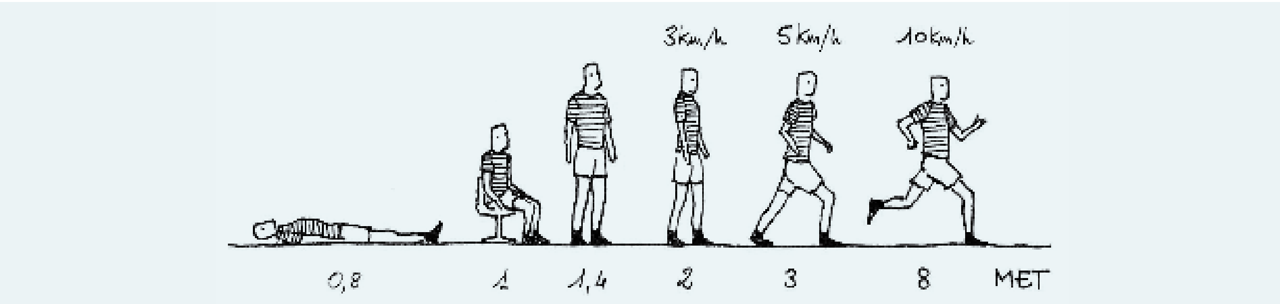
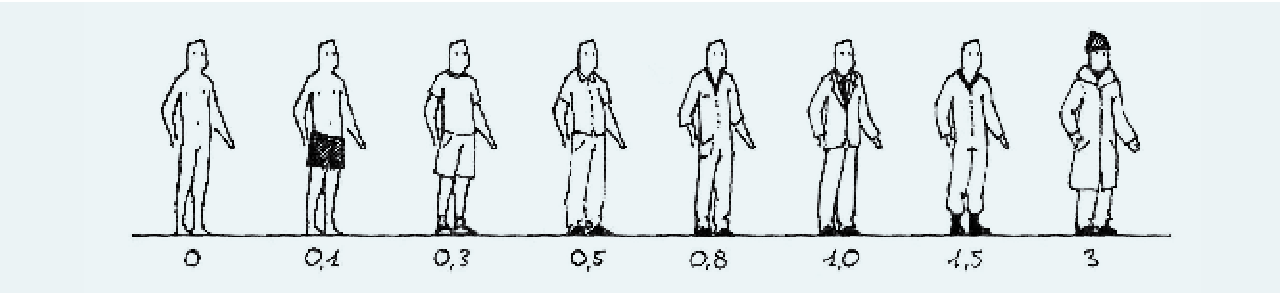


FIGURE A.2-6 **THERMAL RESISTANCE VALUES OF CLOTHING EXPRESSED IN CLO FOR VARIOUS TYPES OF CLOTHING**



The comfort sensation depends not only on environmental conditions but also on the conditions of the person, the activity being carried out and his clothing.

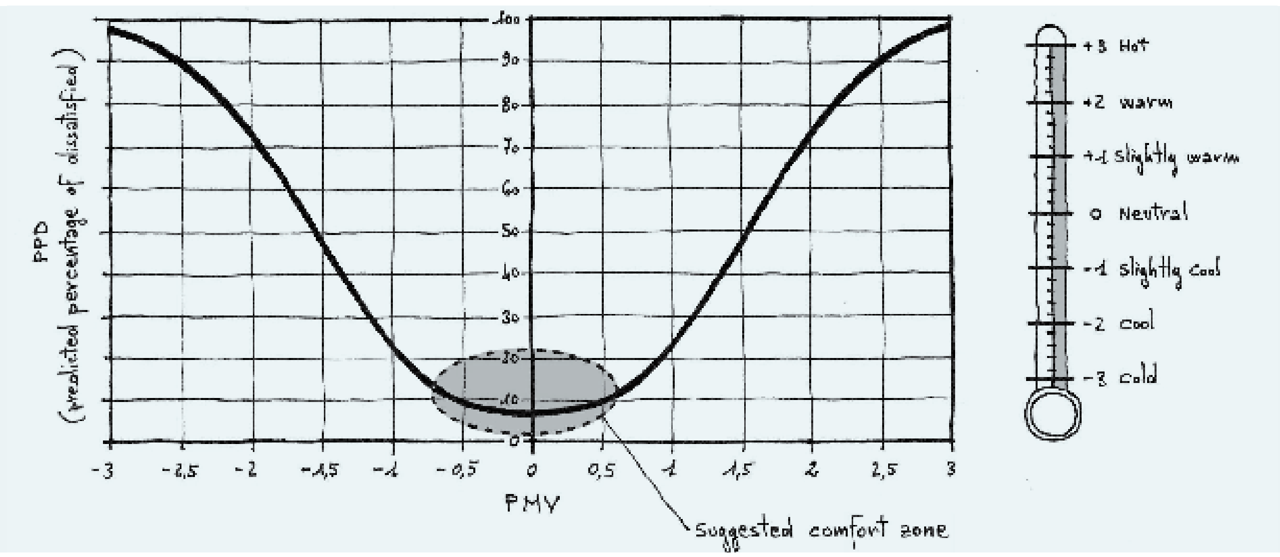
Physical activity is measured by the produced thermal energy (metabolic rate) that must be dissipated in the environment (Fig. A.2-5) and is expressed in met (1 met = 50 kcal/h per square meter of body surface area, the average man has a surface of 1.8 m^2), or in W/m^2. A seated person produces 1 met (58 W/m^2).

The clothing is measured by its thermal resistance (Fig. A.2-6) and is expressed in the unit clo (1 clo = 0.155 m^2 K / W). The value clo = 1 corresponds to the typical winter clothing, the lowest value is clo = 0 (naked person), the value clo = 0.5 corresponds to the typical summer clothing.

1.2 PMV

An overall index for thermal comfort is the PMV (Predicted Mean Vote), which provides the mean value of the votes, according to the thermal sensation scale of figure A.2-7, of a large group of people exposed to the same environment. The PMV, which has a value between -3 and +3, takes into account all environmental factors (temperature, speed and humidity of air, mean radiant temperature), the activity being carried out by the person, and clothing.

FIGURE A.2-7 **THERMAL SENSATION SCALE, PMV AND PPD**



In order to predict the number of people likely to feel uncomfortable in an environment, an index PPD (Predicted Percentage of Dissatisfied) has been introduced, which provides a quantitative prediction of the number of thermally dissatisfied people. The PMV and PPD are bound together, as shown in figure A.2-7. Because of individual differences, it is impossible to obtain a thermal environment that satisfies everyone. Although the PMV is zero, there is always a 5% dissatisfied.

The standard EN 15251 defines a ranking of quality of a mechanically heated or cooled environment in terms of thermal comfort, establishing four categories (Table A.2-1).

TABLE A.2-1 **RECOMMENDED CATEGORIES FOR DESIGN OF MECHANICAL HEATED AND COOLED BUILDINGS**

Category	Category characteristics	PMV	PPD [%]
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	-0.2 < PMV < 02	< 0.6
II	Normal level of expectation and should be used for new buildings and renovations	-0.5 < PMV < 0.5	< 10
III	An acceptable, moderate level of expectation and may be used for existing buildings	- 0.7 < PMV < 0.7	< 15
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	PMV < -0.7 or 0.7 < PMV	> 15

1.3 THERMAL COMFORT IN AIR CONDITIONED BUILDINGS

In air conditioned spaces, where air velocity is less than 0.2 m/s and the relative humidity[111] is between 30 and 70%, and for certain type of clothing and activities, there is a direct correspondence between the PMV and the operative temperature, which is an index more easily understood, also because it coincides with the air temperature if this coincides with the mean radiant temperature.

Taking this into account, the standard EN 15251 provides the design indoor operating temperatures recommended for different categories of comfort and environments, to be used for the design of the HVAC systems (Table A.2-2).

111 *The humidity has a very small effect on thermal comfort. For humidity values below 30% the production of dust increases and plastics can be electrostatically charged. In the summer, high humidity (> 70%) could give rise to an unpleasant indoor air quality.*

TABLE A.2-2 **RECOMMENDED DESIGN VALUES OF THE INDOOR TEMPERATURE FOR DESIGN OF BUILDINGS AND HVAC SYSTEMS**

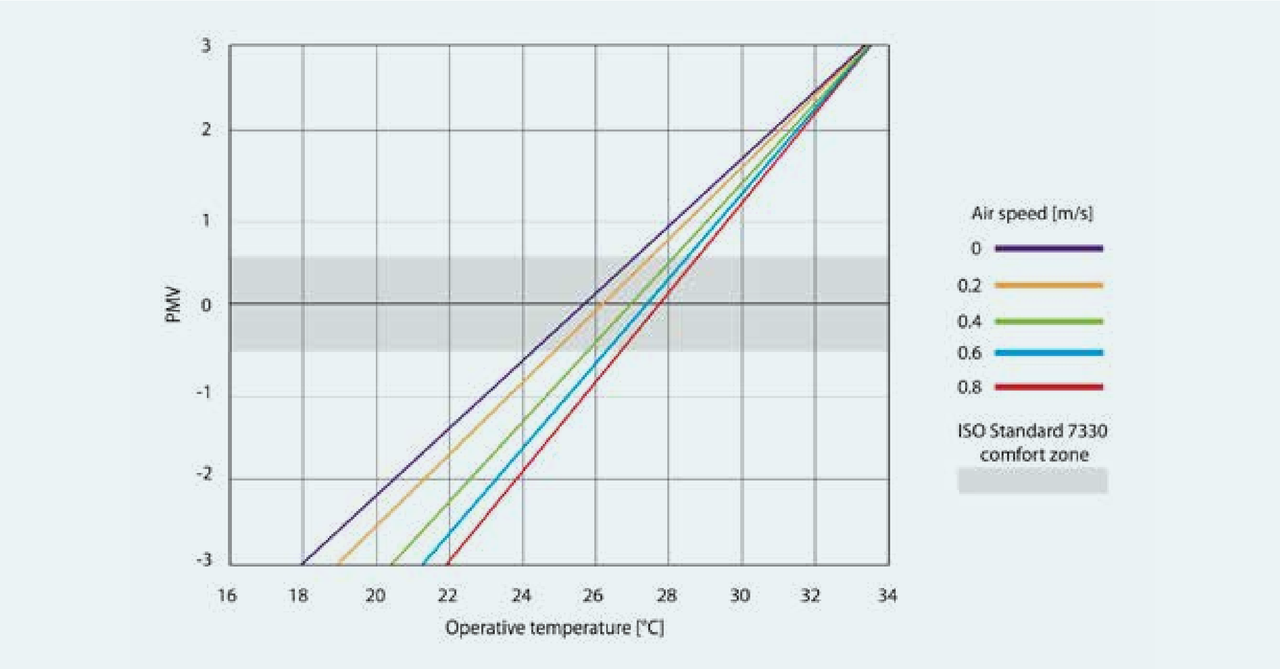
Type of space	Category	Operative temperature [°C]	
		Minimum for heating clothing: 1 clo	Maximum for cooling clothing: 0.5 clo
Residential buildings: living room, bed rooms, drawing room, kitchen Sedentary activity ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	18.0	27.0
Residential buildings: other spaces (storages, halls, etc.) Standing-walking activity ~1.5 met	I	18.0	
	II	16.0	
	III	14.0	
Single office, open plan office, conference room, auditorium Sedentary activity ~ 1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
Cafeteria/restaurant Sedentary activity ~ 1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
Classrooms Sedentary activity ~ 1.2 met	I	21.0	25.0
	II	20.0	26.0
	III	19.0	27.0
Kindergarten Standing-walking activity ~ 1.6 met	I	19.0	24.5
	II	17.5	25.5
	III	16.5	26.0
Department store Standing-walking activity ~ 1.6 met	I	17.5	24.0
	II	16.0	25.0
	III	15.0	26.0

Even if the values shown in Table A.2-2 are maintained, for example, by compensating a high radiant temperature with lower air temperature, there still need to take into account other factors, such as:

- a high temperature difference between the inner surfaces causes radiation asymmetry which results in higher discomfort;
- a high temperature difference between the inner surfaces and the air may cause unpleasant air droughts.

For this reason, it is appropriate to keep the temperature difference air-surface as low as possible, and the speed of

FIGURE A.2-8 **EFFECT OF INCREASING AIR SPEED ON COMFORT IN AIR CONDITIONED SPACES (1 MET, 0.5 CLO)**



cool air introduced in the conditioned space must remain lower than 0.19 m/s.

Increasing air velocity, comfort is attained even if operative temperature values are higher than those in Table A.2-2, as show in figure A.2-8. This approach (use of systems to control the air velocity, fans or other) can also be used to compensate for excessive temperatures that may occur in buildings equipped with air conditioning, or to increase the air temperature, reducing the consumption and leaving intact the comfort.

Table A.2-3 gives information about the relation between air velocity and pleasantness. An air movement of 1.0 m/s is the limit before papers on a desk will start to blow around.

TABLE A.2-3 **AIR VELOCITY AND PLEASANTNESS**

Air velocity [m /s]	Effect
up to 0.25	not perceptible
from 0.25 to 0.5	pleasant
from 0.5 to 0.8	generally pleasant but the air movement is perceived
from 0.8 to 1.5	from slightly to unpleasantly annoying
> 1.5	requires corrective actions to maintain pleasantness and productivity

1.4 THERMAL COMFORT IN NON-AIR-CONDITIONED BUILDINGS

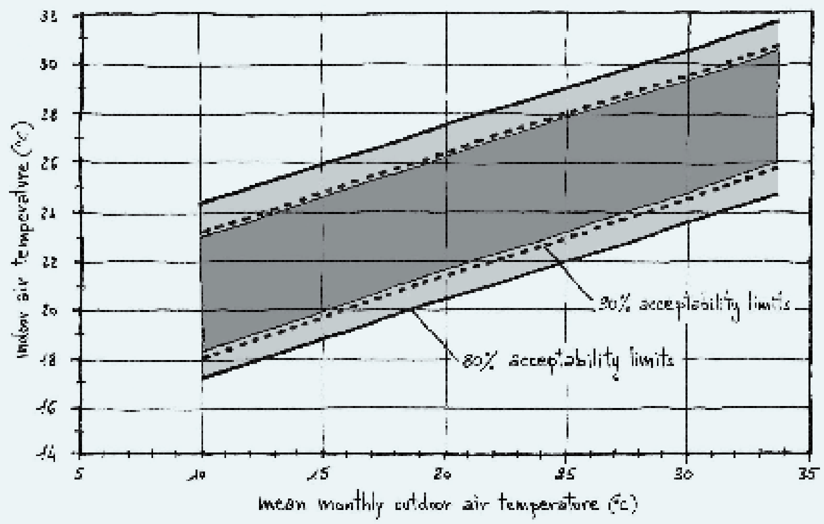
The ANSI/ASHRAE Standard 55-2004 addresses the issue of comfort in non-air-conditioned buildings, or during periods when air conditioning is not used. In these cases, the principles of adaptive comfort is applied, which takes into account not only the purely physiological factors but also include social, psychological, cultural and climatic factors.

The standard applies the principles of the adaptive comfort to warm-hot climatic conditions in spaces without air conditioning system, or when it is turned off, and where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows.

Allowable indoor operative temperatures for spaces that meet these criteria may be determined from figure A.2-9. This figure includes two sets of operative temperature limits—one for 80% acceptability and one for 90% acceptability. The 80% acceptability limits are for typical applications and shall be used when other information is not available. The 90% acceptability limits may be used when a higher standard of thermal comfort is desired.

The limit temperature values shown in Fig. A.2-9 are used to design so as to prevent overheating in summer without the aid of artificial means; for example, by means of the suitable sizing of the windows and their orientation, solar protection devices and the thermal capacity of the construction. Where the limit values cannot be met with

FIGURE A.2-9 **ACCEPTABLE OPERATIVE TEMPERATURE FOR NATURALLY CONDITIONED SPACES**



passive means, inevitably the systems with mechanical cooling are required. When this occurs, the limit values of comfort become those indicated in Table A.2-2.

As in the case of air conditioned buildings, air velocity increases the operative temperature value at which thermal comfort is attained as shown in figure A.2-10, where Δ top is the increment in operative temperature in K and Va is the air velocity in m/s, when relative humidity is in the range 60-70%. The horizontal line indicates the air velocity values beyond which air movement is perceived as annoying. Acceptance of the increased air velocity will require occupant control of device creating the local air movement.

If different values of relative humidity are taken into account, the air temperature offset can be derived from the graph in figure A.2-11.

2. PRINCIPLES OF VISUAL COMFORT

What we call light is the part of the radiation that the sun sends to Earth that our eye perceives, and corresponds to about half of all the solar energy that reaches us.

The range of wavelengths to which our retina is sensitive is comprised between 380 and 780 nm. Within this interval, at each wavelength, we attribute a colour. But our eye is not equally sensitive to all colours/wavelengths: it is little sensitive to blue-violet and red, while is highly sensitive to yellow-green (Fig. A.2-12). Good lighting should be based, whenever possible and appropriate, on natural light - supplemented when necessary by artificial light.

The factors which determine the quality of lighting are: the luminance distribution, the level of illumination, the daylight factor, the dependence on artificial light, the glare, the colour of the light sources and their colour rendering. The exploitation of natural light has a great impact on energy consumption, especially in commercial buildings, reducing the need for artificial lighting.

FIGURE A.2-10 **AIR SPEED REQUIRED TO OFFSET INCREASED TEMPERATURE (EN ISO 7730)**

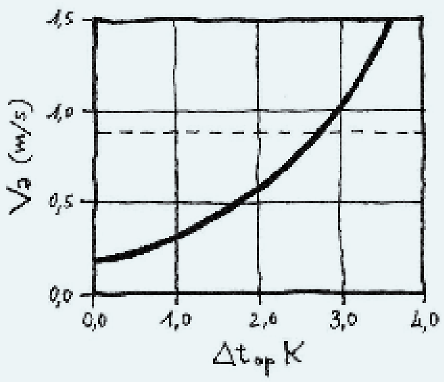
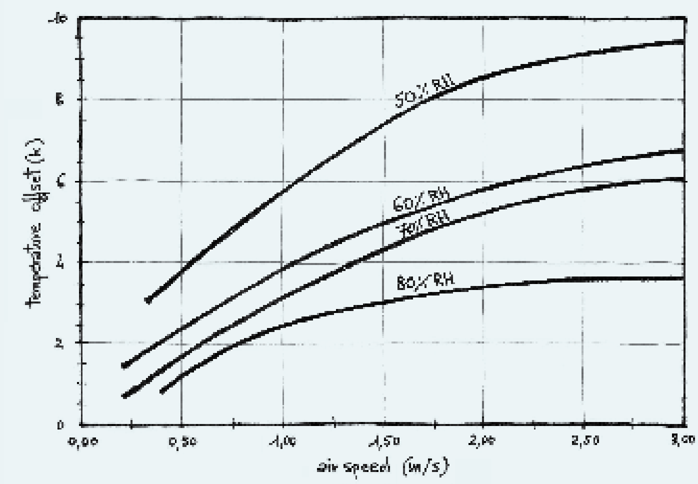
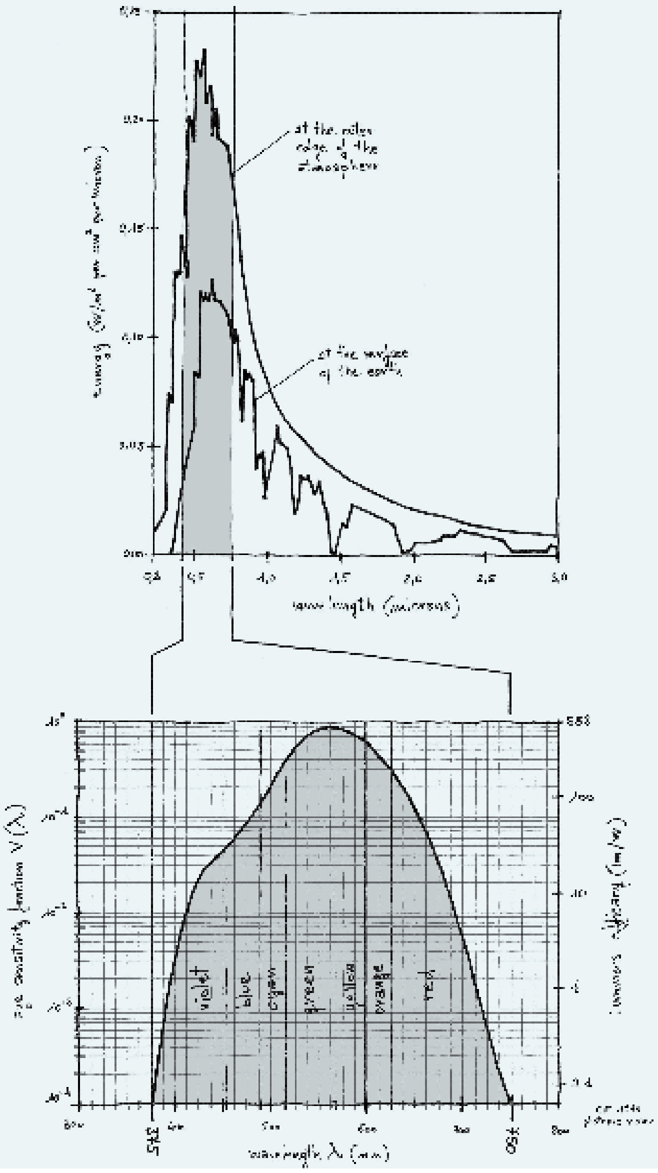


FIGURE A.2-11 **COOLING EFFECT OF AIR MOVEMENT**



Source: *J. Khedari, N. Yamtraipat, N. Pratintong and J. Hinrunlabbh, Thailand Ventilation Comfort Chart, Energy and Buildings, Vol 32, 200, pp 245-249*

FIGURE A.2-12 **– SOLAR SPECTRUM, SENSITIVITY RANGE AND EYE'S SENSITIVITY TO COLOUR (CIE 1978, PHOTOPIC VISION)**



Photometry units

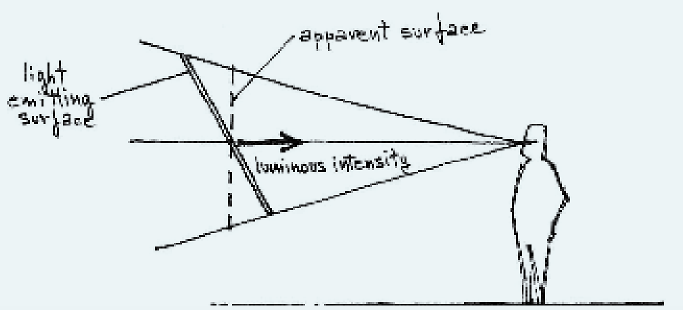
Luminous Flux - Unit: lumen [lm] - This quantity indicates the amount of luminous energy emitted per unit of time (1 second) from a source, i.e. its luminous power. For luminous energy it is meant the radiant energy emitted in the range 380 to 780 nm.

Luminous Intensity - Unit: candela [cd] - A light source emits its luminous flux usually in different directions and at different intensities. The intensity of light radiated in a given direction is defined luminous intensity.

Illuminance - Unit: lux [lx = lm/m²] - This is the ratio of the luminous flux received by a surface to the area of the surface itself. It indicates the amount of light that strikes a unit area.

Luminance - Unit: candela/m² [cd/m²] - It is the ratio of the luminous intensity emitted by a surface in a given direction to the apparent area of that surface. The apparent area is the projection of the surface on a plane normal to the direction considered (Fig. A.2-13).

FIGURE A.2-13 **LUMINANCE DEFINITION**



In practice the luminance indicates the sensation received from a light source, primary or secondary (it is said primary source a body that emits radiation directly, it is said secondary source a body that reflects the radiation from a primary source).

It is important to be clear about the difference between illuminance and luminance. If the first indicates the amount of light, emitted by a source, which affects the surface considered, the second indicates the sensation of brightness received from this surface; this means that on two surfaces, one white and the other black, we can have the same value of illuminance, e.g. 500 lux, but the sensation of light received, and then the luminance, will be completely different, since those two surfaces reflect the light differently.

2.2 VARIABLES AND FACTORS OF VISUAL ENVIRONMENT

The lighting and its distribution greatly influence the perception of the visual task and its accomplishment in a fast, safe and comfortable way.

2.2.1 LUMINANCE DISTRIBUTION

Although the eye is capable of adapting to wide variations in luminance (Table A.2-4), it cannot adapt simultaneously to two very different levels. The eye minimizes the problem by trying to focus on one area of different brightness at a time. However, if those areas are both in the central part of the visual field, the concentration on only one of them becomes difficult, if not impossible, and from this situation arises an unpleasant eye fatigue due to continual adjustments to which it is forced to adapt to different luminance. To prevent this from happening is necessary first of all to avoid that in the visual field fall areas of too different brightness, containing the luminance ratio within the limits of Table A.2-5.

TABLE A.2-4 **LUMINANCE OF SOME SOURCES**

Source	Luminance [cd/m²]
Sun	2,300,000,000
Bulb of an incandescent light (opal bulb)	50,000
Snow in the sun	25,000
Sunny clear beach	15,000
Fluorescent lamp	6,000-8,000
Full moon	4,000
This sheet of paper with normal desk illumination	120
Road surface with street lighting	0.5-2

TABLE A.2-5 **MAXIMUM RECOMMENDED VALUES OF LUMINANCE RATIO**

Max ratio	Situation	Example
3:1	focus area/area immediately surrounding	Book/desk
5:1	focus area/surrounding area	Book/surrounding walls
10:1	focus area/area more far away	Book/wall more far away
20:1	Light source/adjacent area	Window/adjacent area

This means, for example, that working at the computer, whose screen has an average luminance of about 100 cd/m^2, the maximum permissible luminance of a window in the visual field is 1,000 cd/m^2: a value that you can have also in overcast conditions. For this reason workstations must be arranged so that the computer screen is perpendicular to the wall containing the window.

2.2.2 ILLUMINANCE

In normal lighting conditions approximately 20 lux are required to properly perceive the features of a human face. This value was adopted as the lowest scale of illuminance. The scale of recommended illuminance (in lux) is:

20 - 30 - 50 - 75 - 100 - 150 - 200 - 300 - 500 - 750 – 1,000 to 1,500 – 2,000 – 3,000 to 5,000

In Table A.2-6 are shown, as an example, the illumination values recommended by the standard EN 12464-1 for the offices[112].

However, studies in recent years have shown that the value of 500 lux recommended for office work or in the classroom is too high, and it is more reasonable to recommend 300-400 lux, because only a small percentage of occupants feel the need to turn on the light if the level of natural light on the table is about 300 lux[113], provided that the color temperature is not too high, as in the case of blue, green or spectrally selective glasses.

TABLE A.2-6 **OFFICES – RECOMMENDED VALUES OF ILLUMINATION**

Type of interior, task, activity	Mean illumination [lux]
Filing, copying	300
Writing, typewriting, reading, data processing	500
Technical drawing	750
CAD workstation	500
Meeting, conference rooms	500
Reception	300
Archives	200

2.2.2.1 DAYLIGHT FACTOR (DF)

The Daylight Factor (DF) is a measure of the amount of daylight available in a space. It is defined as the ratio of the illumination of the working plane E_{int} in a given position to the illuminance E_{ext} that would be, under identical conditions of time and place, on a horizontal surface exposed outdoors so as to receive light from the entire sky, with no direct sun (Fig. A.2-14). Usually it is expressed as per cent.

$$DF\ [\%] = (E_{int}/E_{ext}) \times 100 \qquad (A.2\text{-}3)$$

The calculation of E_{int} passes through the evaluation of three components:

- Sky Component, SC: the light that comes directly from the part of the sky visible from the point considered; it is greater the larger is the window, and the more transparent is the glass;
- External Reflected Component ERC: the light reflected by external objects, such as buildings; also for this component counts window size, glass transparency, as well as the colour (light, dark, medium) of the ground and surrounding buildings;
- Internal Reflected Component IRC: all the light that enters through the window and that does not reach the work surface directly, but only after being reflected from the internal surfaces; the higher its value the clearer the colours of walls and ceiling.

E_{int} is calculated with (Fig. A.2-15):

$$E_{int} = SC + ERC + IRC \qquad (A.2\text{-}4)$$

112 *EN 12464-1: "The Lighting of Workplaces". This European standard is about the quality aspects of lighting workstations and their direct environment. It also has tables with lighting requirements in accordance with the type of work and the visual task.*

113 *Reinhart, C.F.; Bourgeois, D.; Dubrous, F., Lightswitch: a model for manual control of lighting and blinds, Conference proceedings CISBAT 2003, 8 Oct. 2003, Lausanne, Switzerland, pp. 1-6. http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc46650/nrcc46650.pdf*

FIGURE A.2-14 **DAYLIGHT FACTOR**

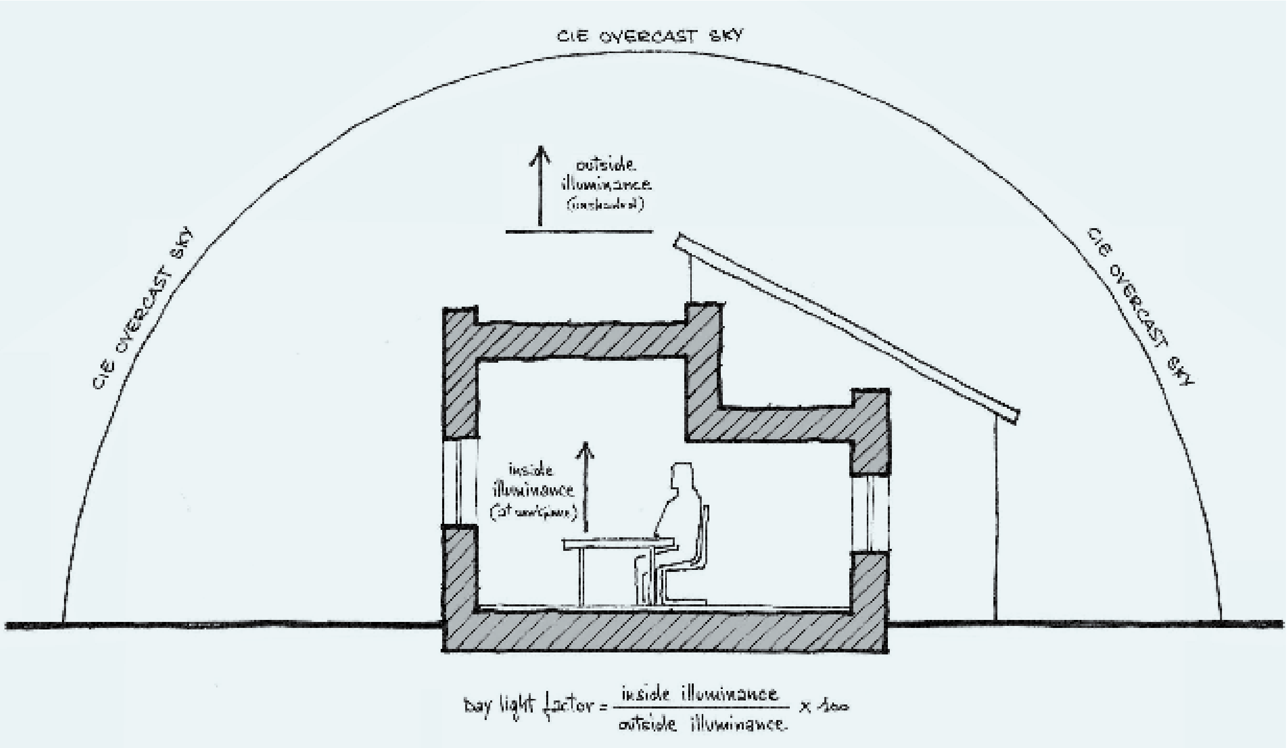
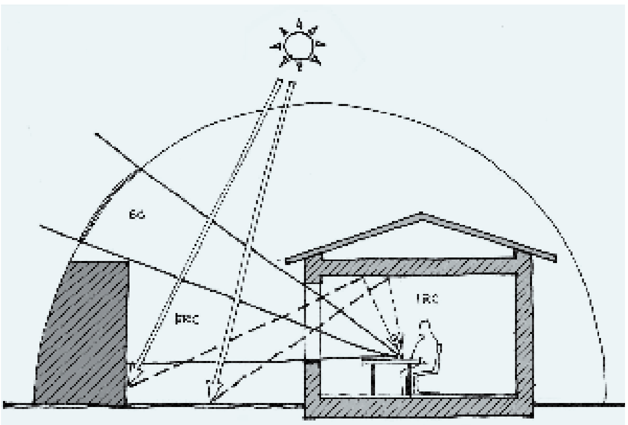


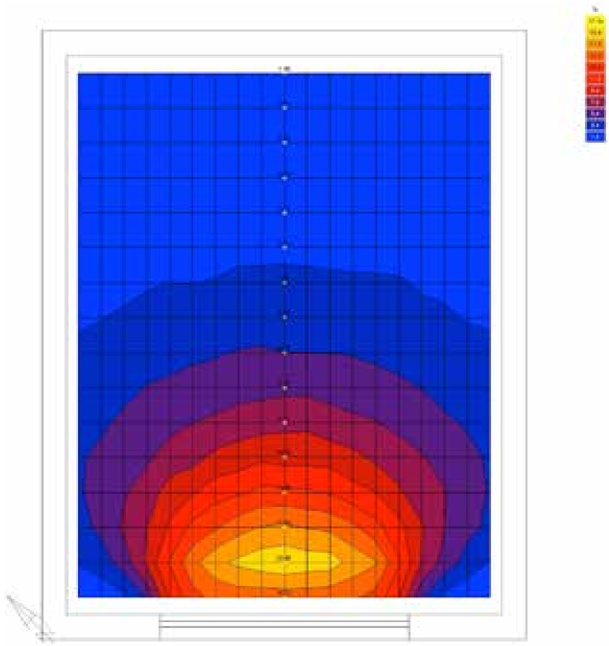
FIGURE A.2-15 **THE COMPONENTS CONTRIBUTING TO THE ILLUMINATION OF A POINT ($E_{INT} = SC + ERC + IRC$)**



Therefore, for given glass area and transparency, and external conditions, the daylight factor at a point of the room will be the greater the clearer are the internal surfaces and the higher the light transmission coefficient of the glass.

The three components can be estimated, as well as with specific software, with different graphical methods, analytical, or tabular. As shown in figure A.2-16, DF decreases rapidly moving away from the window. For this reason the ratio of the minimum to the maximum values of illuminance due to the natural light must be maintained above the value 0.16.

FIGURE A.2-16 **CHANGE OF DAYLIGHT FACTOR MOVING AWAY FROM THE WINDOW**



DF calculation refer to overcast conditions. The model adopted to describe the luminance of the sky covered is the standard CIE (Commission Internationale de l'Eclairage) model. To derive the level of internal illumination in lux from the value of the DF, it is necessary to know the level of external illumination with overcast sky, which is not equal in all parts of the world but decreases with increasing latitude. The daylight factor should never be used alone as an indicator for the design of buildings with low energy consumption and high quality of lighting, especially in tropical climates or where the number of annual hours of sunshine is high, higher than in the countries of northern Europe and North America, where this index was developed.

In fact, a window size based on a day with overcast sky in tropical climate is excessive, causing excessive levels of illumination in most days and, above all, more solar gains: an increase in both investment and operating costs without a counterpart in terms of lighting comfort.

2.2.2.2 MEAN DAYLIGHT FACTOR (DF_M)

The Mean Daylight Factor (DF_m) of an enclosed space is defined as the mean value of daylight factors measured at the level of the working plane by a grid of sensors extended to the whole space. The mean Daylight Factor can be estimated with:

$$DF_m = \frac{\tau_{vis} \cdot \theta \cdot A_{glazing}}{2 \cdot A_{total}(1-\rho_m)} \quad \text{(A.2-5)}$$

τ_{vis} = visible transmittance of glazing (see Appendix 1);
θ = sky angle, angle of obstruction measured from the mid-point of the window (90 degrees minus the actual obstruction angle on section, see figure 3.6-3);

$A_{glazing}$ = net glazing area, [m²];
A_{total} = total area of all interior surfaces, including windows, [m²];
ρ_m = mean surface reflectance, weighted on areas;
ρ_m = 0.5 can be used as first approximation.

In Table A.2-7 are surface reflectance ranges are given and Table A.2-8 shows examples of recommended mean daylight factor in near equatorial skies.

TABLE A.2-7 **MEAN VALUES OF SURFACE REFLECTANCE**

Ceiling, walls, floor, furniture	Surface reflectance
Light colours	0.6 - 0.8
Medium colours	0.3 - 0.6
Dark colours	0.1 - 0.3

TABLE A.2-8 **RECOMMENDED MEAN DAYLIGHT FACTORS**

Type of space	Recommended DF_m
Office/shop	1.0 - 2.0%
Classroom/conference hall	1.0 - 2.0%
Transit area	<1%

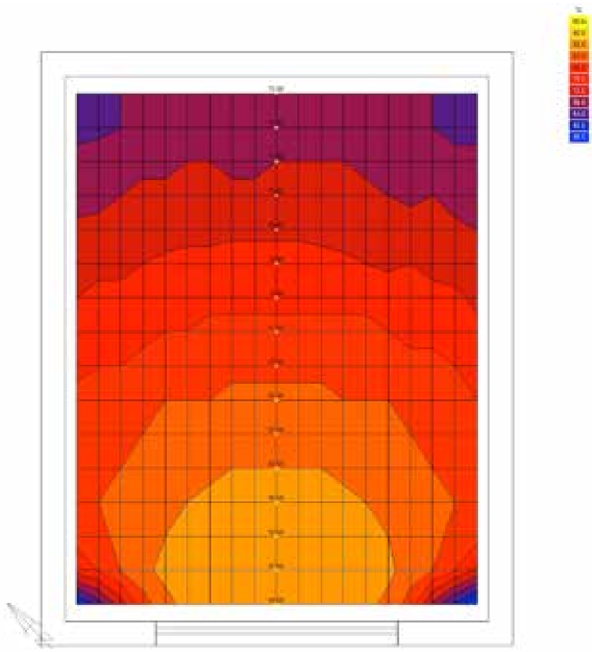
2.2.2.3 DAYLIGHT AUTONOMY (DA)

To overcome the oversizing deriving from the sole use of DF in windows design for optimum daylighting, another index, the Daylight Autonomy, was introduced. The DA in a point of a space is defined as the percentage of the building occupation hours in which the required minimum level of illuminance can be maintained with the natural lighting alone. Unlike the daylight factor, DA considers all sky conditions during the year, not just the overcast sky. Thus, DA is a comprehensive indicator capable of assessing the availability of natural light throughout the year at a given point.

For example, a Daylight Autonomy of 70% at a point of a room used every weekday from 8:00 to 18:00, in which a minimum level of 300 lux illumination is required, indicates that at that point it is possible to work for 70% of the year without resorting to artificial light (Fig. A.2-17). The main advantage of the daylight autonomy with respect to the daylight factor is that it takes into account not only all sky conditions that occur in a given location, but also the orientation and the occupation profile of the space being assessed.

On the other hand, DA can only be calculated through computer simulations, and it can provide inaccurate information when mobile screenings are provided and the software used is not able to deal with it, or when it cannot be predicted with reasonable accuracy the behaviour of the occupants when the operation of sunscreens is not automatic but left to their discretion.

FIGURE A.2-17 **DAYLIGHT AUTONOMY IN THE SAME ENVIRONMENT OF FIGURE A.2-16**



2.2.3 GLARE

According to the definition of the standard EN 12464-1, glare is the visual sensation produced by surfaces which produce high luminance gradients within the field of view. Glare can be generally divided into two types, discomfort glare and disability glare. Discomfort glare results in an instinctive desire to look away from a bright light source or difficulty in seeing a task. Disability glare impairs the vision of objects.

Discomfort glare reduces the ability to perceive details, not necessarily cause visual discomfort. This condition occurs when a person has a direct line of view of a light source such as a window or a lighting apparatus; it occurs also as a consequence of excessive reflection from a sheet of paper while reading, or from a computer screen. The eye is forced to continually adjust to two different luminances, and it follows distressing eyestrain.

Discomfort glare occurs when, even without a significant reduction of visual capacity, the presence of sources excessively bright in the visual field causes a state of discomfort. The sources may be too bright compared to a surrounding darker environment or unpleasantly shining in absolute.

It is important to limit the glare to avoid errors, fatigue and accidents. If the limits are satisfied discomfort generally has a negligible importance. The effects of discomfort glare can be mitigated by reducing the luminance of the light source, increasing the luminance of the object being observed through a better distribution of light and through the use of lighter colours for the walls, whose reflection characteristics have a considerable importance.

Usually, in a room with large glass surfaces glare is an inevitable consequence, and the occupants react by reducing the luminance of the source, through the use of curtains, which end up staying closed even when the phenomenon is no longer present; the result is the preclusion of the view outside and the need to turn on the artificial light.

To assess the level of glare an index was developed, the Daylight Glare Index (DGI)[114]. The DGI allows predicting the glare due to the natural light through the index UGR (Unified Glare Rating), which is used also for evaluating the glare due to an artificial light source.

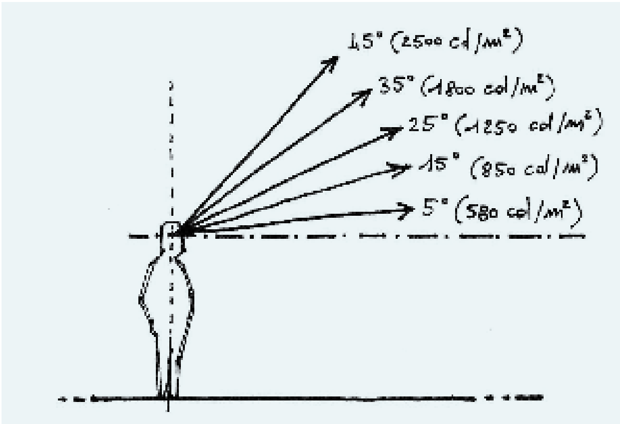
Based on the resulting value of DGI, the level of glare can be evaluated, according to the classification shown in Table A.2-9.

TABLE A.2-9 **VALUES OF UGR, DGI AND CORRESPONDING CATEGORIES OF GLARE**

Categories of glare	UGR	DGI
Barely perceptible	10-13	8-16
Acceptable	16-19	20-22
Annoying	22-25	24-26
Unbearable	28	28

The maximum luminance level of a window, for not causing glare in a person while reading, writing or using a computer, is about 2,500 cd/m^2. The human eye has difficulties to handle high levels of luminance directly in the area of vision which falls in the fovea. As the source of potential glare moves towards the central area of the visual field, the allowable luminance level decreases, as shown in figure A.2-18.

FIGURE A.2-18 **LUMINANCE LIMITS**



2.2.3.1 DIRECT AND REFLECTION GLARE

The direct glare depends on the characteristics of the space and of light sources (natural or artificial) directly in the visual field of a person. For example, when direct sunlight enters the field of view (extending 180° horizontally and 60° above the horizon, figure A.2-19) we simply notice it, but when it enters the centre of the visual field (an area defined by a cone with an angle of 40° which extends from the eye), will result in glare (Fig. A.2-20).

The glare by reflection is caused by shiny surfaces reflecting the image in the eyes of the image of light sources and it happens when the incidence angle of light on the horizontal work plane falls into the view angle of the observer (Fig. A.2-21 and A.2-22). Under conditions of natural lighting the view of the sky through a window can have a disturbing effect (Fig. A.2-23); this is a condition that occurs when one looks towards the wall adjacent to the window or when trying to see details of an object placed against a highly reflective surface in which the light sources are reflected.

114 *Since not all individuals perceive the same level of glare - that of annoyance - on equal terms. Recent studies have led to the development of a new index, the DGP (Daylight Glare Probability) that allows to assess the likelihood of glare in terms of perception by the occupant.*

FIGURE A.2-19 **THE VISUAL FIELD**

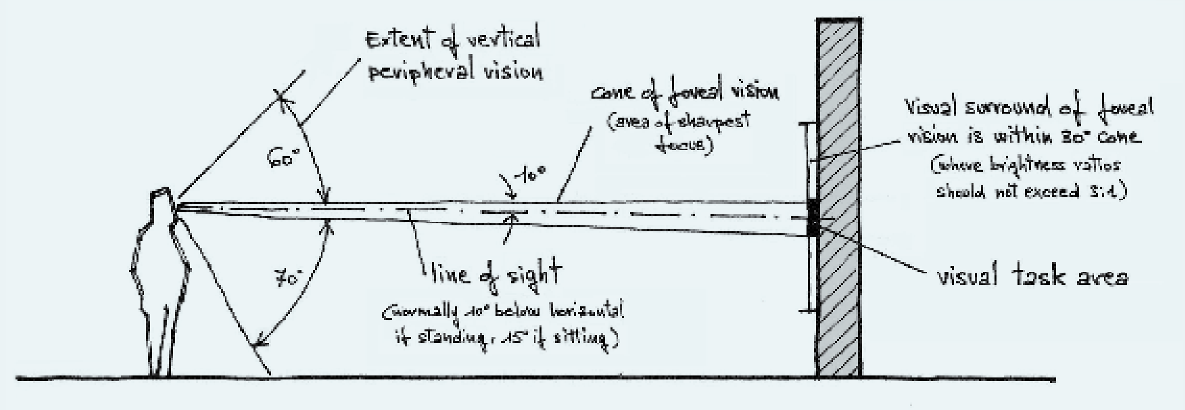


FIGURE A.2-20 **THE CLOSER TO THE CENTRE OF THE VISUAL FIELD, THE MORE LIGHT SOURCES ARE POTENTIAL SOURCES OF GLARE. IN THE FIGURE THE SOURCES ARE PROGRESSIVELY MORE PROBLEMATIC FROM A (NO PROBLEM), GRADUALLY TO B, C AND THE WINDOW (CAUSING GLARE)**

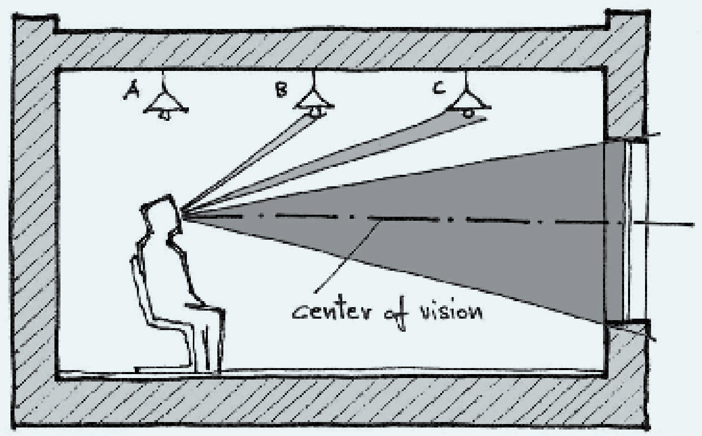


FIGURE A.2-21 **DIFFERENT POSSIBILITIES OF GLARE DUE TO REFLECTION**

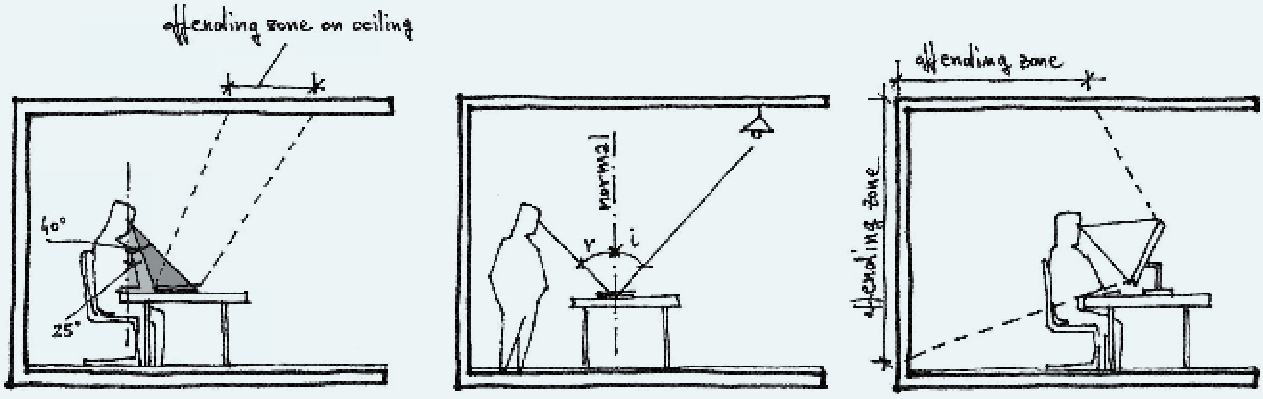


FIGURE A.2-22 **DIRECT AND REFLECTED GLARE**

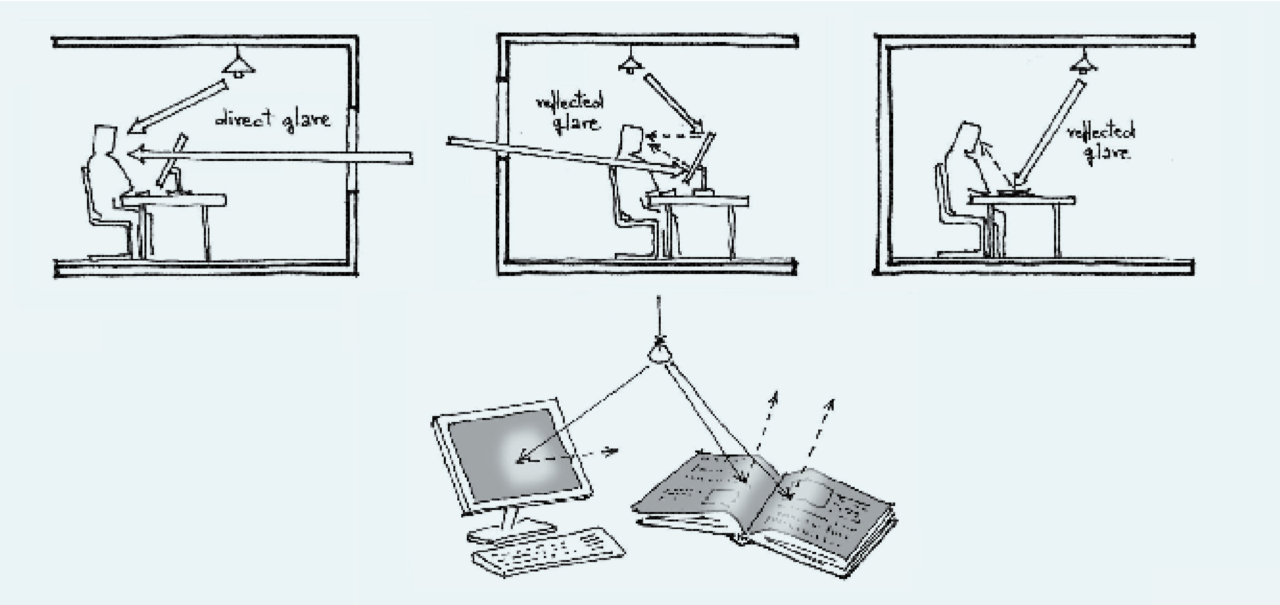
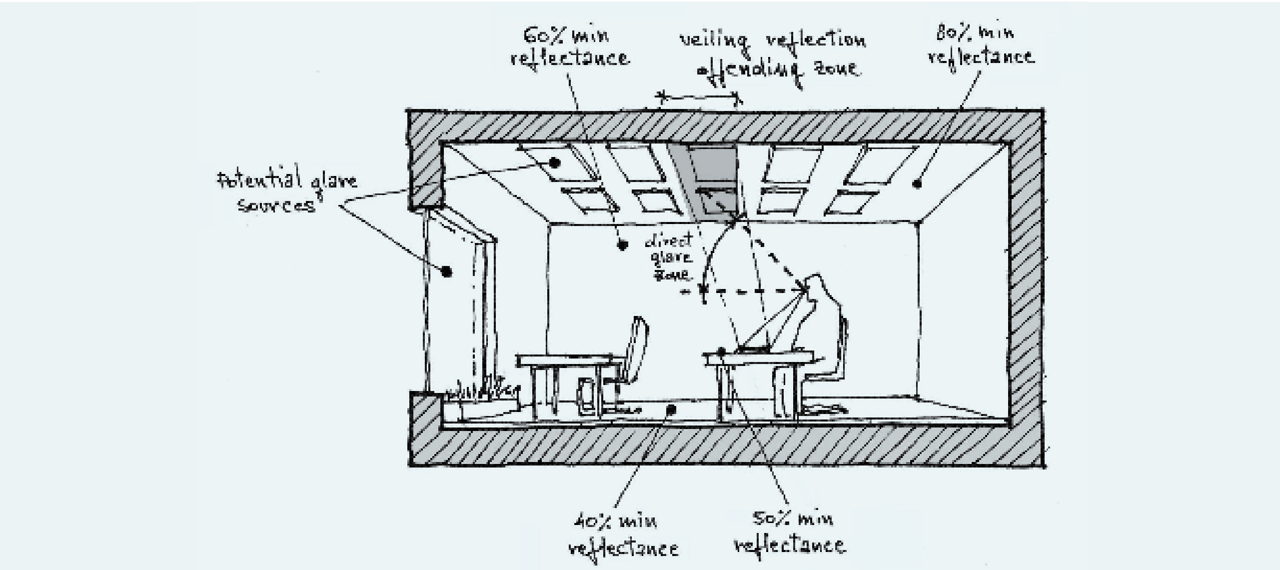


FIGURE A.2-23 **POTENTIAL SOURCES OF GLARE AND RECOMMENDED REFLECTANCES***



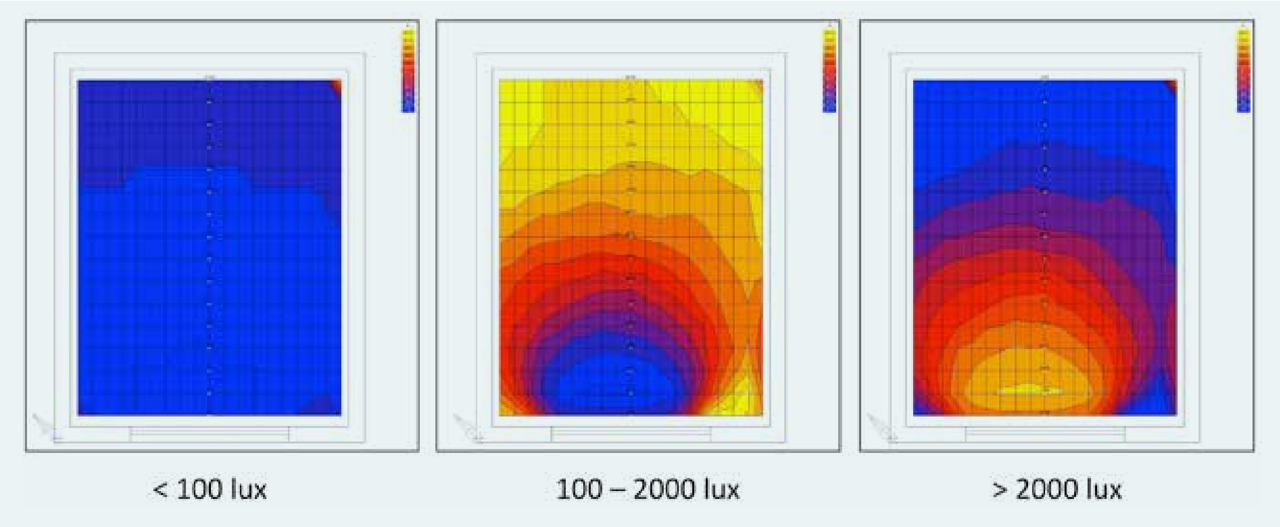
2.2.3.2 **USEFUL DAYLIGHT ILLUMINANCE (UDI)**

UDI is a measure of the dynamic performance of natural lighting, based also on the illuminance level of the work-plane. As the name suggests, it aims to establish when lighting levels are "useful" for the occupants, i.e. it is not too dark (<100 lux) or too bright (> 2,000 lux). The upper limit indicates the periods in which an excess of daylight could lead to visual discomfort. UDI is expressed by three numbers: the percentage of working time in which the illuminance values at a given point falls in the range 100-2,000 lux, that the hours in which is less than 100 lux and that the hours in which exceeds 2,000 lux (Fig. A.2-24). This value is important because represents an indirect index of the probability that glare occurs.

2.2.4 THE COLOUR OF LIGHT

The light can be more or less white, cold or warm. The colours of the objects appear different, by varying the type of light source used. To judge and classify light sources from a qualitative point of view two important parameters are used: colour temperature and colour rendering index. The same parameters can, and should, be used for the choice of glass (windows are light sources): the blue and green tinted ones and those spectrally selective filter and transform natural light, changing the colour temperature and colour rendering, and therefore determine the quality of the visual environment.

FIGURE A.2-24 **USEFUL DAYLIGHT ILLUMINANCE (UDI) FOR A SPACE; IT IS SHOWN THAT THE PROBABILITY THAT GLARE MAY OCCUR IS HIGH EVEN AT A CERTAIN DISTANCE FROM THE WINDOW**



2.2.4.1 **COLOUR TEMPERATURE**

The colour temperature is a parameter used to individuate and categorize, in an objective way, the colour of light from a light source compared to the sample source (black body). To say that a lamp has a colour temperature of 3,000 K, means that the black body, at this temperature, emits light with the same emission spectrum (Fig. A.2-25).

The black body is the reference by which one judges a light source that emits in a similar way (flame, incandescent lamps), i.e. it has a continuous spectrum. The spectrum of a discharge lamp (mercury vapour, fluorescent) or of a LED lamp, instead, is different in shape from that of a black body (Fig. A.2-26). In this case the correlated colour temperature (CCT) is used, which is the temperature of the black body for which the spectrum most approximates that of the lamp considered.

The light sources are divided into three groups, depending on the colour temperature:

3,000 – 3,500 K: warm white colour;
4,000 – 5,000 K: neutral white colour;
5,500 – 7,000 K: cool white colour.

FIGURE A.2-25 **BLACK BODY SPECTRUM**

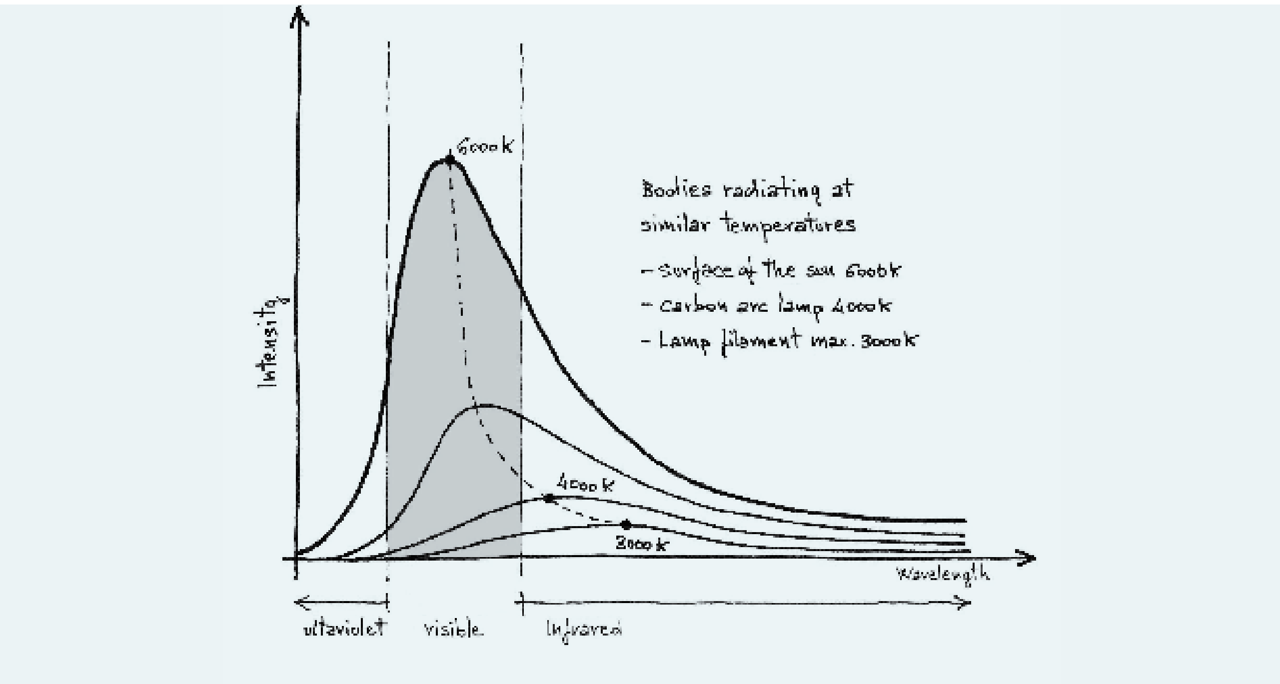
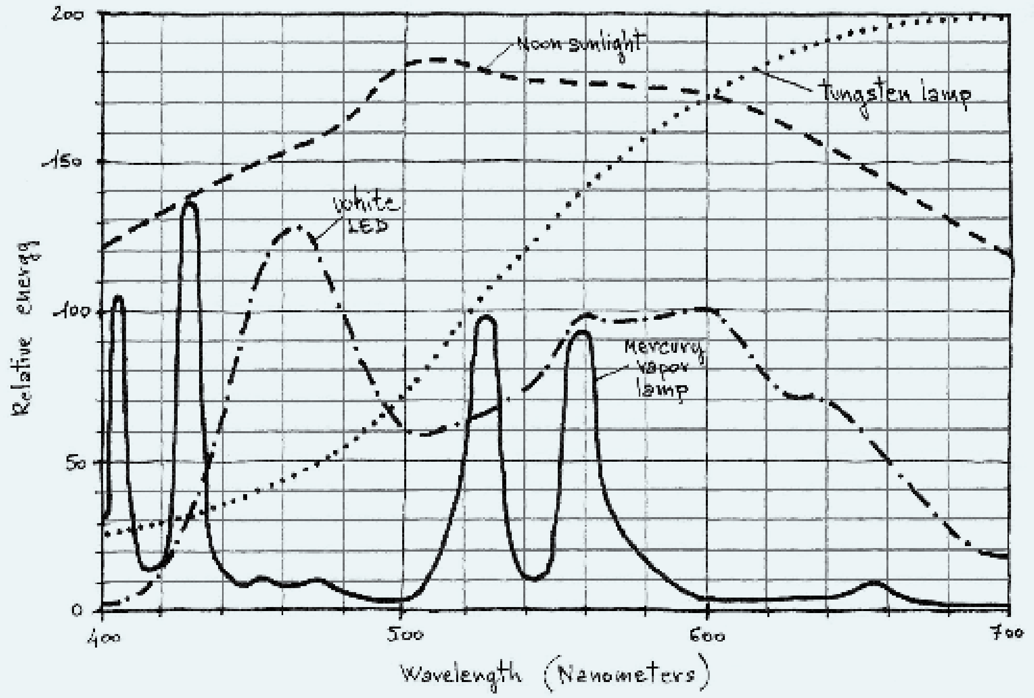


FIGURE A.2-26 **SPECTRA FROM COMMON SOURCES OF VISIBLE LIGHT**



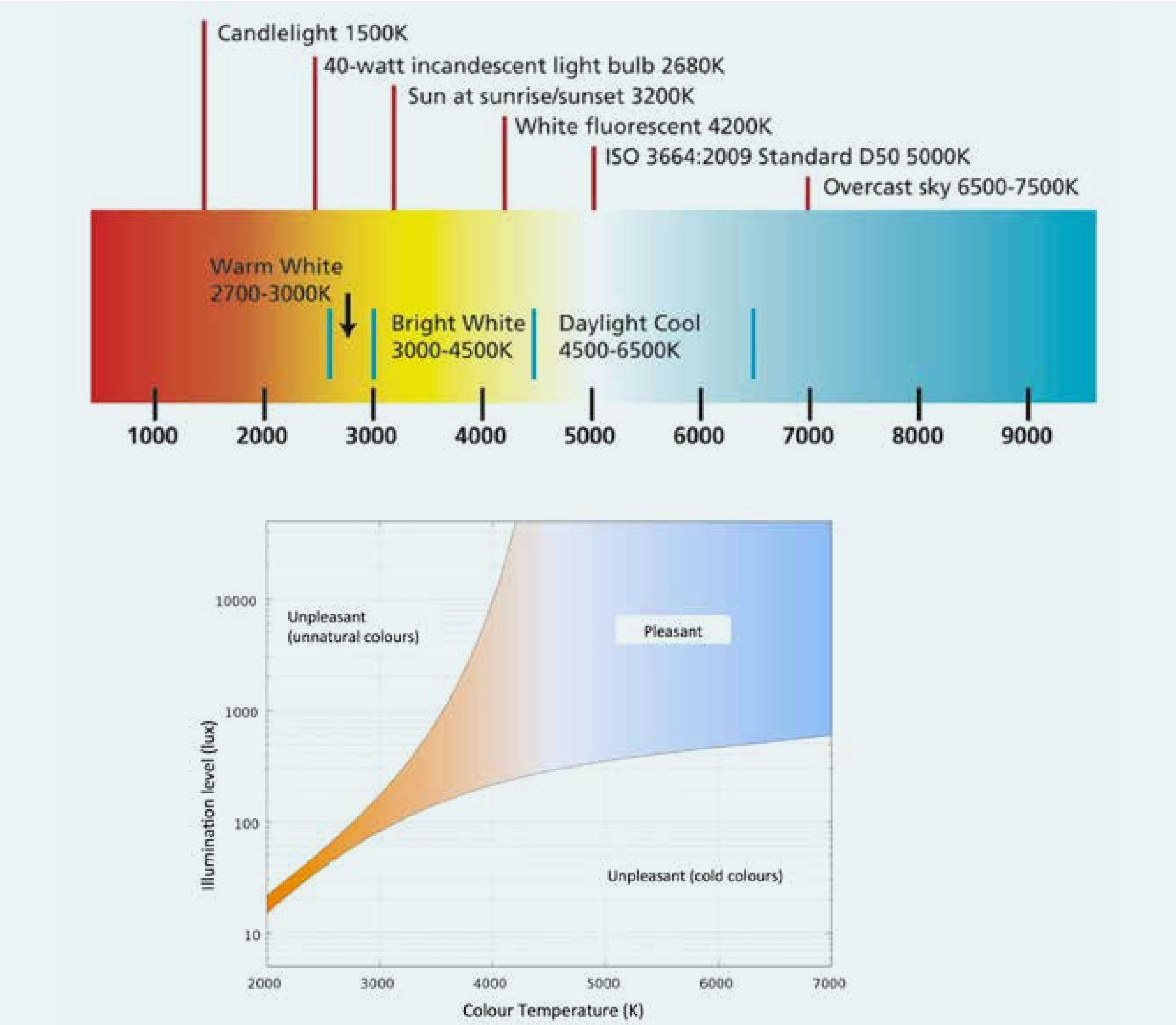
Light sources with a low colour temperature help to create a "warm" environment, if the lighting levels are low, i.e. those typical of home interiors or general lighting in offices. A pleasant lighting of the interior is obtained with light sources having a colour temperature not higher than 3,000 K. If the general level of illumination exceeds 500 lux, it may be preferable to use 4,000 K sources. Sources with higher colour temperature when used with lighting levels below 500 lux create an atmosphere "cold" and unpleasant (Fig. A.2-27). High values of colour temperature should be associated with high levels of illumination: that is what happens with natural light outdoors.

The colour temperature must not be confused with the colour index rendering (CRI, see below), since the former indicates the colour of the light emitted, but tells us nothing about colour rendering.

2.2.4.2 **COLOUR RENDERING INDEX**

The colour rendering index (CRI) is a quantitative measure of the ability of a light source to reproduce the accurately colours of objects by comparison with an ideal source (up to 5,000 K) or daylight (above 5,000 K).

FIGURE A.2-27 **TOP, THE COLOUR TEMPERATURE SCALE; BOTTOM, THE KRUITHOF CURVE WHICH RELATES THE PLEASANTNESS OF A VISUAL ENVIRONMENT WITH THE "WARMTH" OF THE LIGHT SOURCE AND THE ILLUMINATION LEVEL**



A3 EXERCISES

The exercises focus on the following subjects:

- Building physics;
- Thermal and visual comfort;
- Natural ventilation;
- Daylighting;
- Shading systems;
- Artificial lighting;
- Rainwater storage.

1. BUILDING PHYSICS (APPENDIX 1 – PRINCIPLES OF BUILDING PHYSICS)

The exercises in this paragraph refer to the "Appendix 1 - Principles of building physics". They deal with some particular aspects related to the heat transfer of the envelope and the overall thermal balance of the building.

1.1 THERMAL DIFFUSIVITY (PAR. 2.1.1 CONDUCTION)

Calculate the thermal diffusivity α of "Cement mortar", selecting the properties in Table A.1.2-1.

Data

Thermal conductivity λ:	0.719 W/mK
Density ρ:	1646 kg/m³
Specific heat capacity c:	920 J/kgK

Solution

$$\alpha = \frac{0.719}{(1646 \cdot 920)} = 4.75 \cdot 10^{-7}\ m^2/s \qquad \text{(A.3-1)}$$

1.2 SENSIBLE HEATING AND COOLING OF A SUBSTANCE (PAR. 2.1.1 CONDUCTION)

Calculate the quantity of heat qa necessary to increase the temperature of a volume of "Granite stone", selecting the properties in Table A.1.2-1.

Data

Specific heat capacity c:	820 J/kgK
Density ρ:	2600 kg/m³
Volume of the heated body V:	1 m³
Initial temperature t_1:	25 °C
Final temperature t_2:	35 °C

Solution

$$q_a = 820 \cdot 2600 \cdot 1 \cdot (35 - 25) = 2.1 \cdot 10^7\ J \qquad \text{(A.3-2)}$$

Now calculate the quantity of heat qa necessary to obtain the same increase in temperature for a volume of air.

Data

Specific heat capacity c:	1010 J/kgK
Density ρ:	1.2 kg/m³
Volume of the heated body V:	1 m³

Solution

$$q_a = 1010 \cdot 1.2 \cdot 1 \cdot (35 - 25) = 1.2 \cdot 10^4\ J \qquad \text{(A.3-3)}$$

Calculate the thermal power P necessary to actuate this process in 1 minute.

Solution

$$P = \frac{1.2 \cdot 10^4}{60} = 200\ W \qquad \text{(A.3-4)}$$

1.3 CONDUCTION (PAR. 2.1.1 CONDUCTION)

Calculate the heat flux by conduction Q_c between two faces of a wall made by "Concrete block medium" material, selecting the properties in Table A.1.2-1.

Data

Thermal conductivity λ:	0.51 W/mK
Thickness s:	20 cm
Temperature of face 1 ts_1:	32 °C
Temperature of face 2 ts_2:	20 °C
Area S of each face:	10 m²

Solution

$$Q_c = 0.51 \cdot \frac{(32 - 20)}{(20 \cdot 10^{-2})} \cdot 10 = 306\ W \qquad \text{(A.3-5)}$$

Repeat the same calculation with a multi-layered wall. The wall is composed of the following elements:

1. 2 cm of "Plaster (dense)";
2. 20 cm of "Concrete block medium";

3. 2 cm of "Plaster (dense)".

Solution

$$Q_c = \frac{(32-20)}{\left(\frac{2\cdot10^{-2}}{0.50}+\frac{20\cdot10^{-2}}{0.51}+\frac{2\cdot10^{-2}}{0.50}\right)}\cdot 10 = 254\ W \quad \text{(A.3-6)}$$

1.4 NON STEADY STATE HEAT CONDUCTION (PAR. 2.1.1 CONDUCTION)

Calculate the time-lag φ and the decrement factor ψ for a homogeneous wall made of "Concrete block medium" material.

Data

Thermal conductivity λ:	0.51 W/mK
Thickness s:	20 cm
Density ρ:	1400 kg/m³
Specific heat capacity c:	1000 J/kgK

Solution

$$\varphi = 0.023\cdot\left(20\cdot10^{-2}\right)\cdot\sqrt{\frac{1}{\left(\frac{0.51}{1400\cdot1000}\right)}} = 7.62\ h \quad \text{(A.3-7)}$$

$$\psi = exp\left(-0.003\cdot\left(20\cdot10^{-2}\right)\sqrt{\frac{1}{\left(\frac{0.51}{1400\cdot1000}\right)}}\right) = 0.37 \quad \text{(A.3-8)}$$

1.5 RADIATION (PAR. 2.2 RADIANT HEAT)

Calculate the heat flux emitted by longwave radiation of a surface made of "Red tiles", selecting the emissivity ε from Table A.1.2-3.

Data

Emissivity ε:	0.85
Area of the surface S:	10 m²
Temperature of surface t_s:	30 °C

Solution

$$Q_r = 0.85\cdot5.7\cdot10^{-8}\cdot10\cdot(30+273.15)^4 = 4092\ W \quad \text{(A.3-9)}$$

1.6 CONVECTION AND RADIATION (PAR. 2.2.3 CONVECTIVE AND RADIATIVE HEAT EXCHANGES)

Calculate the global heat exchange Qs considering convection and radiation coefficients together, using the heat transfer coefficient given in Table A.1-4 for external walls.

Data

Heat transfer coefficient h:	16.7 W/m²K
Area of the surface S:	10 m²
Temperature of air t_a:	32 °C
Temperature of surface t_s:	25 °C

Solution

$$Q = 16.7\cdot10\cdot(32-25) = 1169\ W \quad \text{(A.3-10)}$$

1.7 OVERALL HEAT TRANSFER OF A HOMOGENEOUS WALL (PAR. 2.2.4 OVERALL HEAT TRANSFER COEFFICIENT)

Calculate the overall heat transfer by conduction, convection and radiation, through a homogeneous wall made of the material "Concrete block medium" with a thickness of 20 cm and using the heat transfer coefficients given in in Table A.1-4.

Data

Internal surface heat transfer coefficient h_i:	8.3 W/m²K
External surface heat transfer coefficient h_o:	16.7 W/m²K
Area of the surface S:	10 m²
Outdoor air temperature t_o:	32 °C
Indoor air temperature t_i:	25 °C

Solution

Step 1 – Calculate thermal transmittance U

$$U = \frac{1}{\left(\frac{1}{8.3}+\frac{20\cdot10^{-2}}{0.51}+\frac{1}{16.7}\right)} = 1.75\ W/m^2K \quad \text{(A.3-11)}$$

Step 2 – Calculate heat flux Q

$$Q = \frac{(32-25)}{\left(\frac{1}{8.3}+\frac{20\cdot10^{-2}}{0.51}+\frac{1}{16.7}\right)}\cdot 10 = 122\ W \quad \text{(A.3-12)}$$

1.8 OVERALL HEAT TRANSFER OF A MULTI-LAYERED WALL (PAR. 2.2.4 OVERALL HEAT TRANSFER COEFFICIENT)

Repeat the calculation of the previous exercise with a multi-layered wall comprising the following elements:

1. 8 cm of "Brick, mud";
2. 5 cm of air gap with a thermal resistance of 0.1 m²K/W;
3. 5 cm of "Blown fibre";
4. 20 cm of "Concrete block medium";
5. 2 cm of "Plaster (dense)".

Solution

Step 1 – Calculate thermal transmittance U

$$U = \frac{1}{\left(\frac{1}{8.3}+\frac{8\cdot10^{-2}}{0.75}+0.1+\frac{5\cdot10^{-2}}{0.04}+\frac{20\cdot10^{-2}}{0.51}+\frac{2\cdot10^{-2}}{0.50}+\frac{1}{16.7}\right)} = 0.48\ W/m^2K \quad \text{(A.3-13)}$$

Step 2 – Calculate heat flux Q

$$Q = \frac{(32-25)}{\left(\frac{1}{8.3} + \frac{8\cdot10^{-2}}{0.75} + 0.1 + \frac{5\cdot10^{-2}}{0.04} + \frac{20\cdot10^{-2}}{0.51} + \frac{2\cdot10^{-2}}{0.50} + \frac{1}{16.7}\right)} \cdot 10 = 34\,W \qquad \text{(A.3-14)}$$

1.9 NON STEADY STATE HEAT TRANSFER (PAR. 2.2.4 OVERALL HEAT TRANSFER COEFFICIENT)

Calculate the non steady state heat transfer through a slab, using the following data.

Data

Location:	Mombasa
Date:	March (typical day)
Hour of the day τ:	1 p.m.
Thermal transmittance U:	1.75 W/m^{2}K
Time lag ϕ:	8 h
Decrement factor ψ:	0.4
Outdoor hourly mean air temperature at time τ to (τ):	31.6° C
Outdoor hourly mean air temperature at time $\tau-\phi$ to ($\tau-\phi$):	25.6° C
Outdoor daily mean air temperature t_o (m):	28.1° C
Indoor daily mean air temperature t_i (m):	26.0° C
Area of the surface S:	10 m^2

Solution

Step 1 – Steady state heat flux Q_m calculation

First of all, we have to calculate Q_m, the average heat flow on a daily basis, using the mean external air temperature and the mean internal air temperature.

$$Q_m = 1.75 \cdot 10 \cdot (28.1 - 26) = 36.7\,W \qquad \text{(A.3-15)}$$

Step 2 – Non-steady state heat flux calculation

In order to evaluate the instantaneous heat flow through a wall in non steady state conditions, the decrement factor and the time-lagged temperature ($\tau-\phi$) must be taken into account using the following formula.

$$Q_{(\tau)} = 36.7 + 0.40 \cdot 1.75 \cdot 10 \cdot (25.6 - 28.1) = 19.2\,W \qquad \text{(A.3-16)}$$

1.10 SOL-AIR TEMPERATURE (PAR. 2.2.5 SOL-AIR TEMPERATURE)

Calculate the sol-air temperature on the surface of a slab.

Data

Outdoor air temperature t_o:	28.0 °C
Heat transfer coefficient h:	16.7 W/m^{2}K
Absorption coefficient of the surface α:	0.55
Total solar radiation incident on the surface I_s:	850 W/m^2

Solution

$$t_{sa} = 28 + 0.55 \cdot \frac{850}{16.7} = 56\,°C \qquad \text{(A.3-17)}$$

1.11 NON STEADY STATE HEAT TRANSFER THROUGH A SLAB SUBJECT TO SOLAR RADIATION (PAR. 2.2.5 SOL-AIR TEMPERATURE)

Calculate the non steady state heat transfer through a slab considering the sol-air temperature on the surface.

Data

Location:	Mombasa
Date:	March (typical day)
Hour of the day τ:	1 p.m.
Thermal transmittance U:	1.75 W/m^{2}K
Time lag ϕ:	8 h
Decrement factor ψ:	0.4
Sol-air air temperature at time τ $t_{sa\,(\tau)}$:	60.8 °C
Sol-air temperature at time $\tau-\phi$ $t_{sa\,(\tau-\phi)}$:	25.6 °C
Mean sol-air temperature $t_{sa\,(m)}$:	36.4 °C
Indoor daily mean air temperature $t_{i\,(m)}$:	26.0 °C
Area of the surface S:	10 m^2

Solution

Step 1 – Steady state heat flux Qm calculation

First of all, we have to calculate Qm, the average heat flow on a daily basis, using the mean external air temperature and the mean internal air temperature.

$$Q_m = 1.75 \cdot 10 \cdot (36.4 - 26) = 182\,W \qquad \text{(A.3-18)}$$

Step 2 – Non-steady state heat flux calculation

In order to evaluate the instantaneous heat flow through a wall in non steady state conditions, the decrement factor and the time-lagged temperature ($\tau-\phi$) must be taken into account using the following.

$$Q_{(\tau)} = 182 + 0.40 \cdot 1.75 \cdot 10 \cdot (25.6 - 36.4) = 106.4\,W \qquad \text{(A.3-19)}$$

1.12 CALCULATION OF SURFACE TEMPERATURE AND VERIFICATION OF CONDENSATION

Calculate the temperature of tilted surface of "aluminium, oxidized" (ref. Table A.1-3) and verify if condensation occurs.

Data

Location:	Mombasa
Date:	March (typical day)
Bioclimatic zone:	Hot-humid
Hour of the day τ:	5 a.m.
Wind speed on surface:	0.2 m/s

Ground temperature t_g: 25.0 °C
Outdoor air temperature t_o: 25.4 °C
Relative humidity RH: 91 %
Longwave emissivity ε: 0.11
Area of the surface S: 10 m²
Tilt angle of the surface ψ: 20 °C
Sky conditions: Clear sky

Solution

Step 1 – Calculate the absolute temperature of the sky T_{sky}

To calculate surface temperature during the night, longwave emission towards the sky must be taken into account and, first of all, the absolute temperature of the sky vault must be determined using the following formula.

$$T_{sky} = 0.0553 \cdot (25.4 + 273.15)^{1.5} = 285.3\ K \quad \text{(A.3-20)}$$

Step 2 – Calculate the view factor coefficients of the surface F_s and F_g.

Assuming that the tilt angle of the surface is equal to 20°, we have to determine the view factors F_s and F_g.

$$F_s = \frac{1 + cos(20)}{2} = 0.97 \quad \text{(A.3-21)}$$

$$F_g = 1 - 0.97 = 0.03 \quad \text{(A.3-22)}$$

Step 3 – Calculate the convection coefficient h_c as a function of wind speed

The convection coefficient can be calculated using the following empirical correlations (see note 2 in Appendix 1).

$$h_c = 5.62 + 3.9v \text{ if } v < 5\ m/s \quad \text{(A.3-23)}$$

$$h_c = 7.2v^{0.78} \text{ if } v > 5\ m/s \quad \text{(A.3-24)}$$

In this case:

$$h_c = 5.62 + 3.9 \cdot 0.2 = 6.4\ W/m^2K \quad \text{(A.3-25)}$$

Step 4 – Calculate the absolute temperature of the surface T_s

In equilibrium conditions, the heat exchanged by radiation can be supposed equal to the heat flux transmitted by convection, as follows.

$$Q_{rs} + Q_r = \sigma\varepsilon\left[F_s\left(T_s^4 - T_{sky}^4\right) + F_g\left(T_s^4 - T_g^4\right)\right]S + h_c \cdot S \cdot (T_S - T_o) = 0 \quad \text{(A.3-26)}$$

The 4th order equation can be solved graphically or numerically.

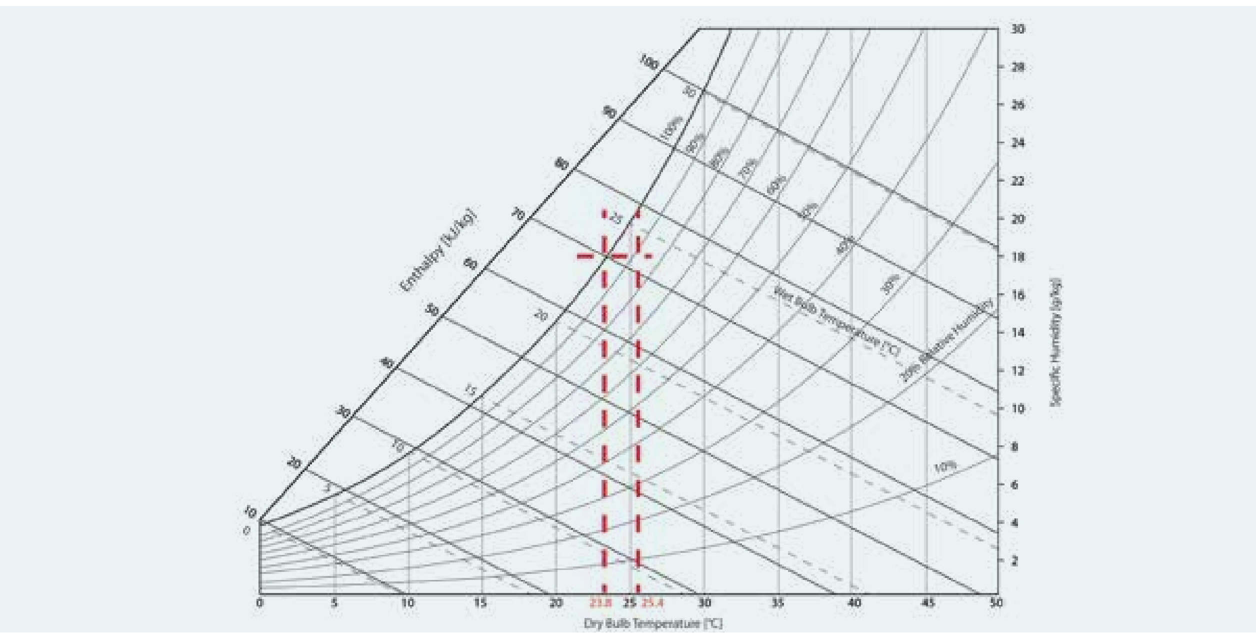
$$5.7 \cdot 10^{-8} \cdot 10\left[0.11 \cdot \left(0.97(T_s^4 - 285.3^4) + 0.03(T_s^4 - 298.2^4)\right)\right] + 6.4 \cdot 10 \cdot (T_s - 298.6) = 0 \quad \text{(A.3-27)}$$

$$T_S = 297.4\ K = 24.3\ °C \quad \text{(A.3-28)}$$

Step 5 – Verify if condensation occurs

On the psychrometric chart, draw the point corresponding to the outdoor environmental condition, by intersecting the 25.4 °C dry bulb temperature line (variation of temperature, sensible heat exchange) and the 91% relative humidity curve. Then, draw a horizontal line in order to intersect the saturation curve (100% relative humidity curve) and read the corresponding dry bulb temperature (dew-point temperature).

FIGURE A.3-1 **PSYCHROMETRIC CHART**



Dew-point temperature is equal to 23.8 °C. With an oxidized aluminium sheet, under these conditions, condensation will not occur, because the temperature of the surface is 24.3 °C as calculated in the previous step. The temperature, however, is very near to the dew point and so, if internal vapour production occurs and, consequently, the internal relative humidity increases, condensation on the internal surface can take place, because the temperature on the internal side of the surface (in condition of equilibrium) is equal to the temperature on the external side.

Repeat the calculation with another location, using the following data and assuming a cloudy sky

Data

Location:	Marsabit
Date:	March (typical day)
Bioclimatic zone:	Hot-arid
Hour of the day τ:	5 a.m.
Wind speed on surface:	6.9 m/s
Ground temperature t_g:	18.0 °C
Outdoor air temperature t_o:	19.4 °C
Relative humidity RH:	76 %
Longwave emissivity ε:	0.11
Area of the surface S:	10 m^2
Tilt angle of the surface ψ:	20 °C
Sky conditions:	Completely cloudy (8 octas)

Solution

The value of cloud cover assumed is equal to 8 Octas, correspondent to a completely cloudy sky. The absolute sky temperature T_{sky} is calculated according to the following.

$$T_{sky} = 0.0553 \cdot (19.4 + 273.15)^{1.5} + 2.625 \cdot 0.8 = 297.7\,K \qquad \text{(A.3-29)}$$

The convection coefficient h_c is the following.

$$h_c = 7.2 \cdot (6.9)^{0.78} = 32.5\,W/m^2K \qquad \text{(A.3-30)}$$

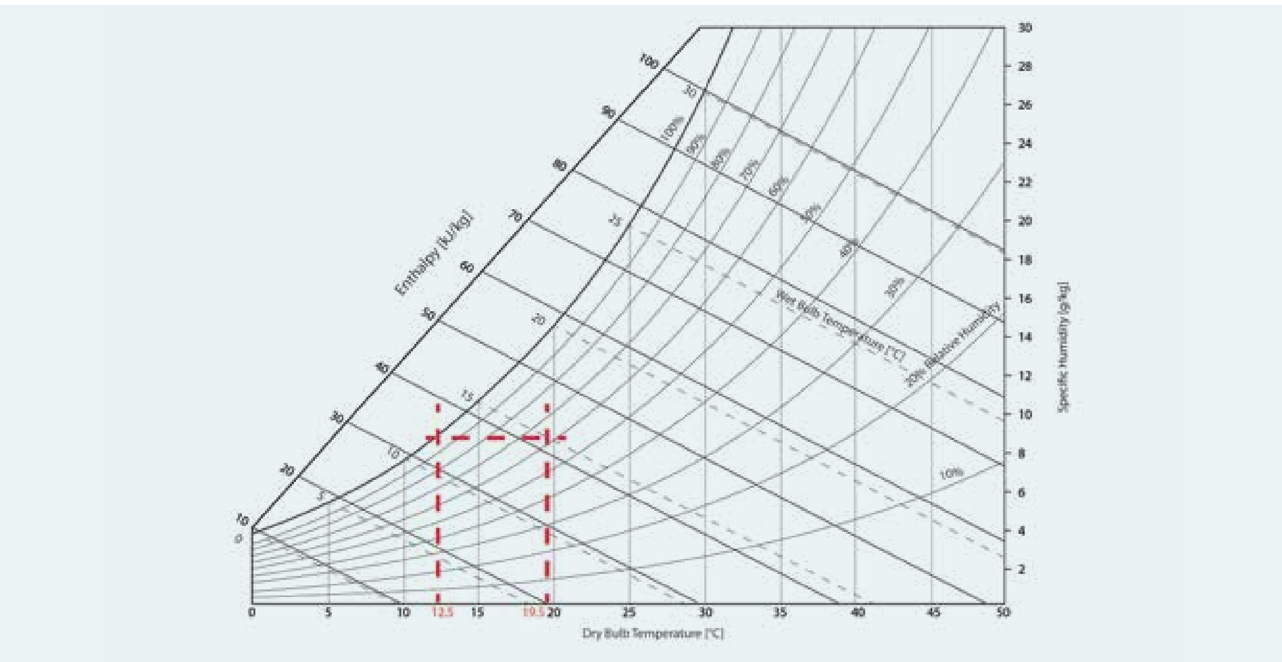
The equilibrium equation becomes the following.

$$5.7 \cdot 10^{-8} \cdot 10\left[0.11 \cdot \left(0.97(T_S^4 - 297.7^4) + 0.03(T_S^4 - 291.2^4)\right)\right] + 6.4 \cdot 10 \cdot (T_s - 292.6) = 0 \qquad \text{(A.3-31)}$$

$$T_S = 292.6\,K = 19.5\,°C \qquad \text{(A.3-32)}$$

In this case also condensation doesn't happen, because the dew-point is approximately at 12.5 °C. We can see from the psychrometric chart that the distance between the temperature of the surface and the dew-point is much larger than in the previous case, because of the much lower specific humidity of the air, typical of conditions in a hot-arid climate.

FIGURE A.3-2 **PSYCHROMETRIC CHART**



1.13 ENERGY BALANCE OF A GLAZED COMPONENT (PAR. 2.2.6 GLASS AND SOLAR RADIATION)

Calculate the instantaneous energy balance of a glazed component.

Data

Solar transmission factor τ:	0.6
External surface heat transfer coefficient h_o:	16.7 W/m²K
Indoor air temperature t_i:	25.0 °C
Outdoor air temperature t_o:	32.0 °C
Thermal transmittance U_{gl}:	2 W/m²K
Absorption coefficient of glass α:	0.1
Solar irradiance incident I_t:	350 W/m²
Area of the glazed component S:	1 m²
SC coefficient:	0.8
SHG of reference glass:	0.87

Solution

The total energy flux through the glass can be calculated as follows.

$$Q_{gl} = \left(0.6 \cdot 350 + \left(\frac{2}{16.7}\right) \cdot 0.1 \cdot 350 + 2 \cdot (32 - 25)\right) = 228.2\ W \quad \text{(A.3-33)}$$

Repeat the same calculation using the methodology of the reference glass.

$$Q_{gl} = ((0.8 \cdot 0.87) \cdot 350 + 2 \cdot (32 - 25)) = 257.6\ W \quad \text{(A.3-34)}$$

1.14 HEAT BALANCE OF A BUILDING (PAR. 3.1 BUILDING ENERGY BALANCE)

Calculate the instantaneous heating or cooling $Q_{m(\tau)}$ flux to be provided to maintain the energy balance of a building at time τ.

Data

Location:	Mombasa
Date:	March (typical day)
Hour of the day τ:	1 p.m.
Net floor area:	100 m²
Net volume:	300 m²
Indoor air temperature $t_{i(\tau)}$:	26 °C
Outdoor air temperature to (τ):	31.6 °C
Sum of the heat flows through the roof, walls and the floor $\Sigma Q_{(\tau)}$:	2100W
Sum of the heat flows through windows $\Sigma Q_{gl(\tau)}$:	3600 W
Ventilation rate V:	0.1 m³/s
Internal heat gains (people, domestic appliances and equipment) $Q_{i(\tau)}$:	800 W

Solution

$$2100 + 3600 + 1200 \cdot 0.1 \cdot (31.6 - 26) + 800 + Q_{m(\tau)} = 0 \quad \text{(A.3-35)}$$

$$Q_{m(\tau)} = -7312\ W \quad \text{(A.3-36)}$$

The sensible heat demand is negative because the building at 1 p.m. requires cooling (heat must be subtracted by the building zone in order to maintain the balance).

2. THERMAL AND VISUAL COMFORT (APPENDIX 2)

The exercises in this paragraph refer to the "Appendix 2 – Principles of thermal and visual comfort", focusing on the calculation of three fundamental quantities, mean radiant temperature, daylight factor and mean daylight factor.

2.1 THERMAL COMFORT – MEAN RADIANT TEMPERATURE (PAR. 1 PRINCIPLES OF THERMAL COMFORT)

Calculate the mean radiant temperature at the barycentre of a room. The temperature is calculated as the weighted average of the temperatures of the different surfaces.

Data

Room dimensions:	5x6.66x2.7 m
Ceiling temperature:	32 °C
Floor temperature:	20 °C
Wall temperature:	24 °C

Solution

$$t_{mr} = \frac{(32 \cdot (5 \cdot 6.66) + 20 \cdot (5 \cdot 6.66) + 24 \cdot (5 \cdot 2.7 \cdot 2) + 24 \cdot (6.66 \cdot 2.7 \cdot 2))}{((5 \cdot 6.66 \cdot 2) + (5 \cdot 2.7 \cdot 2) + (6.66 \cdot 2.7 \cdot 2))} = 25\ °C \quad \text{(A.3-37)}$$

2.2 VISUAL COMFORT – DAYLIGHT FACTOR (PAR 2.2.2.1 DAYLIGHT FACTOR (DF))

Calculate the daylight factor DF with known internal and external illuminance.

Data

External illuminance E_{ext}:	10000 lux
Internal illuminance E_{int}:	650 lux

Solution

$$DF_m = \frac{650}{10000} \cdot 100 = 1.5\ \% \quad \text{(A.3-38)}$$

2.3 VISUAL COMFORT – MEAN DAYLIGHT FACTOR FOR A ROOM (PAR. 2.2.2.2 MEAN DAYLIGHT FACTOR (DF_M)

Calculate the mean daylight factor DF_m with known geometry and physical properties of a room.

Data

Visible transmittance of glazing τvis:	0.8
Sky angle θ:	85°
Net glazing area $A_{glazing}$:	2.86 m^2
Total area of all interior surfaces A_{total}:	129.56 m^2
Mean surface reflectance ρ_m:	0.5

Solution

$$DF_m = \frac{0.8 \cdot 85 \cdot 2.86}{2 \cdot (129.56)(1-0.5)} = 1.5\,\% \qquad (A.3\text{-}39)$$

3. NATURAL VENTILATION (SECTION 3.5 NATURAL VENTILATION; SECTION 3.8 NATURAL COOLING)

The exercises in this paragraph refer to the chapters "3.5 Natural ventilation" and "3.8 Natural cooling" and focus on the step by step procedure to be used in the design of natural ventilation systems in buildings, considering wind driven cross ventilation, indoor air velocity, stack effect and a downdraft evaporative cooling tower.

3.1 CROSS VENTILATION (PAR. 3.5.2.1 SIZING OPENINGS FOR CROSS-VENTILATION)

Determine the appropriate size of openings to obtain an air flow rate equal to 0.8 m^3/s. Initially we assume that the inlet and outlet openings are the same size, then we consider different inlet/outlet sizes.

Data

Location:	Mombasa
Date:	March (typical day)
Hour:	11:00 p.m
Wind speed at the reference height of 10 m:	3.6 m/s
Wind direction:	131°
Location:	downtown
Height of the windows above ground:	18 m
Wind incidence angle:	45°
Design air flow rate:	0.8 m^3/s
Ratio large/small openings:	2

Solution

Step 1 – Calculate the wind speed at the height of the openings

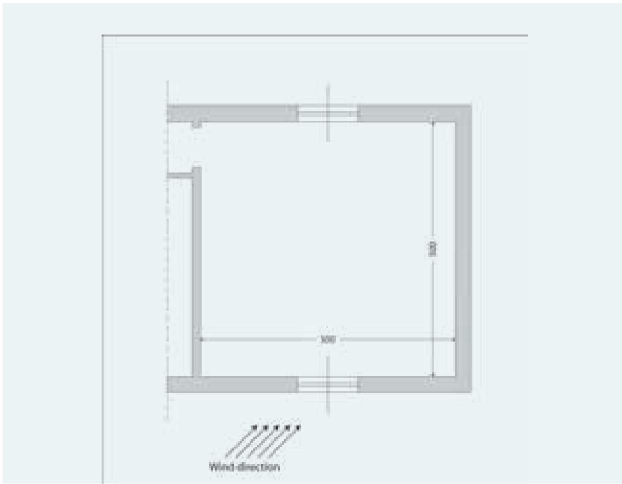
First, we have to calculate the wind speed at the 6th floor (18 m), using the wind speed at the reference height of 10 m and the correction factors given in Table 2.1-5 for downtown, respectively K=0.21 and α=0.33.

$$v_{18} = 0.21 \cdot 18.0^{0.33} \cdot 3.6 = 2.0\ m/s \qquad (A.3\text{-}40)$$

Step 2 – Determine the size of the opening

Now we can determine the net free area of inlet openings, given the design flow rate, assuming that inlet openings are equal to outlet openings.

FIGURE A.3-3 **PLAN OF THE ROOM**

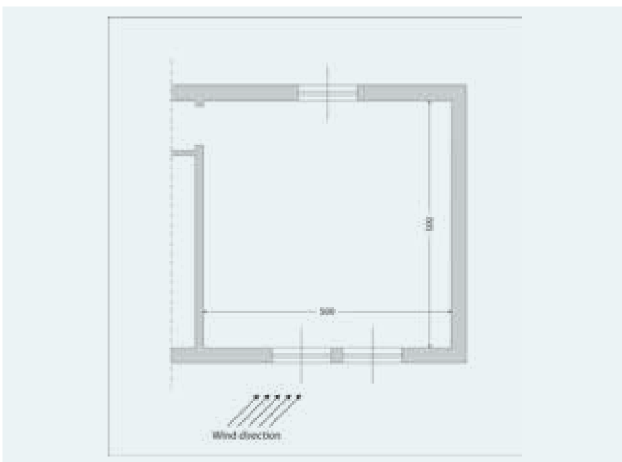


$$A = \frac{0.8}{0.3 \cdot 2.0} = 1.33\ m^2 \qquad (A.3\text{-}41)$$

Step 3 – Determine the effect of a different ratio between inlet and outlet area

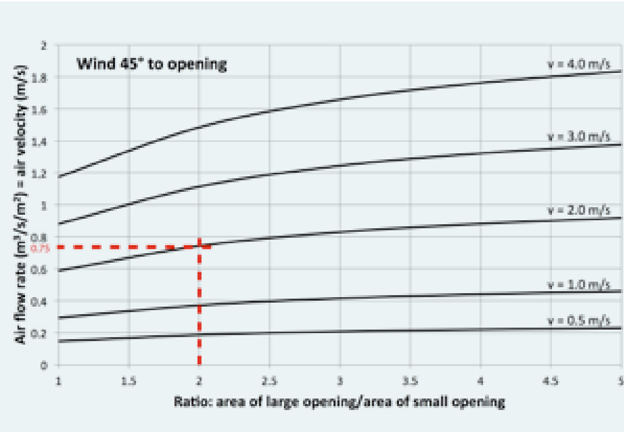
Perform the same calculation assuming that the inlet net area is twice the outlet net area, as shown in the following figure.

FIGURE A.3-4 **PLAN OF THE ROOM**



By using the graph shown below, it is possible to estimate the airflow rate, first tracing a vertical line corresponding to the value of the ratio between inlet and outlet area (assumed equal to 2 on the X-axis). Then, by intersecting the curves corresponding to the wind velocity calculated, the airflow rate per square meter through the smaller opening can be read on the Y-axis.

FIGURE A.3-5 **AIR FLOW RATE PER SQUARE METER THROUGH THE SMALLER OPENING (OR AIR VELOCITY IN M/S) EXAMPLE – WIND INCIDENT AT 45°**



The desired total airflow rate (0.8 m³/s) must be divided by values that can be read on the Y-axis in order to obtain the outlet opening area needed (that corresponds to the "smaller" area). In this case we have the following.

$$A_{outlet} = \frac{0.8}{0.75} = 1.07\ m^2 \quad \text{(A.3-42)}$$

$$A_{inlet} = 1.07 \cdot 2 = 2.13\ m^2 \quad \text{(A.3-43)}$$

The total gross area depends on the type of openings chosen, as will be illustrated in the next exercise.

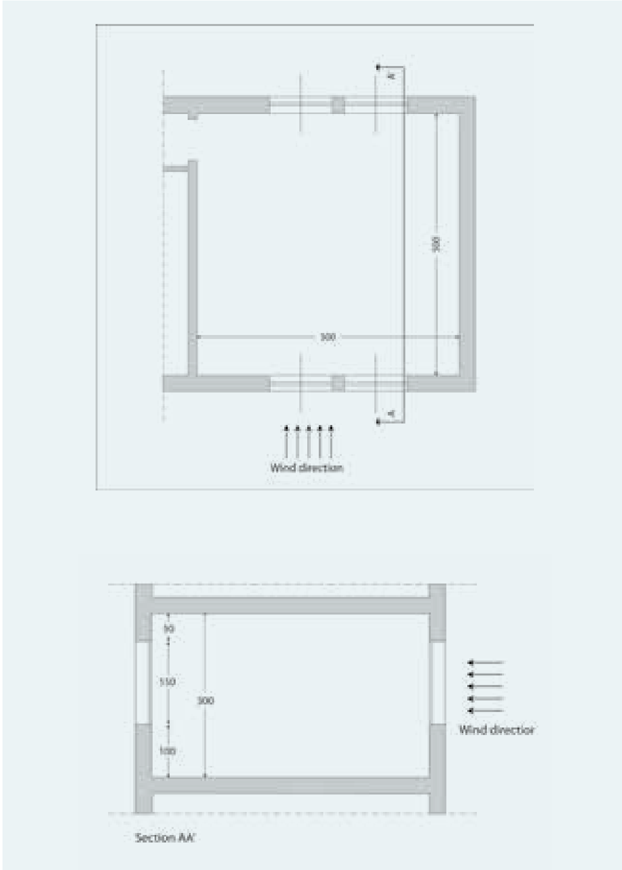
3.2 INDOOR AIR VELOCITY (PAR. 3.5.2.2 INDOOR AIR VELOCITY)

Determine the indoor air velocity, using two different types of windows and considering the presence of a fly screen.

Data

Location:	Mombasa
Date:	March (typical day)
Hour:	11:00 p.m
Wind speed at the reference height of 10 m:	3.6 m/s
Wind direction:	131°
Wind incidence angle:	0°
Location:	downtown
Height of the windows above ground:	18 m
Openings gross area:	3 m²
Window type:	"Jalousie" and "Horizontal sliding"

FIGURE A.3-6 **PLAN AND SECTION OF THE ROOM**



Solution

Step 1 – Calculate the ratio between opening area and wall

First, we have to calculate the ratio between the gross area of the opening and the wall area.

$$\frac{Opening\ area}{Wall\ area} = \frac{1.2 \cdot 1.5 \cdot 2}{5 \cdot 3} = \frac{3.6}{15} = 0.24 \quad \text{(A.3-44)}$$

Step 2 – Calculate the ratio between inlet and total opening area

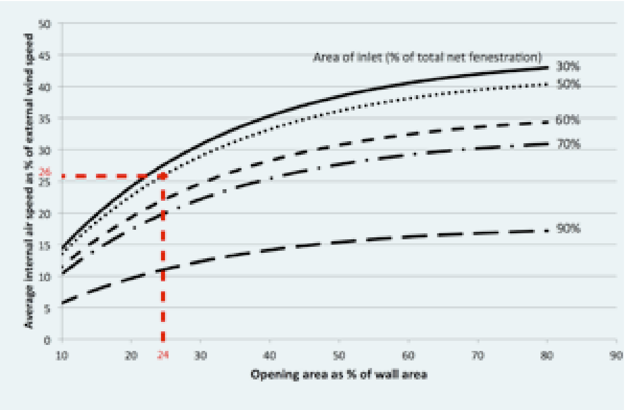
After that, we have to calculate the ratio between the inlet opening area and the total opening area.

$$\frac{Inlet\ area}{Total\ opening\ area} = \frac{1.2 \cdot 1.5 \cdot 2}{1.2 \cdot 1.5 \cdot 4} = 0.5 \quad \text{(A.3-45)}$$

Step 3 – Get average indoor air velocity from the graph

Trace on the X-axis of the following graph the ratio calculated in Step 1, as shown by the vertical red dashed line. Then, read on the Y-axis the value corresponding to the intersection between the vertical red line and the curve, which corresponds to the correct value of the ratio between inlet and total opening area calculated at Step 2. The value found on the graph is approximately 26%.

FIGURE A.3-7 **AVERAGE INTERNAL AIR SPEED FOR CROSS VENTILATION**



Now we can calculate the indoor air speed as a function of the wind speed by multiplying it by the percentage you have just read in the graph and by the permeability coefficient according to the window types indicated below.

$$v_{18} = 0.21 \cdot 18.0^{0.33} \cdot 3.6 = 2.0\ m/s \qquad \text{(A.3-46)}$$

$$\text{"Jalousie" } indoor\ air\ velocity\ = 2 \cdot 0.26 \cdot 0.75 = 0.39\ m/s \qquad \text{(A.3-47)}$$

$$\text{"Horizontal sliding" } indoor\ air\ velocity\ = 2 \cdot 0.26 \cdot 0.45 = 0.23\ m/s \qquad \text{(A.3-48)}$$

Step 4 – Calculate the indoor air velocity reduction considering the effect of a flyscreen

Indoor air velocity reduction can be derived graphically. Remember that in this case wind direction is perpendicular to the window (normal incidence).

$$\text{"Jalousie" } indoor\ air\ velocity\ = 0.39 \cdot (1 - 0.28) = 0.28\ m/s \qquad \text{(A.3-49)}$$

$$\text{"Horizontal sliding" } indoor\ air\ velocity\ = 0.23 \cdot (1 - 0.28) = 0.17\ m/s \qquad \text{(A.3-50)}$$

With a similar methodology we can easily calculate the dependence of average indoor air velocity on window location and the effect of other kind of elements such as louvers and verandas, using the factors given in Table 3.5-1, Table 3.5-2 and Table 3.5-3.

FIGURE A.3-8 **DIFFERENT WINDOW TYPES**

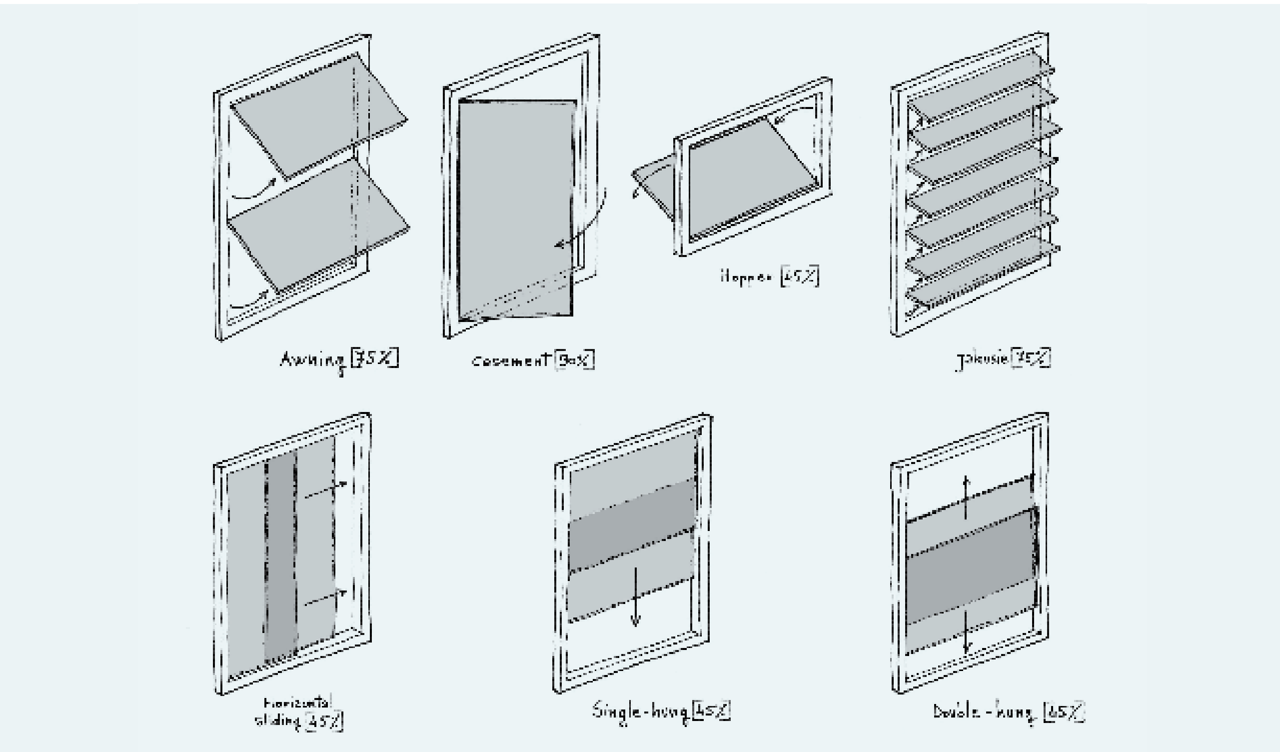
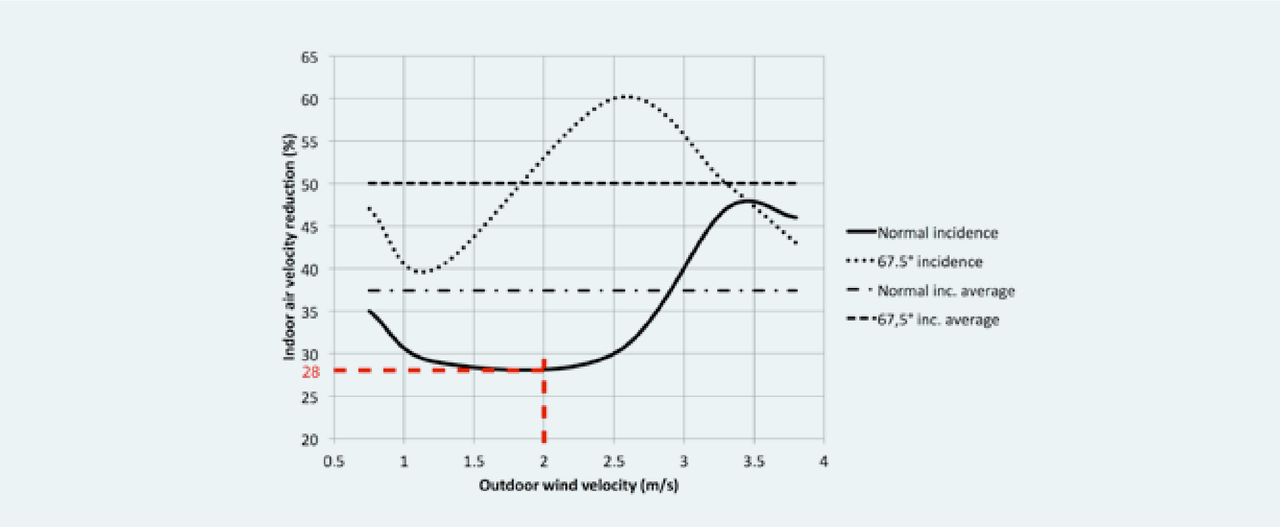


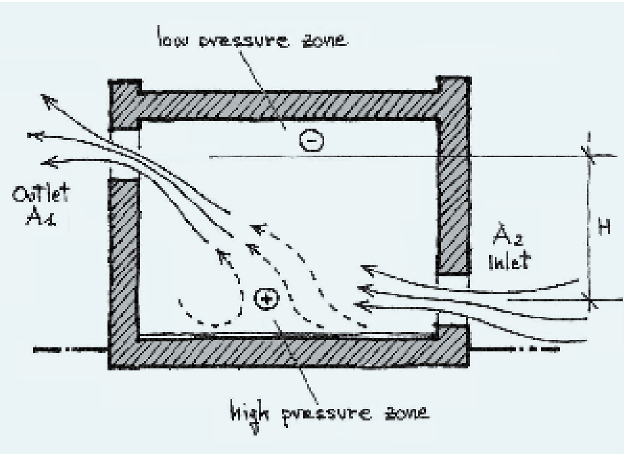
FIGURE A.3-9 **REDUCTION OF WIND VELOCITIES**



3.3 STACK EFFECT (PAR. 3.5.3 STACK EFFECT)

Calculate the air flow rate V due to stack effect in the room shown in the picture, assuming data given below.

FIGURE A.3-10 **STACK EFFECT EXAMPLE**



Data

Height difference H:	2.5 m
Outlet opening area A_1:	1.6 m^2
Inlet opening area A_2:	0.8 m^2
Outdoor air temperature t_o:	25 °C
Indoor air temperature t_i:	29 °C

Solution

Step 1 – Calculate the stack effect given temperature conditions and geometry (inlet area=outlet area)

First, we calculate the stack-effect that we can obtain with 0.8 m^2 of inlet opening area A (assuming the smaller opening area).

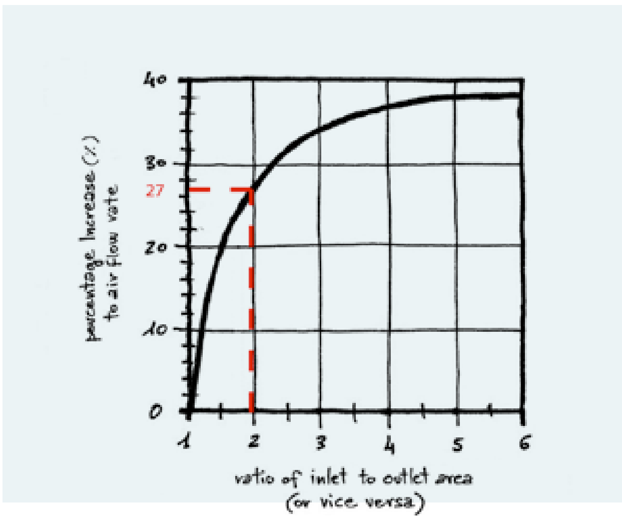
$$V = 2.88A\sqrt{H\frac{T_i - T_o}{T_i}} = 2.88 \times 0.8 \times \sqrt{2.5\frac{4}{29+273}} = 0{,}42\ m^3/s$$

(A.3-51)

Step 2 – Correct the air flow rate considering the ratio between inlet and outlet area

In this case the ratio is equal to 2 (X axis value), so we can look at the intersection between the dotted vertical red line and determine the percentage of increase by reading it on the Y axis.

FIGURE A.3-11 **INCREASE IN STACK FLOW RATE DUE TO DIFFERENTIAL OPENING SIZES**



$$V = 0.42 \cdot (1 + 0.27) = 0.53\ m^3/s \qquad \text{(A.3-52)}$$

3.4 COOLING TOWER SIZING (PAR. 3.8.1 EVAPORATIVE COOLING)

Calculate outlet air temperature and air flow rate V provided by a cooling tower such as the one described in Paragraph 3.8.1 “Evaporative cooling” assuming the following data.

Data

Design outdoor dry bulb temperature: 33 °C
Design outdoor relative humidity: 25 %
Air flow relative humidity coming out from the cooling tower: 70%
Outlet room opening area: 1 m^2
Inlet opening area: 1 m^2
Distance between the centre of the pad and the centre of the outlet: 2.5 m
Temperature difference between internal air and the outlet air from the cooling tower: 2 °C

Solution

Step 1 – Calculate the potential of evaporative cooling using the psychrometric chart

Outlet temperature in the tower will be evaluated by moving from design dry bulb temperature and relative humidity along the corresponding enthalpy line (adiabatic saturation), until intersection of the 70% relative humidity curve occurs. Outlet air temperature will be equal to the dry bulb temperature value that can be read corresponding to this intersection (23 °C).

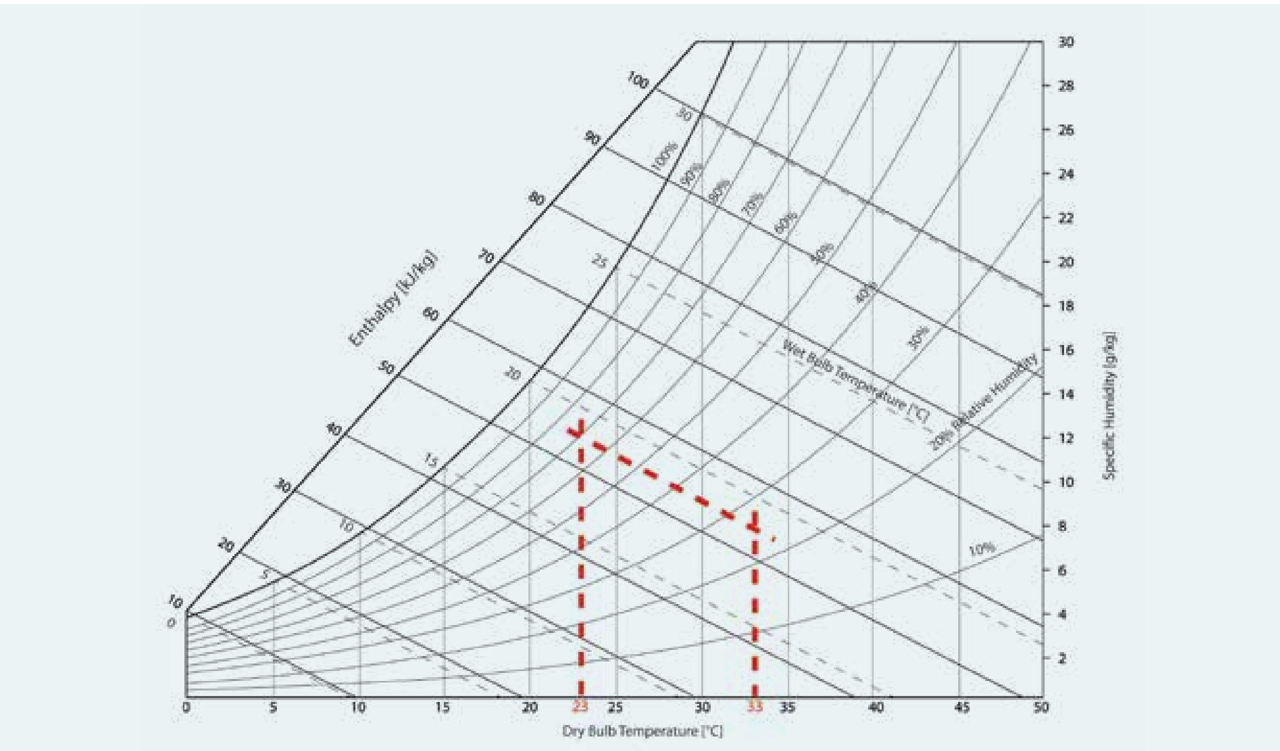
Step 2 – Calculate the stack effect for the downdraft evaporative cooling tower

The calculation of the stack effect of the downdraft evaporative cooling tower should be performed in an iterative way, determining the internal temperature of the building, based on thermal heat balance. In this case we can calculate the effect assuming a temperature difference of 2 °C and a height difference of 3.0 m.

$$V = 2.88A\sqrt{H\frac{T_i - T_o}{T_i}} = 2.88 \times 1.0 \times \sqrt{3.0\frac{10}{33 + 273}} = 0{,}92\ m^3/s \quad \text{(A.3-53)}$$

Because of the cold air flow, indoor temperature will diminish, and the heat flow input from the envelope will increase. A new value of temperature will derive, and the cold air flow has to be recalculated according to this new temperature. The calculation has to be repeated until the heat input through the envelope equals the heat removed by the cool air flow from the cooling tower.

FIGURE A.3-12 **PSYCHROMETRIC CHART**



4. DAYLIGHTING (SECTION 3.6)

The exercises in this paragraph refer to chapter "3.6 Daylighting" focusing on the methodology for the appropriate sizing of windows for daylighting purposes at the earliest stages of the design process.

4.1 SIZING OF A WINDOW AND ROOM FOR DAYLIGHTING MAXIMIZATION

Determine the appropriate sizing of a window to exploit daylighting in a room of a 2 storey building (building 1) with another building in front (building 2). The room considered is on the second floor. The sky angle, the no skyline depth and the limiting depth, calculated in this exercise, are represented respectively in Fig. 3.6-3, Fig. 3.6-4 and Fig. 3.6-5.

Data

Depth of the glazed surface with respect to the façade y':	30 cm
Distance from the building in front of the window d:	7 m
Height of the building 1 (2 storey):	6 m
Height of the building 2:	8 m
Height of the glazed surface (2x):	1.5 m
Distance from the ground of the inferior limit of the glazed surface:	4 m
Window head height Y:	2.5 m
Internal room height:	2.7 m
Width of the room l:	5.0 m
Height of the working plane:	90 cm
Visible transmittance of glass τ_{vis}:	0.65
Average reflectance of surfaces ρ_m:	0.5

Solution

Step 1 – Calculate the effective sky angle θ

First, we have to determine the distance between the centre of the glazed surface and the top of the building 2.

$$y = 8 - (4.00 + 0.75) = 3.25\ m \tag{A.3-54}$$

Then, we calculate the effective sky angle θ, knowing the basic geometric data of our building.

$$\theta = 90 - arctan\left(\frac{30 \cdot 10^{-2}}{0.75}\right) - arctan\left(\frac{3.25}{7}\right) = 43.3° \tag{A.3-55}$$

Step 2 - Determine the value of mean daylight factor (DF_m)

According to the suggestions given in Chapter 5.3, a reasonable first guess for the mean daylight factor (DF_m) value is 1.5%

Step 3 – Calculate the window to wall ratio (WWR) required

We set our desired mean daylight factor DF_m to 1.5 % as seen in the previous step. Given the sky angle θ calculated in the first step and the visible transmittance of the selected glass, we determine our window to wall ratio (WWR).

$$WWR = \frac{0.088 \cdot 1.5}{0.65} \cdot \frac{90}{43.3} = 0.42 \tag{A.3-56}$$

Step 4 – Calculate the maximum depth of the room and the surfaces reflectance required

We can proceed with step 4 and calculate the maximum depth of our room for the exploitation of daylighting, assuming an average reflectance of surfaces ρ_m. We have to determine the maximum depth for daylight exploitation as the minimum value among the following ones.

$$Maximum\ depth = \min\begin{pmatrix} Limiting\ depth = \dfrac{2/(1-\rho_m)}{1/l + 1/h} \\ No\ skyline\ depth = h' \cdot tan(\alpha) \\ Penetration\ depth\ (no\ shading) = 2.5h \\ Penetration\ depth\ (shading) = 2.0h \end{pmatrix} \tag{A.3-57}$$

We can calculate the limiting depth as follows.

$$Limiting\ depth = \frac{\frac{2}{(1-0.5)}}{\left(\frac{1}{5} + \frac{1}{2.5}\right)} = 6.67\ m \tag{A.3-58}$$

After that, we have to calculate the No skyline angle α and, subsequently the No skyline depth.

$$No\ skyline\ angle\ \alpha = \arctan\left(\frac{(8-6)+(3-2.5)}{7}\right) = 70.3° \tag{A.3-59}$$

$$No\ skyline\ depth = (2.5 - 0.9) \cdot \tan(70.3) = 4.48\ m \tag{A.3-60}$$

Finally we have to consider the penetration depth with and without shading, respectively equal to 2 Y and 2.5 Y. We can determine the maximum depth for the exploitation of the daylighting as the minimum of the quantities calculated in the previous passages.

$$Maximum\ depth = \min(6.67, 4.48, 6.25, 5) = 4.48\ m \tag{A.3-61}$$

Step 5 – Determine the required glazed area.

Finally, we can calculate the area of the glazing system Aglazing given the room dimensions of 5x4.48x2.7 m and the parameters hypothesized.

$$A_{glazing} = \frac{1.5 \cdot 2 \cdot 96 \cdot (1-0.5)}{0.65 \cdot 43.3} = 5.1\ m^2 \tag{A.3-62}$$

Given the height of the glazing system of 1.5 m, used in the initial step, the width of the glazing can be calculated as follows (verifying its width with respect to the width of the room).

$$A_{glazing} = \frac{5.1}{1.5} = 3.4\ m \qquad \text{(A.3-63)}$$

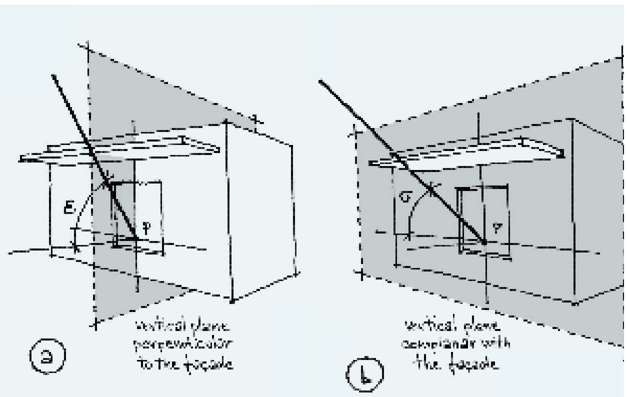
5. SHADING SYSTEMS (SECTION 3.7 SHADING)

The exercises in this paragraph refer to chapter "3.7 Shading" focusing on the methodology for designing horizontal and vertical shading systems and calculating the shadow cast by them in specific conditions.

5.1 SHADING MASK FOR HORIZONTAL OVERHANG (PAR. 3.7.2 SHADING MASKS)

Draw the shading mask for a horizontal overhang for the window shown in the figure, using the data provided. Compare results by orienting the window both to South and West.

FIGURE A.3-13 **SHADING MASK EXAMPLE**



Data

Angle of the horizontal overhang with vertical plan perpendicular to façade ε: 60°

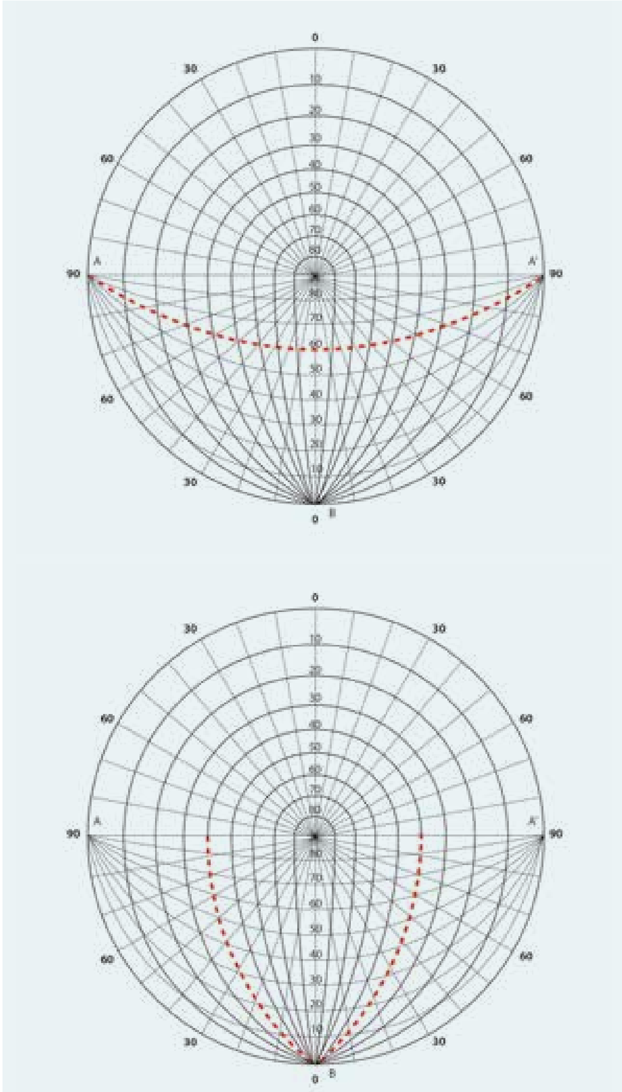
Angle of the horizontal overhang with vertical plan complanar to façade σ: 40°

Latitude: 3°N

Solution

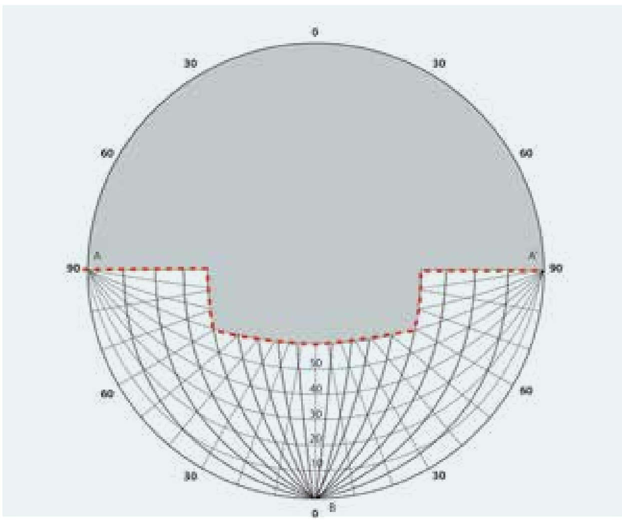
Step 1 – Trace obstruction angle on the solar protractor (ε on the left figure and σ on the right one)

FIGURE A.3-14 **SHADING MASK CONSTRUCTION**



Step 2 – Highlight the region enclosed by the obstruction and the side hidden by the rest of the building

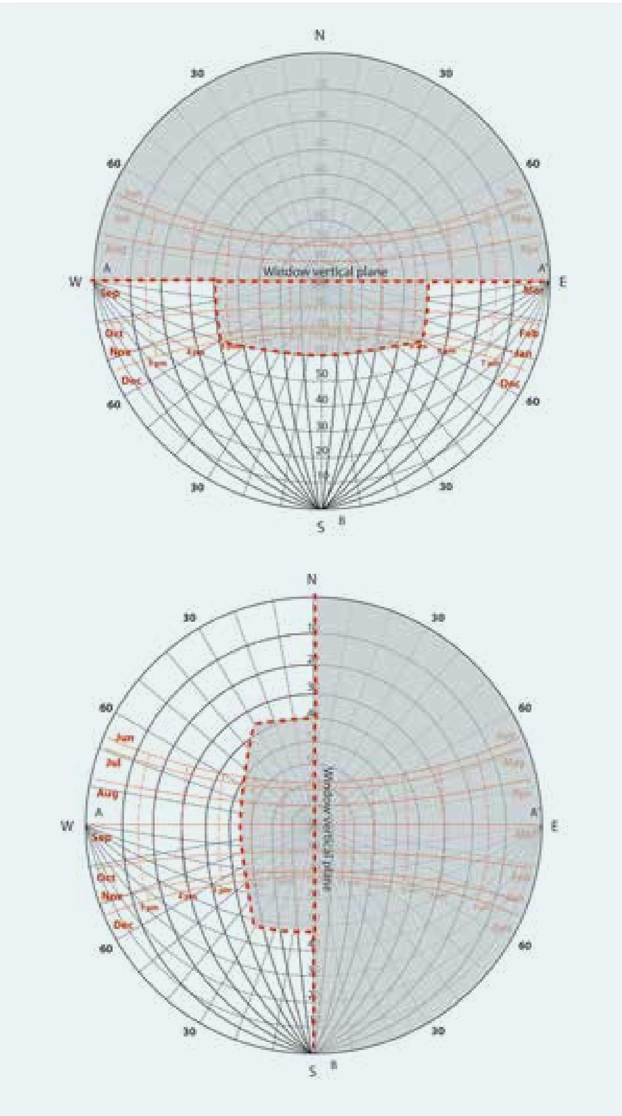
FIGURE A.3-15 **SHADING MASK CONSTRUCTION**



Step 3 – Overlap the grey area to the polar sun path diagram, rotating the axis corresponding to the vertical plane of the window in the correct way

The figure on the top represents the case in which the window is supposed to face South, while the one at the bottom is facing West. In both cases, the hidden parts of the sun paths are the ones corresponding to the periods in which the window is shaded by the overhang and by the rest of the building.

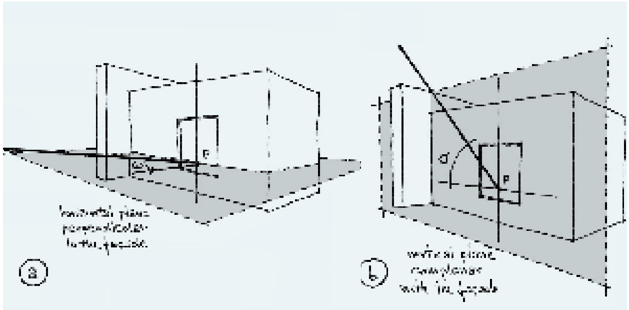
FIGURE A.3-16 **OVERLAYING THE SHADING MASKS ON THE POLAR DIAGRAM**



5.2 SHADING MASK FOR VERTICAL FIN (PAR. 3.7.2 SHADING MASKS)

Draw the shading mask for a vertical fin for the window shown in the figure, using the data provided.

FIGURE A.3-17 **SHADING MASK EXAMPLE**



Data

Angle of the vertical fin on the horizontal plane perpendicular to façade ω: 70°

Angle of the vertical fin with vertical plane complanar to the façade σ: 60°

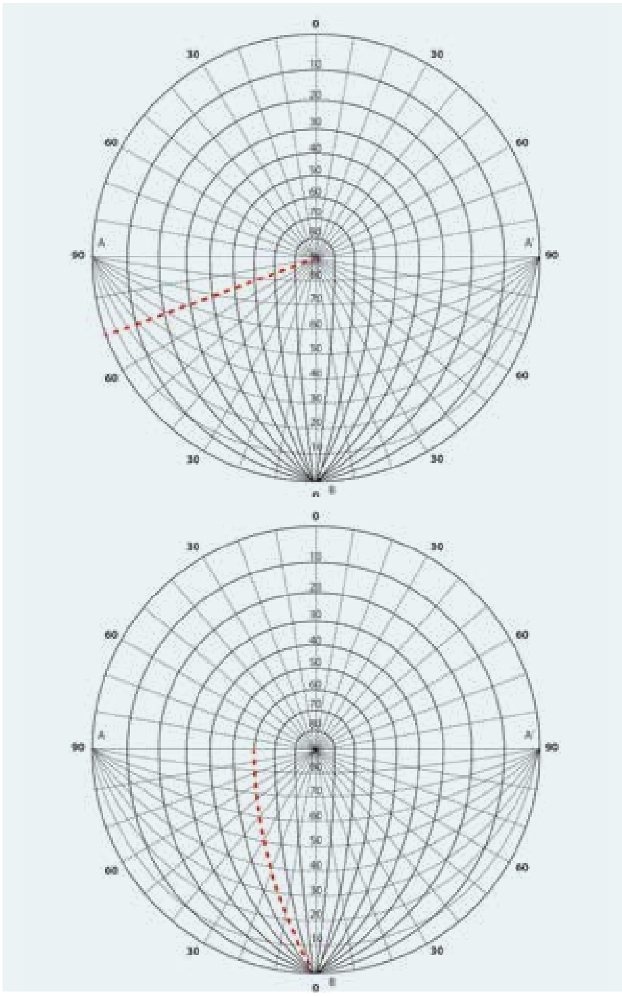
Window orientation: South

Latitude: 0°

Solution

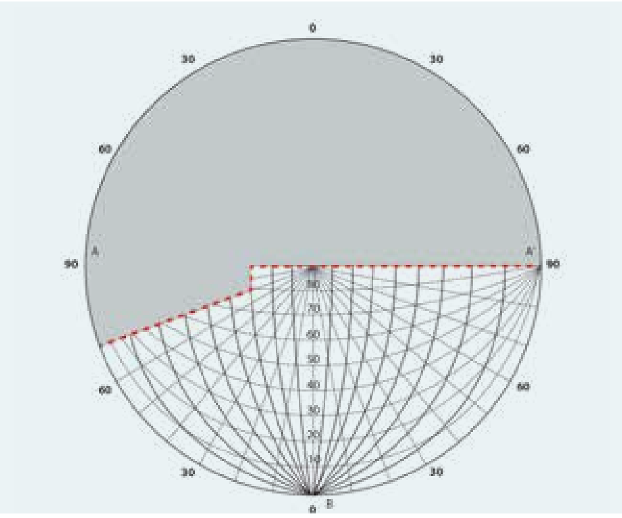
Step 1 – Trace obstruction angle on the solar protractor (ω on the top figure and σ on the bottom one).

FIGURE A.3-18 **SHADING MASK CONSTRUCTION**



Step 2 – Highlight the region enclosed by the obstruction and the side hidden by the rest of the building.

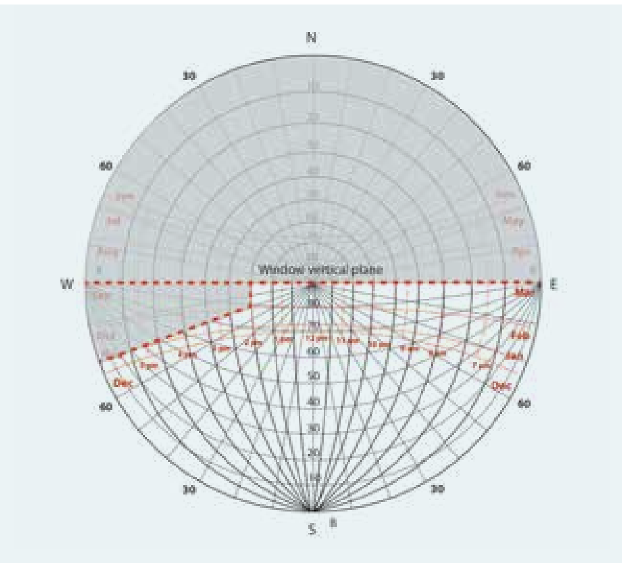
FIGURE A.3-19 **SHADING MASK CONSTRUCTION**



Step 3 – Overlap the grey area to the polar sun path diagram, rotating the axis corresponding to the vertical plane of the window in the correct way.

The hidden parts of the sun paths are the ones corresponding to the periods in which the window is shaded.

FIGURE A.3-20 **OVERLAYING THE SHADING MASKS ON THE POLAR DIAGRAM**



5.3 OVERHANG SHADING CALCULATION - HORIZONTAL (PAR. 3.7.3. OVERHANG SHADING CALCULATION)

Calculate the effect of a horizontal shading system for a south facing window.

Data

Location:	Nairobi
Date:	December (typical day)
Hour:	3:00 p.m
Latitude:	1.28° S
Longitude:	36.81° E
Window width w:	4.6 m
Window height h:	1.5 m
Window azimuth γ:	0°
Overhang depth D:	0.5 m

Solution

Step 1 – Determine the sun height β and solar azimuth α at 3:00 pm in the month of December in Nairobi

For this task, it is possible to use the solar chart for latitude 1° S. We can read the values of the sun height angle (β = 40°) and of the solar azimuth (α = -60°).

Step 2 – Calculate the height of the shadow cast

We can calculate the height of the shadow cast on the window h with a horizontal overhang using the geometric data.

$$h = \frac{0.5 \cdot tan(40)}{cos(-60-0)} = 0.8\,m \qquad \text{(A.3-64)}$$

6.4 OVERHANG SHADING CALCULATION - VERTICAL (PAR. 3.7.3. OVERHANG SHADING CALCULATION)

We can calculate the width w of the shadow cast by a vertical shading with a depth D of 1 m, in the same conditions considered for the previous exercises.

Solution

$$w = 1 \cdot |tan(-60-0)| = 1.7\,m \qquad \text{(A.3-65)}$$

6. ARTIFICIAL LIGHTING (SECTION 4.2 BUILDING SERVICES)

The exercises in this paragraph refer to paragraph "4.2.4 Artificial lighting" focusing on the methodology for the design of artificial lighting systems using the nomogram in Fig. 4.2-49.

6.1 SIZING OF A ARTIFICIAL LIGHTING SYSTEM

Calculate the number of luminaires to be installed using the nomogram and the following data.

Data

Room length:	10 m
Room width:	5 m
Room height:	4 m
Ceiling reflectance coefficient:	0.7
Walls reflectance coefficient:	0.5
Average illuminance level E_m:	300 lux
Luminous flux for each luminaire:	9000 lumen
Height of the working plane:	80 cm

Solution

Step 1 – Calculate the room index i

Calculate the room index i to characterize the room from the geometric point of view, using the dimensions of the room.

$$i = \frac{10 \cdot 5}{(4 - 0.8)(10 + 5)} = 1 \qquad \text{(A.3-66)}$$

Step 2 – Calculate the utilization factor

The utilization factor u can be found using the following figure and knowing the characteristics of the internal finishing (ceiling and walls) described above. Thus, u is equal to 0.37.

Step 3 – Use of the nomogram

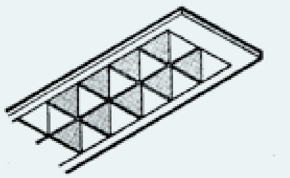
First, the classroom dimensions have to be marked on Scale 1 (length = 10 m) and Scale 2 (width = 5 m). The extension of the line connecting the two points intersects Scale 3 at a point that represents the area of the working plan (equal to 50 m²).

The point on Scale 3 has to be connected to the point on Scale 4 where the required illuminance Em is specified (300 lux). The extension of this line reaches Scale 5 finding the incident flux on the working plan (15.000 lumen). The total flux can be also calculated analytically as follows.

$$\varphi_u = 300 \cdot 50 = 15000 \; lm \qquad \text{(A.3-67)}$$

The total flux can be found by connecting the point on Scale 5 to the utilization factor u found in the previous figure (0.37) and marked in Scale 8, and by extending the line to intersect Scale 9. In Scale 9, we can identify the total flux of 54.000 lumen. By connecting the total flux to the luminous flux of every luminaire (9000 lumen) in Scale 11, we can determine the total number of luminaires required, equal to 6, from Scale 10. The overall graphical procedure is reported in the following figure (nomogram) with a dashed red line.

FIGURE A.3-21 **UTILISATION FACTOR**

Description of Luminaire, and Typical Downward Light Output Ratio %	*Typical Outline*	*Basic DLOR*	*Ceiling*	*Reflectance % 70*			*50*			*30*		
			Walls	*50*	*30*	*10*	*50*	*30*	*10*	*50*	*30*	*10*
		%	*Room Index*									
(F) Recessed louvered trough with optically designed reflecting surfaces (50)		50	0·6	0·28	0·25	0·23	0·28	0·25	0·23	0·28	0·25	0·23
			0·8	0·34	0·31	0·28	0·33	0·3	0·28	0·33	0·3	0·28
			1	0·37	0·35	0·32	0·37	0·34	0·32	0·37	0·34	0·32
			1·25	0·4	0·38	0·35	0·4	0·37	0·35	0·4	0·37	0·35
			1·5	0·43	0·41	0·38	0·42	0·4	0·38	0·42	0·39	0·38
			2	0·46	0·44	0·42	0·45	0·43	0·41	0·44	0·42	0·41
			2·5	0·48	0·46	0·44	0·47	0·45	0·43	0·46	0·44	0·43
			3	0·49	0·47	0·46	0·48	0·46	0·45	0·47	0·45	0·44
			4	0·5	0·49	0·48	0·49	0·48	0·47	0·48	0·47	0·46
			5	0·51	0·5	0·49	0·5	0·49	0·48	0·49	0·48	0·47

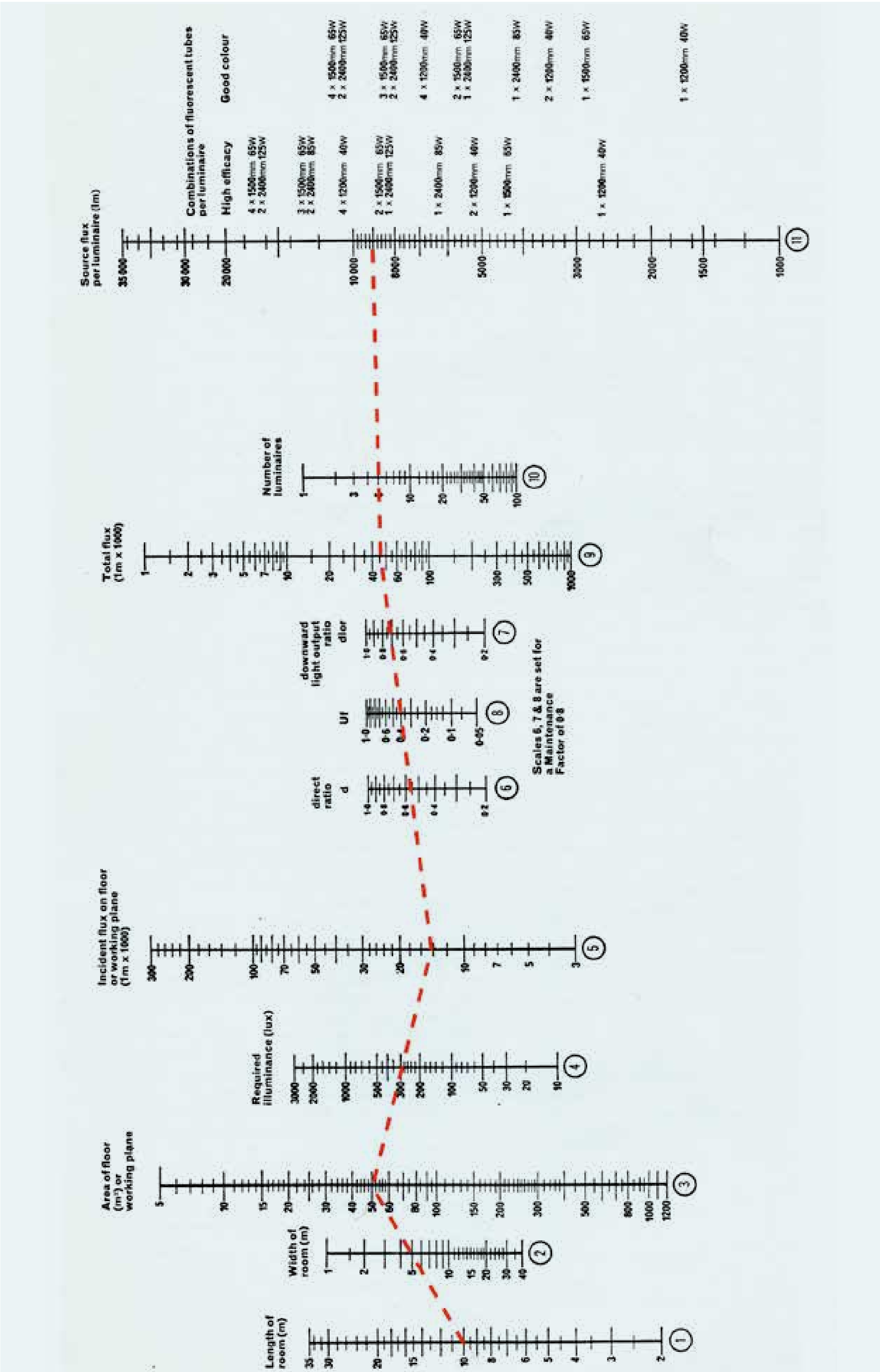


FIGURE A.3-22 **NOMOGRAM FOR DETERMINING NUMBER AND POWER OF LUMINAIRES**

We can verify the result also with an analytical calculation, selecting a depreciation factor d of 1.3, corresponding to direct illumination.

$$\varphi_u = \frac{300 \cdot 50}{0.37} \cdot 1.3 = 52703\ lm \qquad (A.3\text{-}68)$$

$$Number\ of\ luminaires = \frac{52703}{9000} = 5.9 \qquad (A.3\text{-}69)$$

7. RAINWATER STORAGE (SECTION 5.2 WATER AND SANITATION)

The exercise in this paragraph refers to the chapter "5.2 Water and sanitation", focusing on the methodology for the design of a storage system for rainwater, using specific site and end-user's conditions.

7.1 SIZING OF A RAINWATER STORAGE SYSTEM

Calculate the necessary storage volume for a rainwater system of a detached dwelling.

Data

City:	Dar es Salam
Number of users:	4
Roof collecting area A_c:	120 m²
Surface of garden A_w:	10 m²
Yield coefficients e:	0.8
Hydraulic filter efficiency η:	0.9
Water for toilets P_d:	24 l/(person day)
Watering garden:	2 l/m²day
Low consumption washing machine W_m:	60 l/wash
Washing machine uses:	12/month
Water for car washing:	300 l/wash
Car washes:	1/month

Solution

Step 1 – Calculate the monthly rainwater yield

We report the monthly rainwater yield, W_{ry}, for Dar es Salaam in the following table.

Month	h_n [l/m²month]	W_{ry} [l/month]
January	70	6804.0
February	49	4762.8
March	120	11664.0
April	229	22258.8
May	153	14871.6
June	40	3888.0
July	26	2527.2
August	23	2235.6
September	25	2430.0
October	49	4762.8
November	106	10303.2
December	114	11080.8

Step 2 – Calculate the water requirement in the household

The annual water requirement in the household (toilets, watering the garden, washing machine uses and car washes) is calculated from the data for daily uses, monthly uses and then applied to all months.

$$Daily\ use = (24 \cdot 4) + (2 \cdot 20) = 116\ l/day \qquad (A.3\text{-}70)$$

$$Monthly\ consumption = (60 \cdot 12) + 300 = 1020\ l/month \qquad (A.3\text{-}71)$$

The overall monthly requirements W_{wr} are reported in the following table.

Month	W_{ry} [l/month]
January	4616.0
February	4268.0
March	4616.0
April	4500.0
May	4616.0
June	4500.0
July	4616.0
August	4616.0
September	4500.0
October	4616.0
November	4500.0
December	4616.0

Step 3 – Calculate the storage volume

The difference between monthly rainwater yield Wry and monthly water requirement W_{wr} define the monthly surplus W_s or deficit W_d of rainwater (i.e. the balance between water supply by rainfall and demand, it is therefore negative in the case of deficit and positive in the case of surplus).

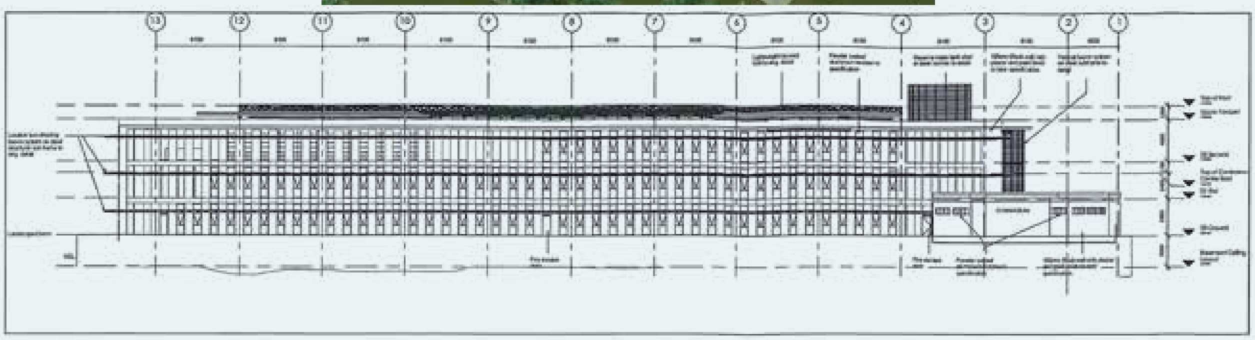
Period	W_s [l/month]	W_d [l/month]
January	2188.0	0.0
February	494.8	0.0
March	7048.0	0.00
April	17758.8	0.00
May	10255.6	0.00
June	0.0	-612.00
July	0.0	-2088.80
August	0.0	-2380.40
September	0.0	-2070.00
October	146.8	0.00
November	5803.2	0.00
December	6464.8	0.00
Annual	50160.0	-7151.2

The useful volume V_n is the minimum of W_s or W_d. In this case the minimum value is annual W_d so the storage tank volume can be calculated as follows, using the sizing factor 1.2.

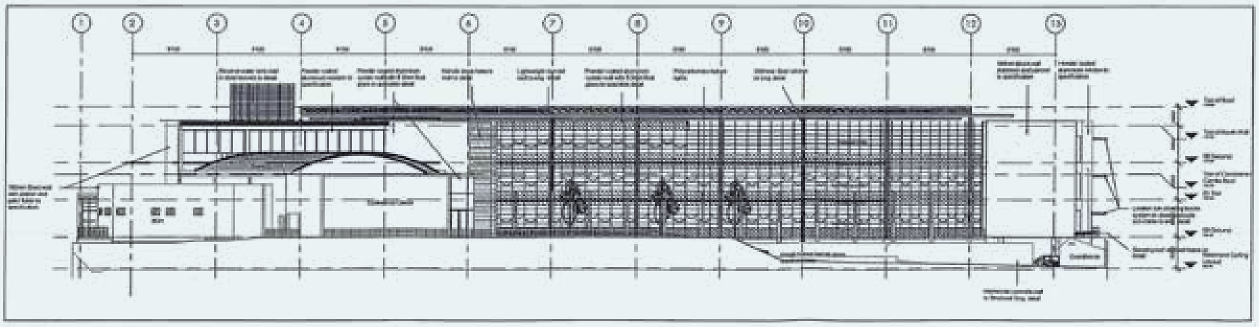
$$V_n = 7151.2 \cdot 1.2 = 8581.4\, l = 8.58\, m^3 \quad \text{(A.3-72)}$$

A4 CASE STUDIES

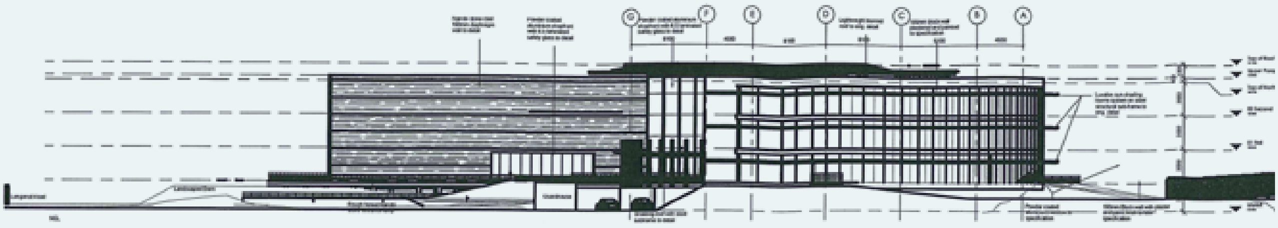
CASE STUDY 01	COCA-COLA EAST & WEST AND AFRICA BUSINESS UNIT HEAD OFFICE
Location	Nairobi, Kenya
Type of climate	Upland
Type of building	Commercial (institutional)
Date of construction	2007-2008
Owner	Coca-cola Company Ltd
Design team members	GAPP Architects & Urban Designers of South Africa, in association with Triad Architects of Kenya
The building	Coca-cola Headquarters Office in Nairobi is the business unit for the company's operations in 30 countries in Central, East and West Africa. It is located in the upper part of Nairobi city, in a site heavily constrained by road reserves and building lines. The floor area is about 12, 140 m^2 including office spaces, auditorium, staff support facilities like gym and cafeteria, and car parking. The particular semi-circular shape was derived from the Coca-Cola brand ribbon, while the curved building envelope was designed in order to maintain the indoor comfort according to the Nairobi climate. The building is an example of passive building design for an upland climate. The complex consists of two wings set off from a triple-volume reception which acts as a hinge and provides views through the building to the gardens beyond. The office wing to the north is a moon-shaped segment in plan with an indoor-outdoor garden behind a row of drinking-straw-like pole lights. The second wing combines a conference centre with staff support facilities, and accommodates a large central conference venue, breakaway rooms, restaurant, kitchens, other servicing elements and a Coke museum. Terraces on the east, west and south extend the sinuous lines of the building into the site while providing function and entertainment spaces.



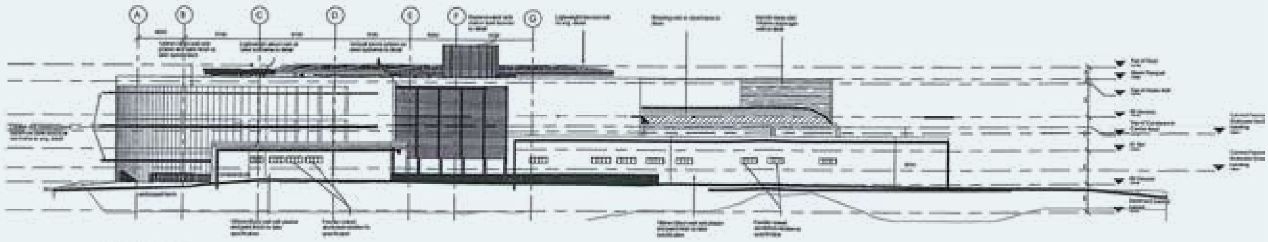
1 North Elevation
1 : 200



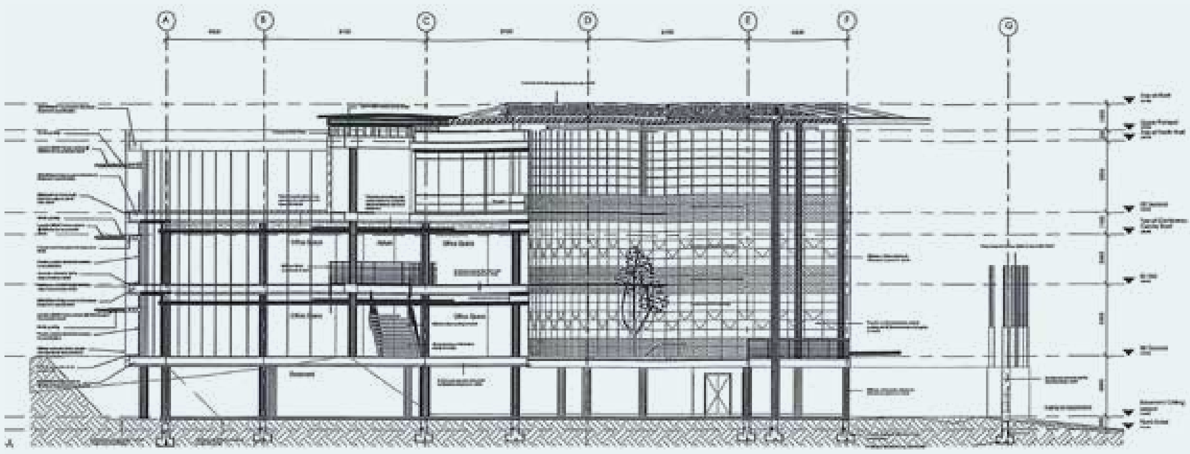
2 South Elevation
1 : 200



1 East Elevation
1 : 200



2 West Elevation
1 : 200



Significant characteristics

The building has been designed according to the upland climate. It is the result of the combination of an adequate orientation, good natural ventilation, passive temperature control and natural lighting. Its passive design avoids the use of an artificial air conditioning system both in the colder and in the hottest season. Additional sustainable features like water harvesting and automation of the artificial lighting system are an added value to the building's energy efficiency. The building's overall dependency on the municipal infrastructure is thus also minimised.

SUSTAINABILITY FEATURES

Energy concept

The building is oriented with the major facades facing North and South, thus solar heat gains from the east-west orientation are avoided.

OPENINGS AND SOLAR DEVICES

Despite the semi-circular shape of the building, all the windows in the main façade are oriented facing the North. In order to prevent direct solar radiation and glare they are deeply recessed in the massive northern wall, with horizontal aluminium light shelves in place, which provide solar shading whilst reflecting light that facilitates the illumination of the offices. The South façade is fully glazed and shaded with a wide aluminium louvered roof that protects the façade from direct solar radiation, reflecting heat but allowing natural lighting. The lightly tinted glass windows in this façade avoid glare but reduce natural lighting in the offices. The few windows facing East are protected with vertical aluminium louvers to avoid solar heat gains.

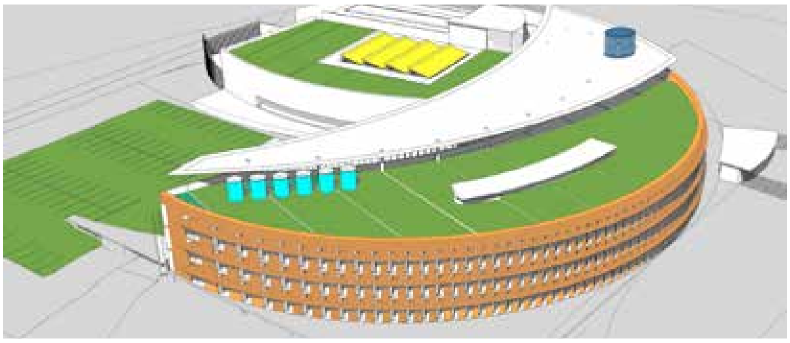
NATURAL VENTILATION

Operable windows in the North and South façades allow cross ventilation. In order to enhance natural ventilation a void atrium has been created, enhancing air movement through the stack effect whilst releasing indoor heat and providing daylight in spaces that are not facing the main facades.

BUILDING MATERIALS

Heavyweight material made up of a double hollow concrete block wall in the North facade retains the heat during the day and releases it during the night thus contributing to passive heating in the colder season and insulating from daytime heat gains in the hottest season.

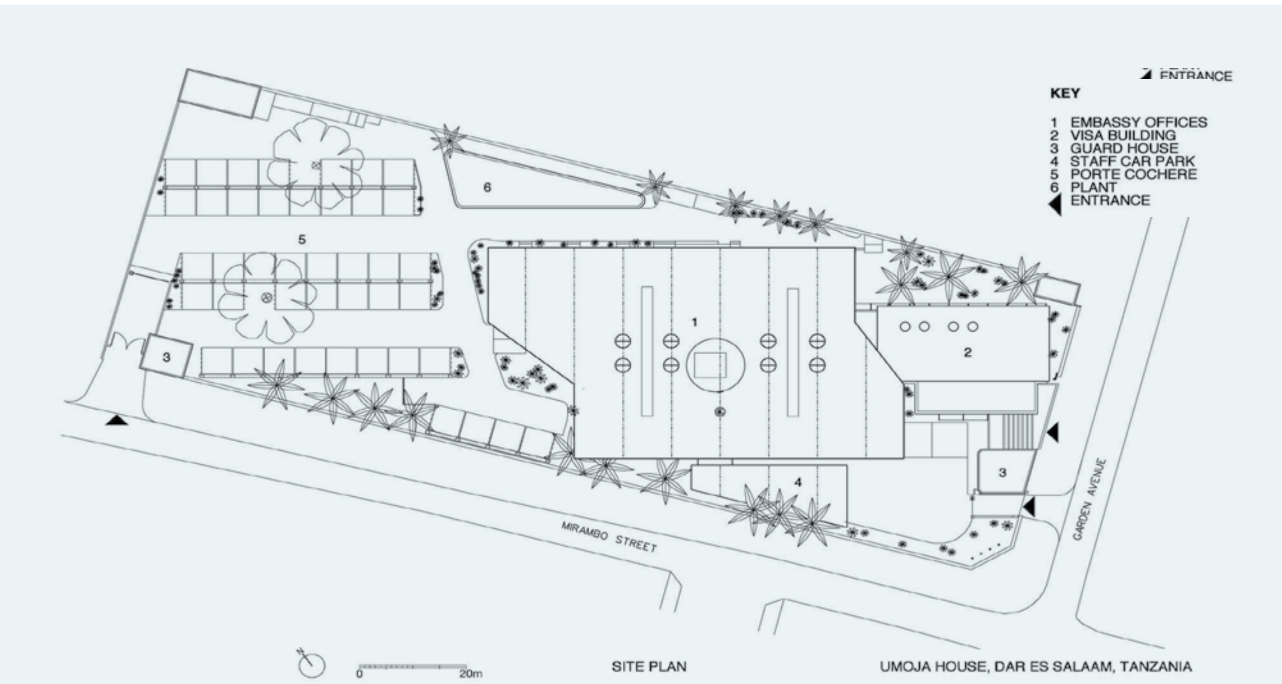
A garden covers half of the roof and apart from creating a friendly retreat space also protects the upper slab from solar radiation hence keeping the space below cool. Interior partitions are made up of blocks, glass and prefabricated panels

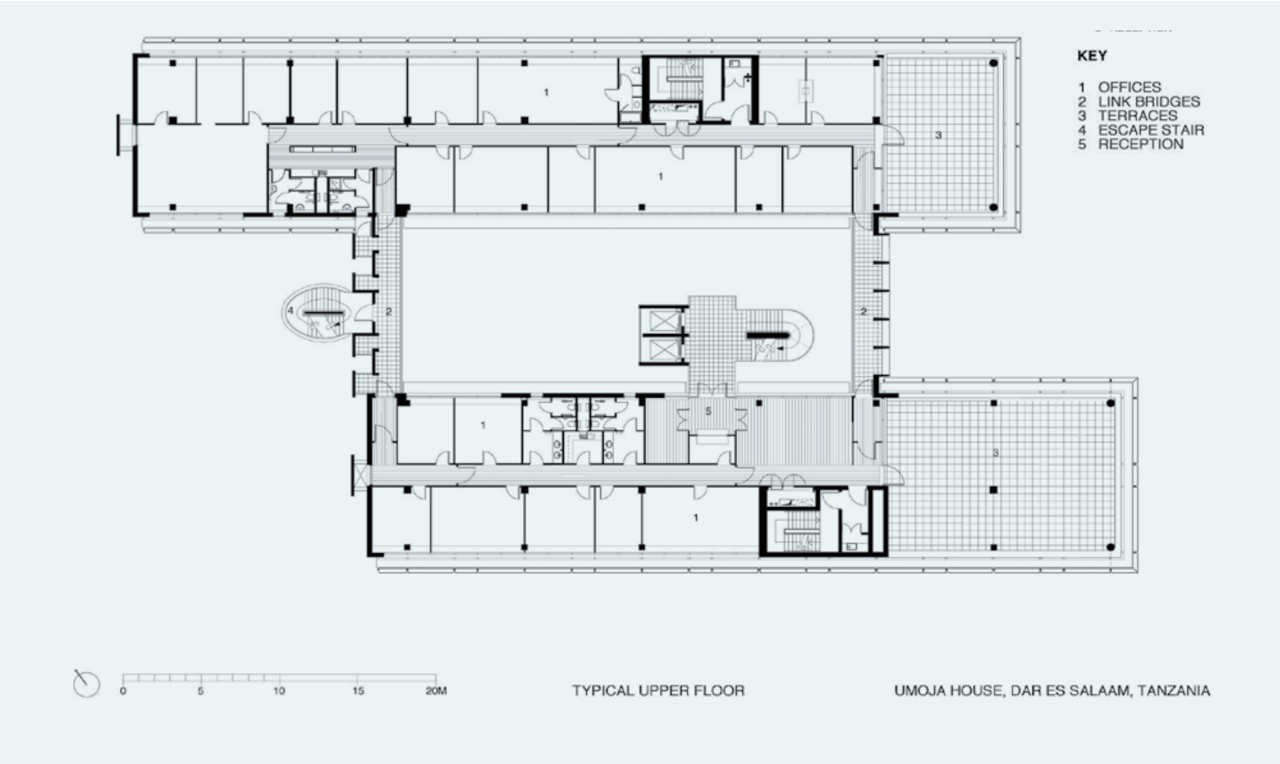


Materials	Double hollow concrete blocks locally provided are the main materials used in the North facade.
Energy data	-
Water cycle	Some of the rainwater is harvested, stored and used for irrigation and cleaning purposes on the site. 50 m^3 capacity tanks are located underneath the large earth berms on the compound. Warm water from the solar water heaters located on the roof is used in the kitchen and in the gym. Water saving fixtures like sensors, dual flush systems in toilets and water saving aerators in taps, have been applied in all the water devices.
Waste management	Paper and plastic waste is separated and sent to the local recycling enterprises. Human waste is discharged into the main sewer line of the city. Organic and other kinds of waste from the kitchen are managed by a catering company.
Energy saving measures	Presence sensors in the rooms. When these sensors detect no occupation in the rooms, they automatically turn the lights off hence saving energy.
	PERFORMANCE INDICATORS
Energy Comfort	-
	RESULTS
Lessons learned	This building is a good example of passive building design adapted to the upland climate in Nairobi, where the temperature is warm throughout the year but in the cold season can go down to temperatures below 15ºC. It provides solar protection while allowing natural lighting and providing passive heating for the cold season. Natural ventilation is assured in the whole building, and energy saving features both in lighting and water heating and supply help to reduce energy consumption. The design seems to aim more at providing thermal rather than visual comfort; natural lighting in the building generally needs to be complemented by artificial lighting.

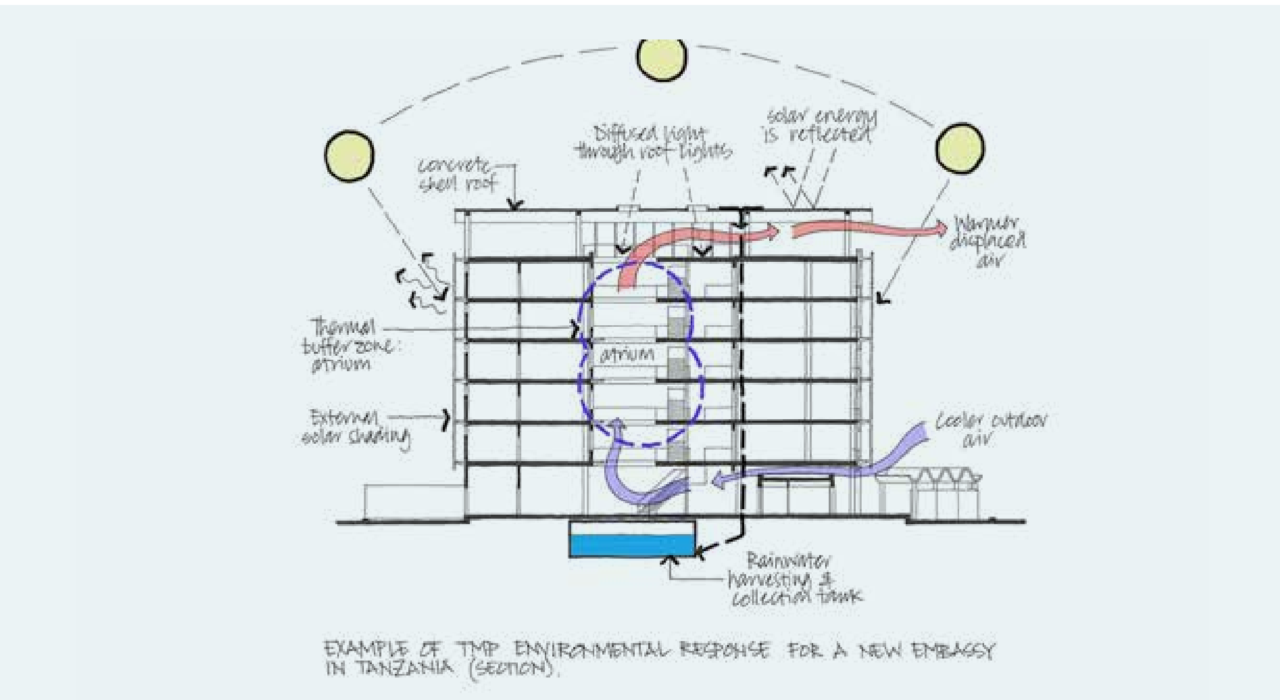
CASE STUDY 02	UMOJA HOUSE
Location	Dar es Salaam, Tanzania
Type of climate	Hot-Humid Climate
Type of building	Umoja House is a purpose built shared diplomatic compound which includes, The British High Commission, The Embassy of the Federal Republic of Germany, The Embassy of the Kingdom of the Netherlands, The Delegation of the European Commission, and The United Kingdom's Department for International Development.

Date of construction	2002
Owner	Foreign & commonwealth Office
Design team	Building Design Partnership (BDP)
The building	Umoja House is considered to be a fitting response to the city of Dar es Salaam and its climate. BDP designed the structural and environmental engineering for the building, in which the British High Commission and embassies of Germany and the Netherlands and for the European Commission in Tanzania were co-located. Protection against the climate pervaded all aspects of the design. To prevent overall heat gain design have a floating solar roof and external louvres on three of its elevations. Materials were sourced locally wherever possible and supported via local agents and contractors. BRIEF • to create a secure building • to build to European standards in a country with an extremely aggressive climate • to provide the client with acceptable internal conditions with due regard to sustainable energy sources The total construction cost of the building was £2.5m.





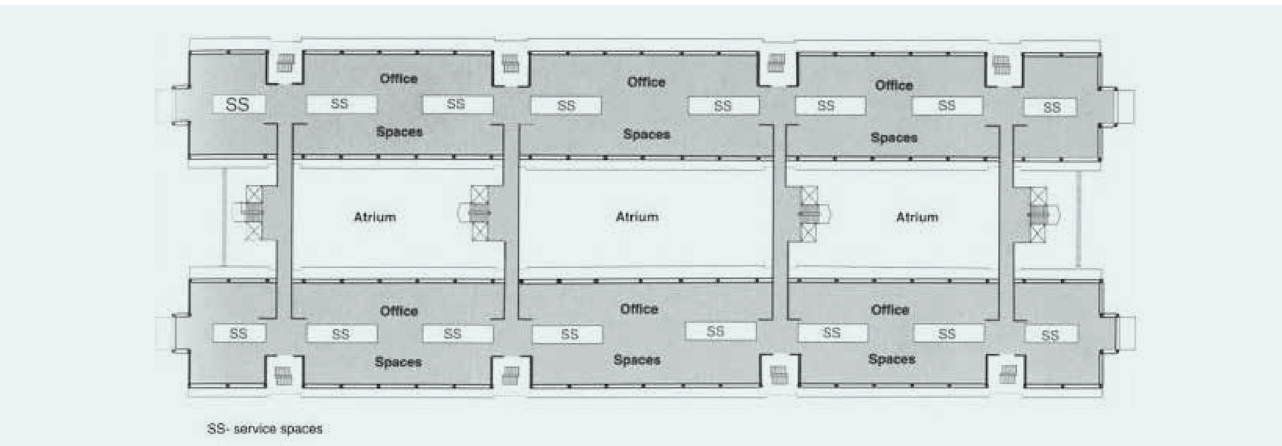
	INTEGRATED SERVICES Environmental engineering, structural engineering, landscape architecture, lighting, acoustics
Significant characteristics	The building is positioned with respect to the movement of the sun. The longer facades have a north-south orientation while the shorter facades face east and west to avoid morning and evening sun. The facades are shaded to protect them from the effects of the sun and the increase of indoor temperatures. The building has two main wings with an open central bay linked with corridors and staircases. An open bay in the middle creates a courtyard that creates the stack effect in the building. The glazed surfaces in all facades are protected by shading devices comprising stainless steel screens, which both shade the building and maximize the comfort of the users throughout the year. Moreover, these solutions promote energy savings due to the reduction of the heat load in the building. They also reduce the direct thermal load.



	SUSTAINABILITY FEATURES
Energy concept	The building orientation avoids the impact of solar radiation on the east and west facades, the main facades being oriented north-south. The application of shading devices reduces the effect of solar radiation.

Materials	The construction used reinforced concrete.
Energy data	To be completed.
Water cycle	The building has a rainwater harvest system that collects water in the basement. This water is used for cleaning the building and irrigation of grass.
Waste management	Text, photo, drawings, pictures, sketches, schemes
Energy saving measures	-
	PERFORMANCE INDICATORS
Energy Comfort	To be completed.
	RESULTS AND REFERENCES
Lessons learned	This building is a good example of adaptation to the hot humid climate of the city because: Firstly, the facades are oriented predominantly north south, with the glass windows protected by eaves and steel screens. In this climate solar control devices are crucial in order to avoid excessive thermal gains; the building also has a form that allows daylighting and natural ventilation, with rooms that are not very deep and with windows in both facades protected from solar radiation. Secondly, the building makes use of the stack-effect as it is designed in such a way that it allows air movement; colder air moves in as the warm air rises.

CASE STUDY 03	EASTGATE CENTRE
Location	Central Harare, Zimbabwe
Type of climate	Subtropical highland climate
Date of construction	1996
Owner	Pension Fund parent company
Design team	Mick Pearce, Ove Arup
The Building	The Eastgate Centre is a shopping centre and office block in central Harare, Zimbabwe. The architect is Mick Pearce. Designed to be ventilated and cooled by entirely natural means, it was probably the first building in the world to use natural cooling to this level of sophistication. It was opened in 1996 on Robert Mugabe Avenue and Second Street, and provides 5,600 m² of retail space, 26,000 m² of office space and parking for 450 cars. The building form is two nine-storey parallel 146 m ×16 m plan blocks, linked by a 16.8 m wide glass-roofed atrium, with its long axis oriented east-west. The upper seven storeys of office accommodation have double slab floors to enable overnight cooling by outside air. The two lower storeys and the two basement car parking levels have conventional mechanical supply and extract ventilation; the former can be equipped with mechanical cooling if required by their retail tenants. The atrium houses all the vertical circulation elements (stairs, escalators, elevators) as well as four sets of bridges across the atrium and a skywalk along its length at level two.



Significant characteristics	The building was modeled on the way that termites construct their nest to ventilate, cool and heat it entirely through natural means. The climate, with warm days and cool nights, is ideal for natural ventilation combined with night cooling. The other key factor (an economic one in this case) against the use of a conventional HVAC and refrigeration system was the relatively high cost of importing such plant, the potential lack of skilled labor to service and maintain it, the cost of running it in energy terms, and the disabling effects of power cuts that occur frequently in that area. Appropriate building orientation, extensive shading and glazing restricted to 25% of the façade were used to keep external heat gains to a minimum, while great efforts were made to limit internal heat gains.

According to computer simulations, the natural stack effect was not sufficient to cool down the building so simple, low power, locally made supply fans are used to ensure that all floors received the same quantities of cooling fresh air.

SUSTAINABILITY FEATURES

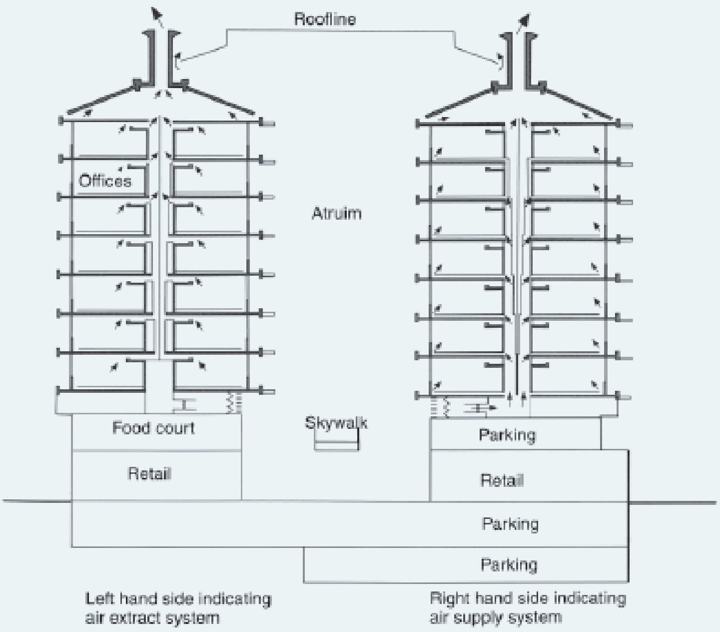
Energy concept

Based on the termite mound analogy, Mick Pearce's Eastgate building uses the mass of the building as insulation and the diurnal temperature swings outside to keep its interior uniformly cool. With Ove Arup & Partners, he devised an air-change schedule that is significantly more efficient than other climate-controlled buildings in the area. Fans suck fresh air from the atrium, blow it upstairs through hollow spaces under the floors and from there into each office through baseboard vents. As it rises and warms, it is drawn out through 48 round brick funnels. During cool summer nights, big fans send air through the building seven times an hour to chill the hollow floors. By day, smaller fans blow two changes of air an hour through the building. As a result, the air is fresh, much more so than that from an air conditioner which recycles 30 percent of the air that passes through it.

Each of the office floors is subdivided into 16 bays. The main supply air fans are housed in a corresponding set of 16 plant rooms at mezzanine level immediately below the bays of the seven floors of offices they serve. Each plant room houses a filter bank and two pairs of single-stage, axial-flow fans, one with a capacity of about 1m^3/s designed for daytime use, the other in the 4–5 m^3/s range for night-time operation.

The distribution system incorporates small-capacity (250–500 W) electric heaters in the supply grilles.

The exhaust air is finally extracted into vertical stacks with motorized dampers in the central core of each bay, which in turn lead to the chimneys visible on the roof.



Materials

On the exterior of the building there are heavy masonry walls, while the interior atrium has a high-tech feel created by glass and steel.

It is designed with the guiding principle that no direct sunlight must fall on the external walls at all and the north façade window-to-wall area must not exceed 25%

The supply fans which move fresh air were locally made, avoiding the relatively high cost of importing a conventional HVAC and refrigeration system.

Energy data

-

Water cycle

There is no rain-water collection, water reuse or recycling.

Waste management

There is no waste management.

Energy saving measures

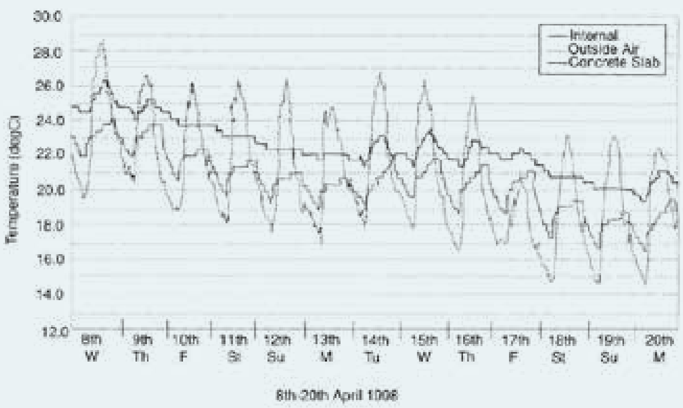
-

PERFORMANCE INDICATORS

Energy Comfort

Eastgate's ventilation system costs one-tenth that of a comparable air-conditioned building and uses 35 per cent less energy than comparable conventional buildings in Harare.

The peak temperatures in the offices and in the inter floor spaces tend to lag behind that outside by ~1 and 3 hours respectively, while under average conditions the inside peak temperature is some 3 °C less than it is outside.



RESULTS AND REFERENCES

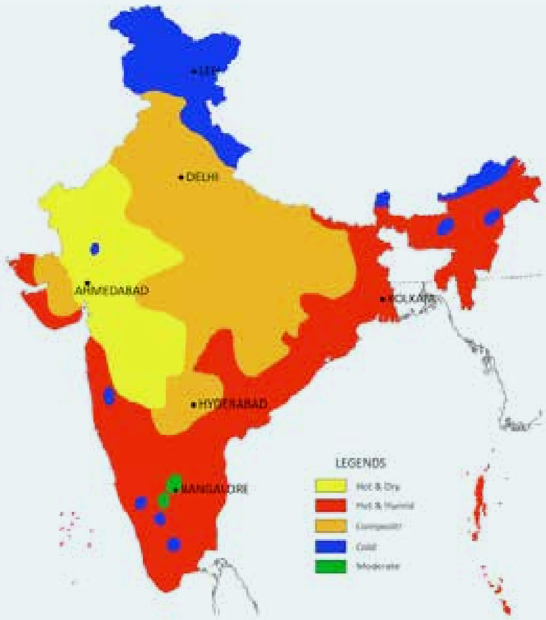
Lessons learned

The Eastgate Centre provided an alternative to the glass and steel office buildings, with an interesting façade and a livable inner court.

The cooling system was studied both for the climatic and for the economic constraint that an imported conventional HVAC system was not to be used.

With the help of locally-made supply fans the building is successfully conditioned with natural ventilation and night cooling.

CASE STUDY 04	WEST BENGAL RENEWABLE ENERGY DEVELOPMENT AGENCY
Location	Kolkata, India.
Type of climate	Warm humid climate.



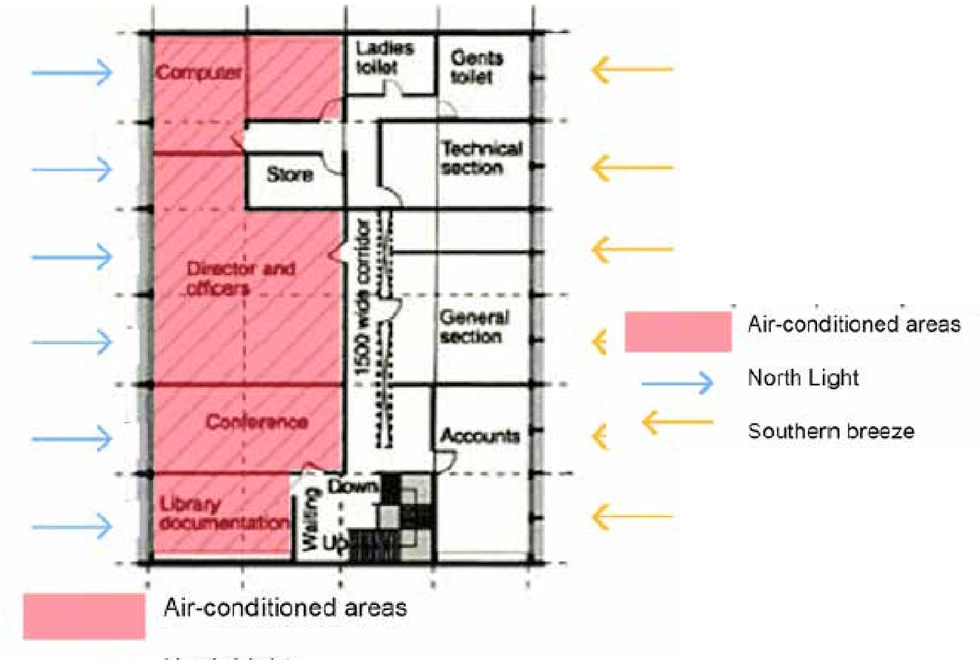
Date of construction	2000
Owner	West Bengal Renewable Energy Development Agency
Design team	Architect: Gherzi Eastern Ltd Energy consultant: TERI (the energy and resource institute), New Delhi
The building	Kolkata lies in a hot and humid climatic zone. Generally speaking, induced ventilation to counter the high humidity is essential in Kolkata. Simple energy efficient measures taken at the design stage resulted in a microclimate quite suitable for everyday office work. The plot area of the building is 10,895 m^2 while the built up area is 2,026 m^2 with a ground floor plus three storeys of office space. In addition there are also spaces for exhibition, conference, library and documentation.

Significant characteristics	Energy efficiency measures are provided following the basic concepts of solar architecture. The building layout, internal planning and selection of materials were carefully considered in order to reduce energy consumption. The longer sides of the building face north and south. The windows in the north and south sides provide for daylighting in all the office areas. Natural ventilation is also provided. The building is virtually divided into two parts (north and south) serviced by a corridor in between. To take best advantage of the prevailing southerly breeze, a water feature has been created in the southern part of the building at ground level. This is also aesthetically sound.

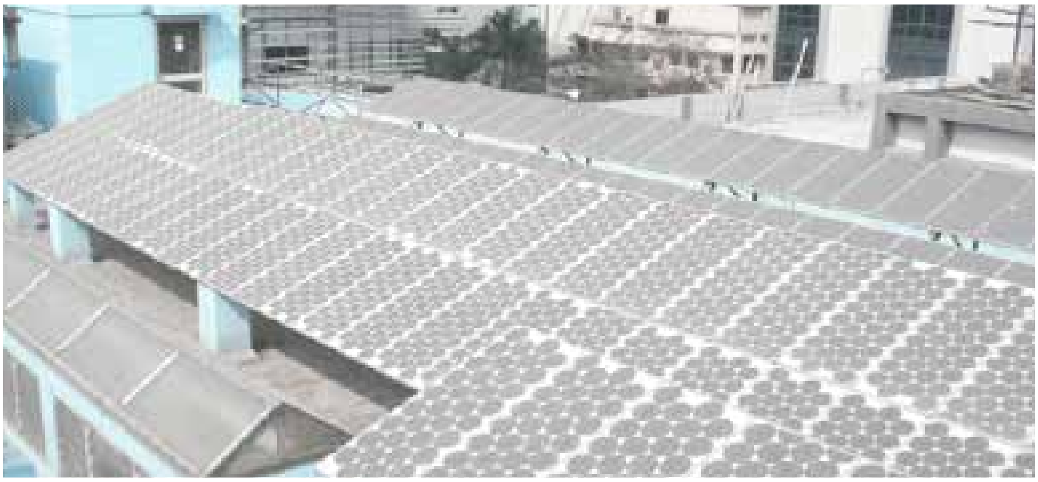
	SUSTAINABILITY FEATURES
Energy concept	In general, in Kolkata, office buildings have cooling needs from April to September. In the West Bengal Renewable Energy Development Agency building various strategies were incorporated to cool the indoor environment, reducing energy consumption as follows: • Protection of east, south and west facing facades; • Reduction of reflection and radiation of heat from the ground surface; • Priority given to natural ventilation and cross ventilation; • Use of vegetation and water to mitigate microclimatic conditions. Further: • The building was designed so that all the air conditioned spaced are located on the northern side to cut down the cooling loads; • Areas not conditioned are located on the southern side in order to take advantage of the prevailing wind; • A portion of the roof has been raised and is used as solar chimney to improve cross ventilation • The southern façade is protected by overhangs designed as light shelves; • Daylight penetrates the building through the openings that run along the northern and southern sides of the building. The northern side can maximize natural light since it has no solar protection. • A cut-out over the water feature draws in fresh air and vents it out through the roof. It also provides natural light inside. • The water feature in the south-western corner of the ground floor helps to mitigate microclimatic conditions. • Solar protection devices allow only diffused light to enter during summer. At the same time, windows provide natural ventilation. • The integration of day-lighting and artificial lighting was optimized. • During daytime the offices do not require artificial illumination. • High efficiency lamps are installed in the whole building. • The western façade is a blank wall with the stairwell and lift lobby acting as an immediate buffer inside. • Trees on the south and west sides provide further shading.



Materials	Insulation was provided to reduce cooling needs and mean radiant temperature taking into account the budgetary constraints. Locally available bricks were used as masonry. Airtight double glazed windows were recommended for the air conditioned areas and single glazed windows for the non air conditioned areas. But the double glazed windows could not be provided due to lack of funds.



Energy data	There is a grid connected PV system of 25 kWp. Revenue generated by the solar electricity produced is more than the electricity bill of the building. Occupants don't require hot water but a solar thermal system will be installed outside the office for demonstration purposes.



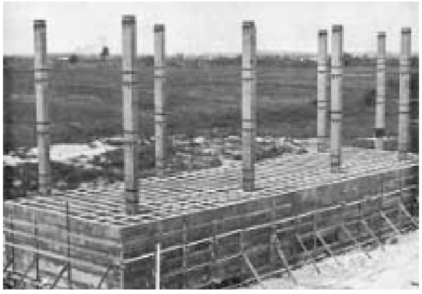
Water cycle	-
Waste management	-
Energy saving measures	-
	PERFORMANCE INDICATORS
Energy Comfort	-
	RESULTS AND REFERENCES
Lessons learned	Good application of bioclimatic principles. The case demonstrates the possibility of providing comfort conditions in commercial buildings located in extreme climatic conditions by a modest use of cooling devices.

CASE STUDY 05	CIUDAD UNIVERSITARIA JOSÉ ANTONIO ECHEVERRÍA (CUJAE)
Location	Havana, Cuba
Type of climate	Warm-Humid
Type of building	University
Date of construction	Inaugurated in 1964
Owner	Cuban Government
Design team	Humberto Alonso, José Fernández, Fernando Salinas, Josefina Montalván and others
The building	The first built step of the University City is composed of 9 student buildings oriented north and south with the main axes east – west, articulated by the office building. It also includes a theatre, dining room, cafeterias and a kitchen. The ground floor is opened for circulation. Buildings at different levels are connected by stairs, galleries and terraces, directly linked with vegetation in the open spaces and on the green roof terraces. The construction system is based on the "lift slab" principle, composed of concrete columns prefabricated on site, spaced between 9 m and 11 m supporting a reticulated slab 80 cm high. The structural module is approximately 100m² and the student buildings are formed of between 4 and 8 modules. Thus, the floor area of the student buildings ranges between 500 and 1000 m².

Significant characteristics

The building design takes advantage of daylight and natural ventilation, providing the necessary solar protection. It is achieved by the building's orientation, volume, space and envelope, as well as by the use of vegetation in the open spaces.

Critical aspects are architectural barriers because of the differences of levels, interior drainage in buildings and artificial lighting not designed to be used as a complement of daylight.

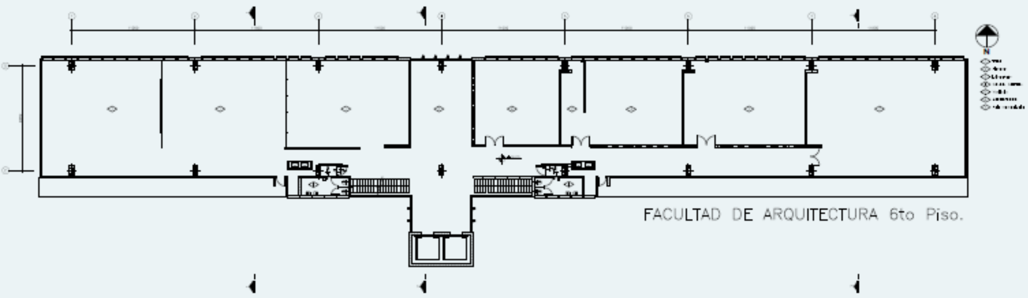


SUSTAINABILITY FEATURES

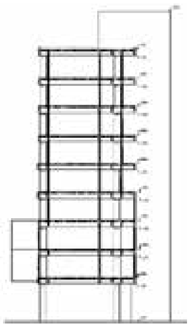
Energy concept

Classrooms are designed for daylight and natural ventilation and they are protected against solar radiation. There is no energy consumption for air conditioning in schools.

All buildings with classrooms are elongated with the main axis in an east – west direction; classrooms face north, avoiding the need for solar protection and enhancing diffuse daylight through the glass windows. Circulation galleries are located the south, acting as solar protection for the classrooms. East and west facades are minimised and have no windows.



VOLUME: Buildings are shaped like prisms with a maximum depth of 11 m, in order to guarantee bilateral daylight and natural cross ventilation. The open ground floor improves cross ventilation because of the difference of pressures in the facades, and then increases air velocity inside, which is crucial for comfort in a warm and humid climate. On the other side, the volumetric shape of the building creates auto shading, mainly in the south facade.



VEGETATION: All the open spaces are covered by grass and other vegetation preventing heat absorption and contributing to a reduction in the heat island effect in the University City. The trees also help in solar protection of the building's facades and windows.


SPACE

The open plan allows the use of light interior divisions, permeable to daylight and ventilation. These modular panels can be temporarily removed or changed when needed, allowing spatial flexibility.



ENVELOPE

Glass windows on the northern façade favour daylight. Since the opened windows direct the air flow to the upper part of the space, opaque louvered windows are located below them, in order to promote air flow through the zone occupied by the users.

Cross ventilation is produced between the windows in the northern façade and the wall dividing the classroom from the corridor, in which movable glass louvers are located from the floor to the ceiling.

In spaces located on both extremes of the building, there are no divisions, cross ventilation is provided by large movable glass louvered areas in the south façade, or glass louvered windows protected against solar radiation by overhangs.

The Smaller facades oriented to the east and the west have no windows and are made from modular panels of insulating light concrete.



Materials

The structure's skeleton (columns and slabs) is made of reinforced concrete, prefabricated on site. The envelope is mainly composed of windows and the extreme walls of the volume are made of modular panels of light concrete with low heat transfer coefficient.

Windows protected against solar radiation in classrooms and workshops are made of simple glass, are of louver type, and have aluminium frames, and there are louvered aluminium windows at the bottom. Also, wooden tropical windows are used in lobbies, corridors and parts of the south façade without solar protection.

In addition, the buildings have very low thermal mass, as recommended for warm and humid climates. They are also highly permeable to daylight and ventilation and the envelopes (walls and windows) are protected against solar radiation by the buildings' own volume.

Interior divisions between classrooms and offices are made of the same modular panels of light concrete, which facilitate spatial transformation because the way they are fitted to the building allows them to be easily taken out. This is also an advantage for deconstruction at the end of their useful life.

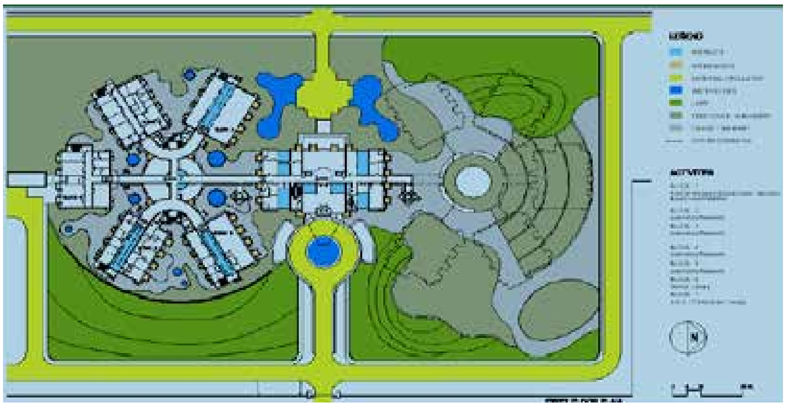
Interior divisions between workshops are made of light wooden panels that allow daylight and ventilation at the top and the bottom. They are also easily taken out to facilitate spatial transformation.

Installations for water supply, sanitation and rain water evacuation are exposed, instead of being embedded in the built mass, facilitating maintenance, durability and deconstruction at the end of their useful life.

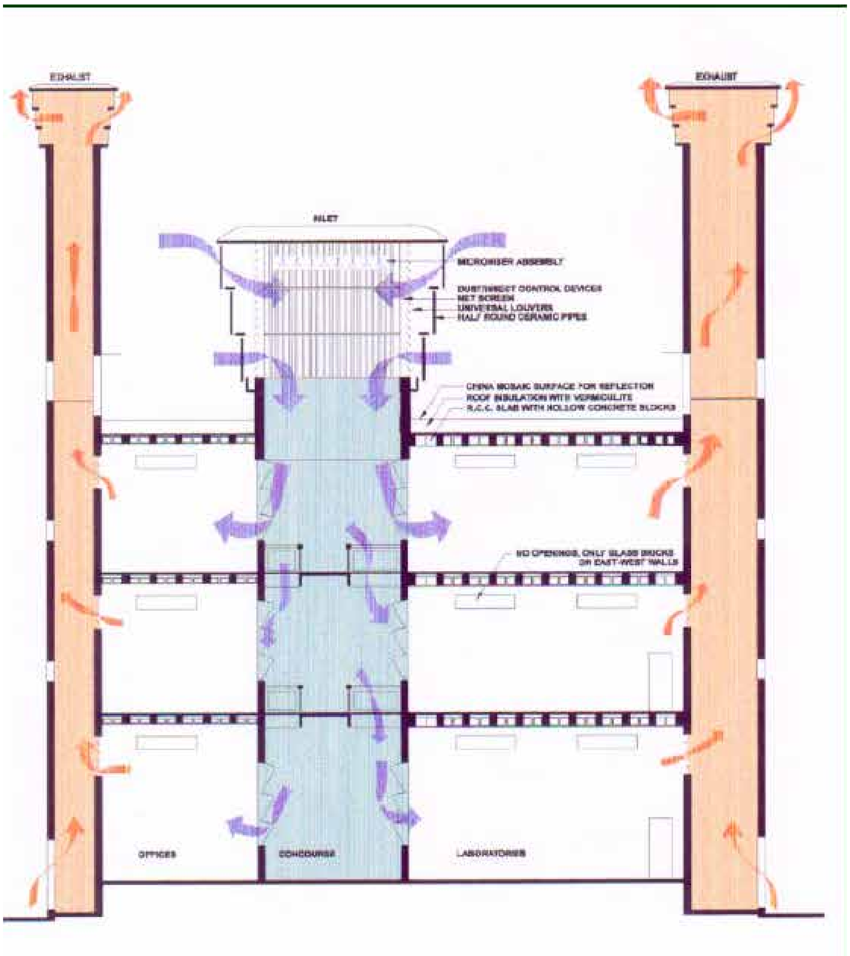
Energy data	-
Water cycle	-
Waste management	-
Energy saving measures	-
	PERFORMANCE INDICATORS
Energy Comfort	Thermal comfort is achieved even in the hottest hours of the day, because of the high air velocity generated by cross ventilation in classrooms and workshops (over 1 m/s). Comfort is only difficult on some summer days with temperatures over 32^{0}C and relative humidity higher than 70%.
	RESULTS AND REFERENCES
Lessons learned	This case shows that it is possible to achieve thermal and visual comfort by natural means in warm and humid climates, based on an architectural design that makes it possible to avoid using air conditioning and also reduces energy consumption. The first way to take advantage of renewable energy in buildings is bioclimatic design. As this example shows, the main architectural design principles to achieve this goal in such a climate are: vegetation for reducing the heat island effect; volumetric solution providing solar protection of the envelope and space, according to the orientation; open, flexible and not very deep space; envelope permeable to daylight and ventilation, protected against solar radiation, with low heat transfer and thermal mass.

CASE STUDY 06	TORRENT RESEARCH CENTER, AHMEDABAD.
Location	Ahmedabad, State of Gujarat, India.
Type of climate	Hot and dry.
Date of construction	2000 (project period: 1994-1999; partial occupation since 1997)
Owner	Torrent Pharmaceuticals Ltd.
Design team	Architects: Nimish Patel and Parul Zaveri, Abhikram, Ahmedabad. Energy consultants: Brian Ford, Brian Ford and Associates, London, UK (for the typical laboratory block in all aspects); C L Gupta, Solar Agni International, Pondicherry (for the rest of the blocks, vetting Abhikram designs). Structural Consultant: Yogesh Vani Consulting Engineers, Ahmedabad, India. Utility Consultant : Dastur Consultant Pvt. Ltd., Delhi, India. Landscape Consultant : Kishore Pradhan, Mumbai, India. Lighting Consultant : Paresh Shah, Sukriti Design Incorporated, USA. Civil Contractors: Laxmanbhai Constructions (India) Pvt Ltd., MB Brothers Ltd., Shetusha Engineers and Contractors Pvt. Ltd., Materials Corner, JK Builders.
The building	The Torrent Research Centre is a complex of research laboratories with supporting facilities and infrastructures (built-up area of approximately 19700 m^2) located on the outskirts of Ahmedabad. This building uses Passive Downdraft Evaporative Cooling (PDEC) for a large scale office building and demonstrates that it is possible to achieve human comfort in hot dry regions without using regular HVAC systems and without compromising the cost of construction. The comfort conditions and the energy demands of the building were monitored during appropriate campaigns.

Significant characteristics	After an in-depth study of the local climatic conditions, the building was designed following the approach known as the Passive Downdraft Evaporative Cooling method. A central open concourse on three levels allows air cooled by evaporative process to be introduced into laboratories and offices at each level and exhausted via perimeter stacks. Different management strategies are applied depending on the season. The principal seasons are: From March to June: hot and dry (daily maximum temperature above 35° and relative humidity below 20%); From July to September: monsoon (daily maximum temperature below 30° temperature and relative humidity above 65%); From October to February: cool and dry (daily maximum temperature below 35° of temperature and relative humidity below 30%). Further, the external building envelope has been designed to minimize solar heat gain and to use locally available materials. Overall control of the solar heat gain is achieved by judicious design of the glazing; the buildings are thermally massive; external surfaces are white, the walls painted and the roof using a china mosaic finish. Each laboratory building has a similar 22 x 17 m^2 plan, with a 4 m wide corridor flanked by 5 m deep office spaces and 8 m deep laboratory spaces. Two of the five laboratory buildings are air conditioned while the other three are equipped with the PDEC system. The larger main administrative building is located to the north of the laboratories and a utility building to the south with a two level corridor spine linking them.



	SUSTAINABILITY FEATURES
Energy concept	Passive Downdraft Evaporative Cooling method as shown in the diagrams.

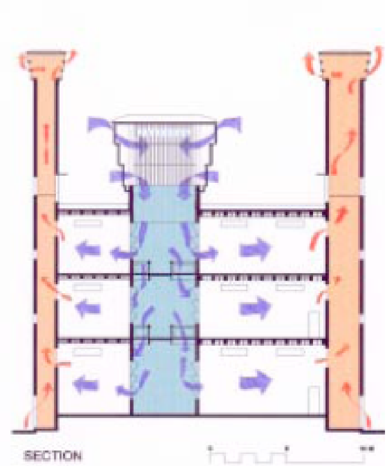


SECTION
TYPICAL LABORATORY BLOCK

FIRST FLOOR PLAN
TYPICAL LABORATORY BLOCK

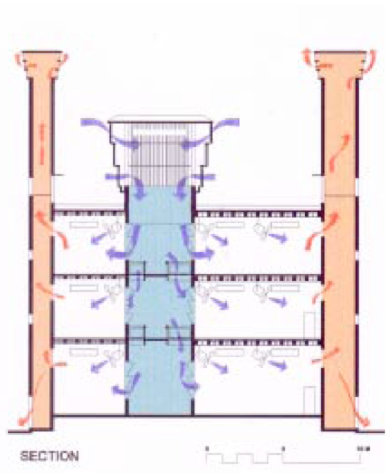
HOT SEASON STRATEGY
(MARCH – JUNE)

- Passive evaporative cooling
- micronisers provide a down draft of cool air.
- Night ventilation.
- Ambient temperature 41 to 43 C.
- Insulated building mass and roof.
- High air change rates achievable (8 – 15)
- Air moves across the laboratory through risk of short circuiting.
- Controls: Micronisers to be controlled automatically by reference to ambient temperature and relative humidity.



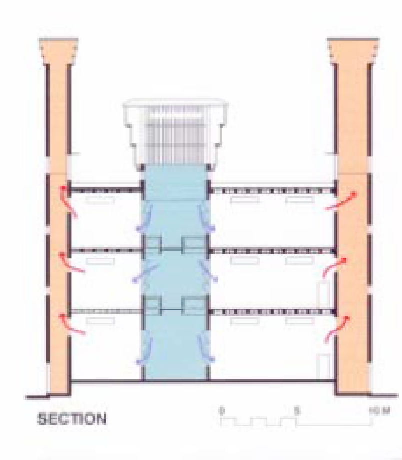
MONSOON SEASON STRATEGY
(JULY – SEPTEMBER)

- Maximise ventilation rate with micronisers switched off.
- Ceiling and wall fans to induce air movement in the same direction as natural flow.
- Air speed upper limit 1.5 Mt./Sec.
- Possibly close all exhausts in the afternoon.



COOL SEASON STRATEGY (OCTOBER – FEBRUARY)

- Minimize ventilation rates.
- Inlets closed by shutters.
- Exhausts also closed by shutters.
- Insulated walls and roof reduces heat losses.
- Internal gains raise temperature.
- Encourage ventilation during the day (possibly evaporatively cooled on hot days).
- Close inlets and exhausts at night.



Materials

The following strategies were taken into account:

- maximum use of locally available natural materials and the use of synthetic materials avoided;
- RCC-framed structure with brick in-filled walls, with glossy enamel paint on cement/vermiculite plaster on the internal surface;
- vermiculite, a natural mineral, extensively used for the insulation in roof and cavity walls to achieve the required values of thermal resistance, along with cement–brickbat-based waterproofing;
- innovative use of half-round ceramic pipes, on the outer face of the inlet and exhaust shafts of the PDEC system, to reduce the entry of larger dust particles by creating local turbulence.

Energy data

The central plant includes two oil fired steam boilers, two air compressors, two diesel generators and refrigerators.

The total energy consumption for PDEC and AC combined (including light, equipment and AC for two blocks) for the 6 blocks in 2005 was 647 MWh. This averages out to 54 kWh/m^{2}y (about the 38% of the consumption of buildings located in analogous climates and with analogous functions); clearly, the climate responsive approach to building design has resulted in a high level of energy savings.

Water cycle

-

Waste management

-

Energy saving measures

-

PERFORMANCE INDICATORS

Energy Comfort

Despite the intensive internal gains, the monitoring of the building demonstrated that:

In the summers, the inside temperatures have generally not exceeded 31 °C to 32 °C, when the outside temperatures have risen up to 44 °C;

The temperature fluctuations inside the building have rarely exceeded beyond 3 °C to 4 °C over any 24 hour period, when the temperature fluctuations outside were as much as 14 °C to 17 °C.

An adaptive comfort theory was adopted since the team defined a threshold temperature of about 28 °C which could be exceeded for a certain number of hours.

The team designed the building in order to allow work to be done during daylight hours using the minimum electricity.

The economic viability of the project is demonstrated by the following indicators, which are computed for the total project, on the basis of the results from the buildings under observation.

Additional civil works cost of the project including insulation etc. works out to about 12% to 13% of the civil works cost of a conventional building;

The pay-back period of the additional capital cost, from the saving of the electrical consumption alone, works out to a little less than 1 year;

The pay-back period for the cost of the construction of the entire complex, from the savings of the electrical consumption as well as plant replacement costs, works out to around 15 years.

	RESULTS AND REFERENCES
Lessons learned	Torrent Research Centre demonstrates innovative technological solutions to cut down space-conditioning and artificial lighting loads without compromising on required levels of thermal and visual comfort. The Torrent Research Centre demonstrates excellent environmental outcomes. The findings of the post occupancy survey show that this building continues to satisfy expectations for a contemporary workplace of high quality that is simultaneously energy efficient. While the wider implications of the success of such buildings for the Indian subcontinent, where there is currently large scale development of "glass boxes" that are both energy intensive and inappropriate for the climate, the building performance outcomes in Torrent clearly reinforce the value of a climate responsive approach to building design in any location. Considering the characteristics of the project, the method can be repeated in several areas of the world.

A5 INTEGRATED DESIGN APPLICATIONS

Examples of sustainable buildings design in EAC climates are provided in this appendix, applying the integrated design approach illustrated in chapter 1 and exploiting the potential offered by some of the simulation tools described in chapter 4.

Two different building types were designed: single family houses and multi-storey residential buildings. The former were supposed to be located in a suburban context, while the latter in an urban context. Wind data were adjusted accordingly (see section 2.1).

The first step was to design the buildings according to the design guidelines and sizing the components by means of of the simplified tool provided in Chapter 3.

Five building locations were chosen, each in a different EAC climatic zone, as follows:

- hot humid climate: Mombasa;
- hot arid climate: Lodwar;
- upland climate: Nairobi;
- savannah climate: Tabora;
- great lakes climate: Kampala.

The buildings' thermal and comfort performances were then simulated with BESTenergy as interface of Energyplus. Hourly climate data (TRY) were the ones provided in the EnergyPlus database or derived by monthly data by means of the software Meteonorm.

All the simulations were carried out without any heating or cooling systems, to optimise the architectural design: the better the building performs on its own, in terms of comfort provided, the lower the need for cooling or heating and thus the lower the associated energy consumption if mechanical heating or cooling is provided.

Hourly mean radiant temperature, indoor air temperature and operative temperature (all calculated in the geometrical barycentre of the room) and outdoor air temperature variations were evaluated in the two most significant periods: the first one (from March 15 to March 21), was assumed to represent the warmest period in the location's typical year, and the second one (from July 15 to July 21) to represent the cool (or the least hot) period. In the graph in which the temperatures are plotted, the comfort band according to ASHRAE 55 adaptive model (see Appendix 2) was overlapped, for two air velocities: ≤ 2 m/s and = 0.5 m/s[115].

Further, for each case, living room and bedroom hourly operative temperatures were calculated in the hottest and cool (or least hot) month and plotted in the graph, overlapping the comfort band according to ASHRAE 55 adaptive model. In this way, it was possible to evaluate the number of hours in which thermal comfort is achieved. Also checked was whether air velocity = 0.5 m/s (obtainable with cross ventilation or with a ceiling fan) could improve comfort conditions, and to what extent. In some cases, CFD simulations were carried out.

In all building simulations, windows were assumed to be equipped with fly-screens and the airflow crossing them was reduced accordingly (see section 3.5).

A.5-1 SINGLE-STOREY RESIDENTIAL BUILDING IN HOT HUMID CLIMATE (MOMBASA)

The single-storey residential building (Fig. A.5-1, A.5-2, A.5-3) is raised above the ground and its long axis is oriented east-west. North and south façades are mainly occupied by jalousie-type windows; a deep overhang shades them. East and west façades do not have any windows. The roof is detached from the ceiling, acting as a shading umbrella. In order to enhance natural cross ventilation, a single banked room layout was chosen. Top openings in interior vertical walls between bedroom and corridor were provided to allow cross ventilation when the door is closed (see figure A.5-3); exterior corridor windows are operable.

Sliding exterior blinds provide protection against intrusion allowing ventilation and privacy. The simulation was carried out for the entire building, but results are presented only for the living room.

115 *Note that the assumed indoor air velocity (0.5 m/s) only affects comfort band position in the graph (see Appendix 2 – Principles of thermal comfort and visual comfort).*

FIGURE A.5-1 **SINGLE-STOREY RESIDENTIAL BUILDING IN HOT HUMID CLIMATE (PLAN AND SECTION)**

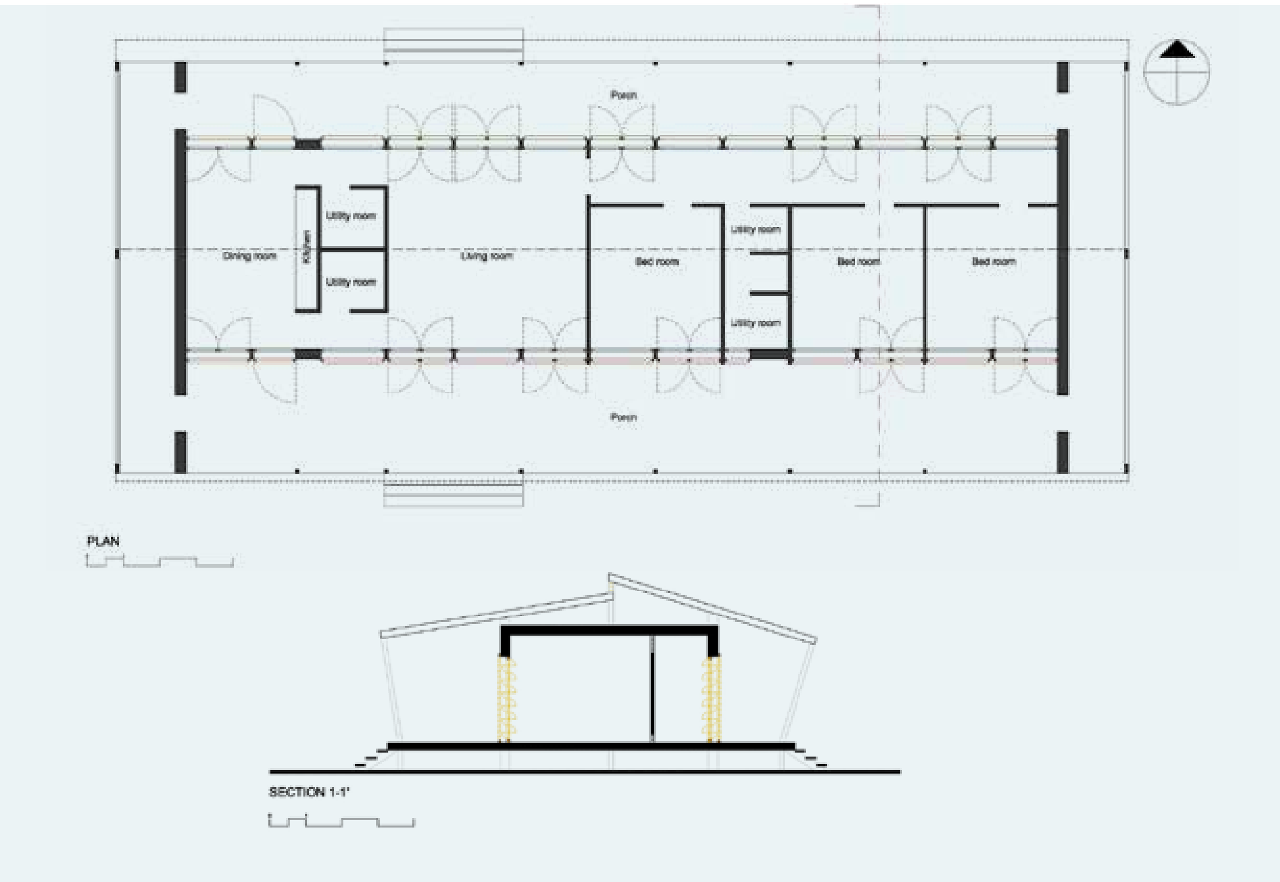
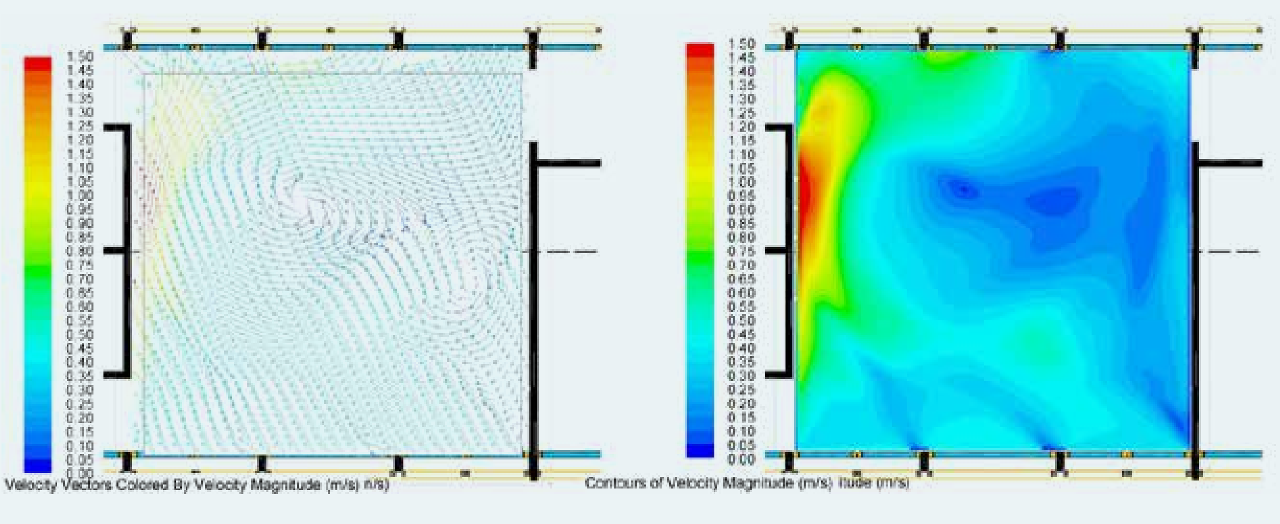


FIGURE A.5-2 **SINGLE-STOREY RESIDENTIAL BUILDING IN HOT HUMID CLIMATE (ELEVATIONS)**

FIGURE A.5-3 **CFD SIMULATION OF THE LIVING ROOM WITH OUTDOOR WIND SPEED = 3 M/S FROM SOUTH-EAST. IT IS ASSUMED THAT THE EXTERNAL WOODEN SHUTTERS ARE OPEN AND THAT A FLYSCREEN IS INSTALLED.**



A.5.1.1 ENVELOPE COMPONENTS

The exterior envelope was designed with light-weight components and a double pitched ventilated roof, as described below:

- Exterior walls: lightweight walls made of a 6 cm air-gap enclosed within two 3 cm wood layers;
- Floor: suspended 3 cm wood boards;
- Ceiling: 3 cm wood boards;
- Roof: aluminium sheets;
- Windows: glass jalousie-type components.

A.5.1.2 SIMULATION ASSUMPTIONS

Energy simulation was carried out assuming:

- summer clothing (0.5 clo)
- occupancy constant during the simulation period, with 4 persons in the living room and two persons in the bedroom;
- internal gains rate due to appliances, 2 W/m^2;
- windows always open, with flyscreens.

A.5.1.3 SIMULATION OUTPUTS

CFD simulations were first carried out to check if the preliminary window sizing, which was carried out with the simplified methods illustrated in section 3.5, was acceptable.

Fig. A.5-3 shows that good air velocity is achieved with cross ventilation in a large part of the room for a wind velocity and direction corresponding to the average wind velocity and direction in the hottest hours in March in Mombasa[116]. In any case, 0.5 m/s air velocity, or more, can be obtained with the activation of a ceiling (or table) fan.

In figure A.5-4 (upper part) temperature hourly values during the hottest period are plotted for the living room; the adaptive ASHRAE comfort zone is overlaid, to show the comfort achieved, for two cases: 0.2 m/s air velocity and 0.5 m/s.

The figures show that, for air velocity ≤ 0.2 m/s, in the hottest period comfort is never achieved in the middle of the day (the operative temperature goes out of the comfort range), but the use of a fan (air velocity 0.5 m/s) can overcome the problem; otherwise, during the least hot period (bottom, left) even with air velocity ≤ 0.2 m/s comfort conditions are always met.

Figure A.5-5 shows the plot of indoor hourly operative temperatures in the living room in conjunction with the outdoor air temperature at the same time, with the adaptive ASHRAE comfort zone overlaid, for the hottest and least hot months of the year and for indoor air velocity 0.2 m/s and 0.5 m/s.

In Table A.5-1, the percentage of hours in which adaptive thermal comfort is achieved in the living room are summarised with different indoor air velocities, for the two entire months considered: the hottest (March) and least hot (July). Table A.5.1 shows that with a fan in action (0.5 m/s air velocity) during the hottest period adaptive comfort conditions are not met for a very small percentage of hours. In these conditions, air conditioning should not be necessary.

116 *The air velocity distribution can be significantly modified by the furniture. The occupants, however, can adjust air velocity and direction by changing the tilt of the jalousie slats.*

TABLE A.5-1 **PERCENTAGE OF HOURS THROUGH THE HOTTEST MONTH (MARCH) AND THE LEAST HOT MONTH (JULY) IN MOMBASA IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS REACHED IN THE LIVING ROOM.**

Indoor Air Velocity	% hours in 90% Acceptability Zone		% hours in 80% Acceptability Zone	
	March	July	March	July
≤ 0.2 m/s	56.5%	100%	75.5%	100%
0.5 m/s	87.5%	100%	99.2%	100%

FIGURE A.5-4 **LIVING ROOM HOURLY TEMPERATURES IN THE HOTTEST (03/15 TO 03/21) AND LEAST HOT (07/07 TO 07/21) PERIOD AND ASHRAE 55 ADAPTIVE COMFORT BAND FOR INDOOR AIR VELOCITY ≤ 0.2 M/S AND 0.5 M/S**

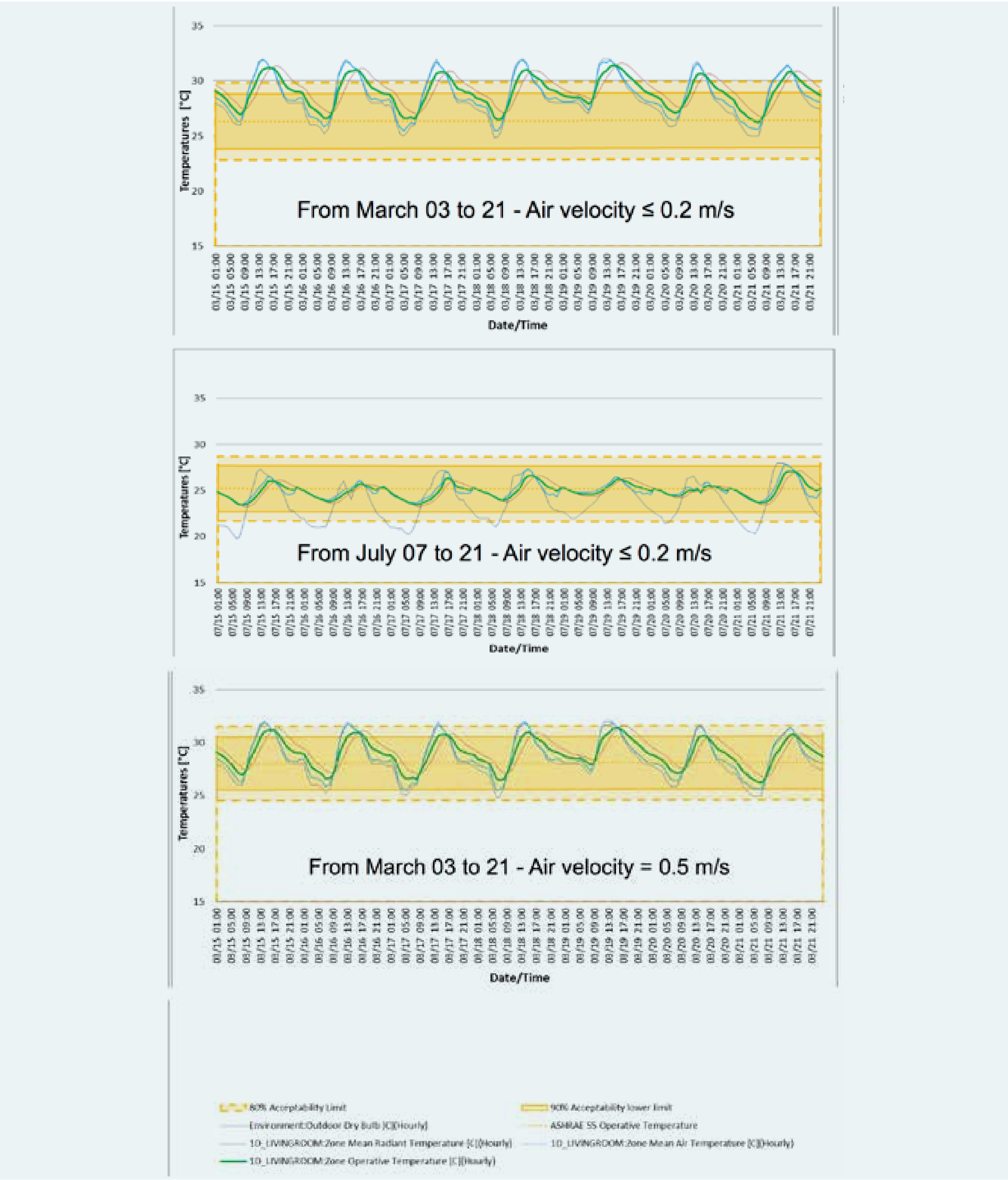
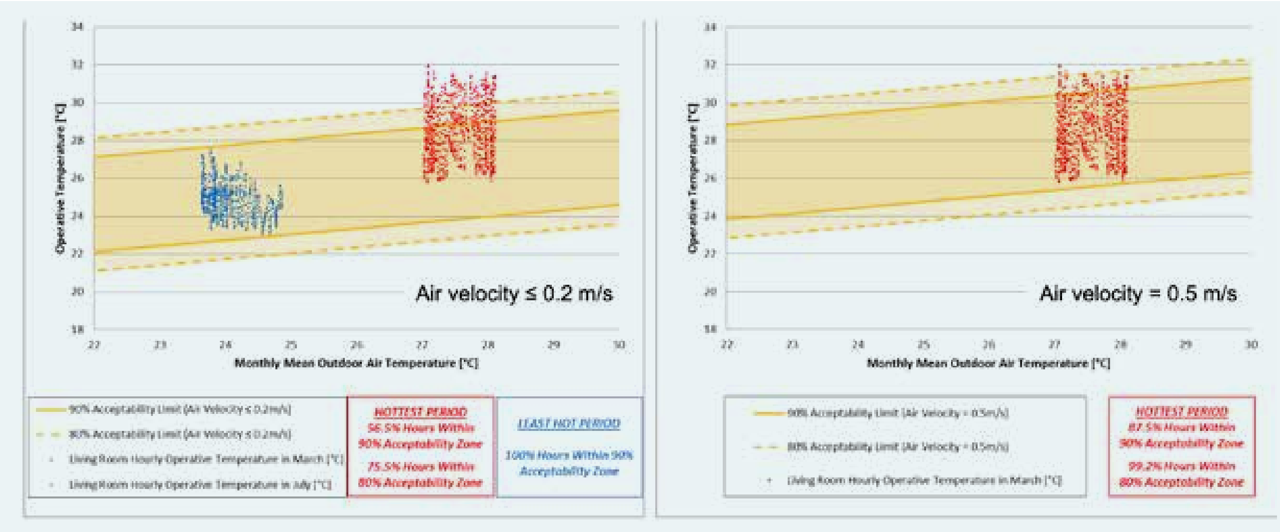


FIGURE A.5-5 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM DURING THE HOTTEST MONTH (MARCH) AND LEAST HOT MONTH (JULY) IN MOMBASA, PLOTTED OVER THE COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING AN INDOOR AIR VELOCITY ≤ 0.2 M/S AND = 0.5 M/S.**



A.5.1.4 ADDITIONAL EVALUATIONS

A second set of simulations was run on the same model, substituting the timber walls and ceiling with lightweight masonry. The ceiling was assumed to be 15 cm hollow block type and the walls to be made of 15 cm solid bricks plastered masonry. The comparison between the main outputs of the previous simulation (labelled "Case 0") and the one with brick walls (labelled "Case 1") is shown in Table A.5.2.

The comparison shows that lightweight masonry (only 15 cm thick) behaves slightly better, providing more hours of adaptive comfort. This is due to the fact that the operative temperature is "smoothed" (Fig. A.5-6 and A.5.7).

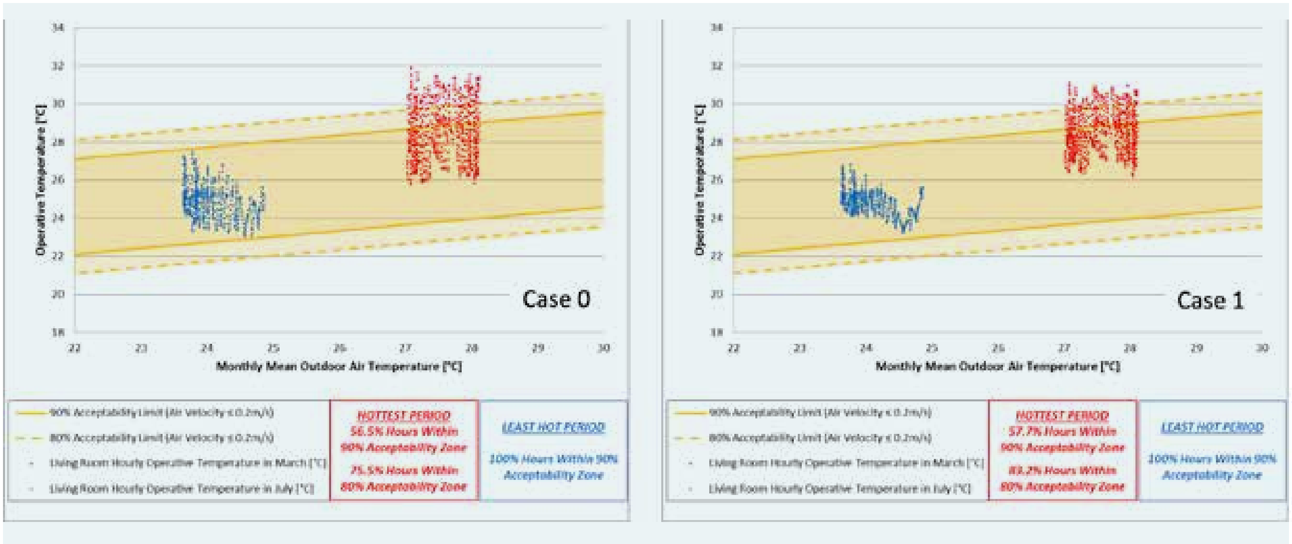
The conclusion is that 15 cm brick walls can be used instead of timber walls, reaching both the goals of a lower construction cost and slightly better comfort, reducing to a very limited number of hours in which air conditioning, if available, needs to be used.

FIGURE A.5-6 **"CASE 0" (ON THE LEFT SIDE) AND "CASE 1" (ON THE RIGHT SIDE) LIVING ROOM HOURLY OUTPUT COMPARISON**

TABLE A.5-2 **"CASE 0" AND "CASE 1" COMPARISON FOR THE LIVING ROOM, REFERRED TO THE PERCENTAGE OF HOURS FALLING INTO ASHRAE 55 ADAPTIVE COMFORT RANGE ALONG THE HOTTEST AND LEAST HOT MONTH, ASSUMING AN INDOOR AIR VELOCITY ≤ 0.2 M/S.**

	% hours in 90% Acceptability Zone		% hours in 80% Acceptability Zone	
	March	July	March	July
Case 0	56.5%	100%	75.5%	100%
Case 1	57.7%	100%	83.2%	100%

FIGURE A.5-7 **"CASE 0" (LEFT) AND "CASE 1" HOURLY OPERATIVE TEMPERATURES OCCURING IN LIVING ROOM DURING THE HOTTEST MONTH (MARCH) AND LEAST HOT MONTH (JULY) IN MOMBASA, PLOTTED OVER COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING AN INDOOR AIR VELOCITY ≤ 0.2 M/S.**



A.5.2 SINGLE STOREY BUILDING IN HOT ARID CLIMATE (LODWAR)

The house has a compact shape; the rectangular shaped rooms are in contact with small courtyards (Fig. A.5-8 and A.5-9). Large porches provide shading. All rooms have a flat roof, except the living room, whose roof is pitched. This room is located in the middle of the plan and, since its height is twice that of the other rooms, it catches light from small vertical openings in the upper part of the walls.

Bedrooms are in the north side, while kitchen and dining room are in the opposite side (south facing).

Glazed openings are minimised and located in the uppermost part of exterior walls. To favour airflow at night, doors are provided on walls adjacent to shaded courtyards and to porches and at the top of the staircase; the upper small windows at the top of the living room are also operable.

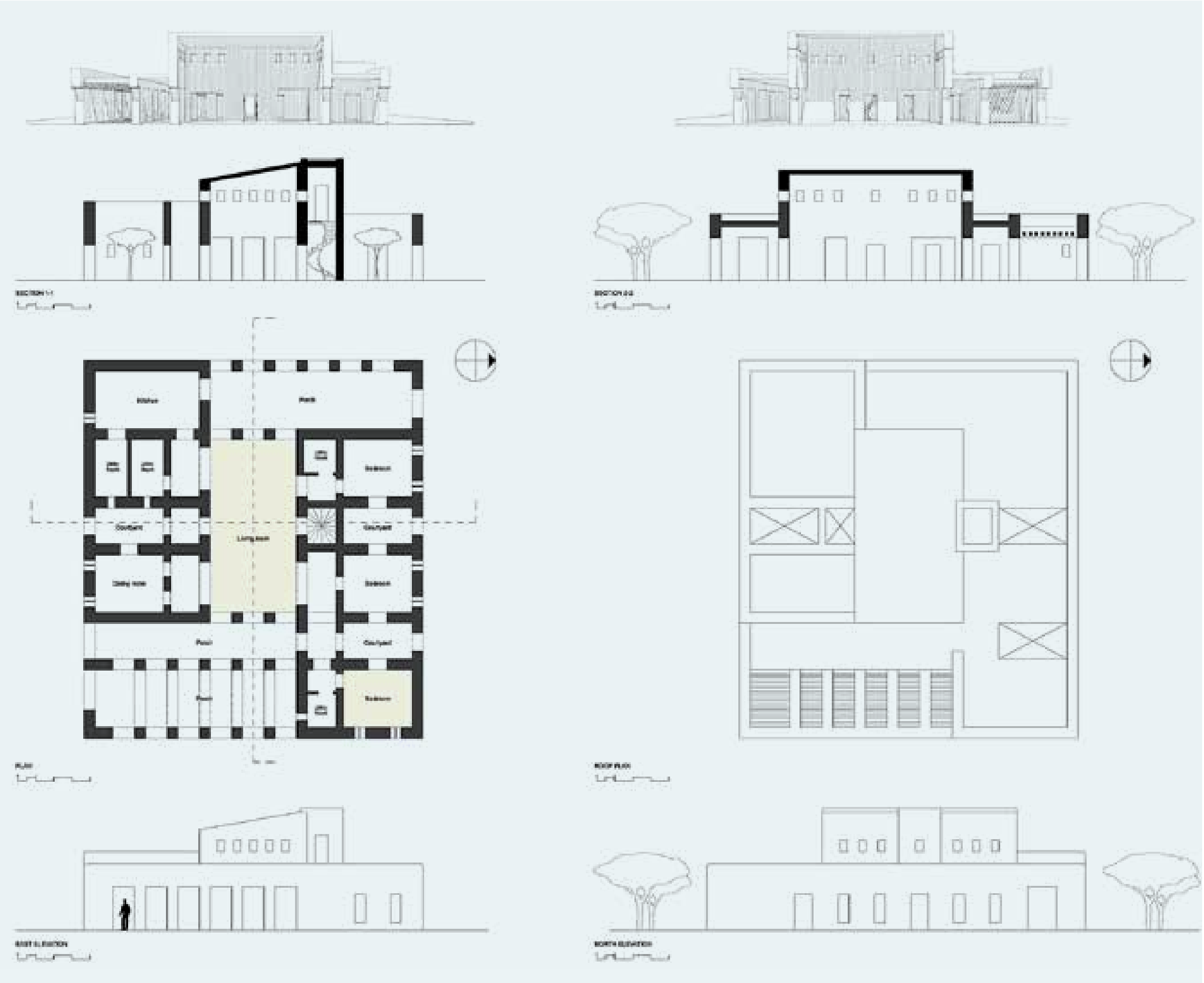
The simulation was carried out for the entire building, but results are presented only for the living room and the bedroom in the north-east corner.

A.5.5.1 ENVELOPE COMPONENTS

Exterior envelope is characterised by heavy weight components:

- Exterior walls: 60 cm solid bricks plastered masonry;
- Floor: 20 cm concrete layer in contact with the ground;
- Roof: 24 cm hollow block ceiling and a 35 cm soil layer;
- Windows: casement-type with 3 mm single clear glass pane and timber frame.

FIGURE A.5-8 **HOUSE IN HOT ARID CLIMATE (PLAN, ELEVATIONS AND SECTIONS)**



A.5.2.2 SIMULATION ASSUMPTIONS

Energy simulation was performed assuming:

- summer clothing (0.5 clo)
- occupancy constant during the simulation period, with 4 persons in the living room and two persons in bedroom 2;
- internal gains rate due to appliances, 2 W/m^2;
- windows, with flyscreen, open from 18:00 hrs. to 9:00 and closed in the remaining time. Inter-zone doors were assumed to be always open.

A.5.2.3 SIMULATION OUTPUTS

CFD simulations were first carried out to check if the preliminary window sizing, carried out with the simplified methods illustrated in section 3.5, was acceptable. Fig. A.5-10 shows that good air velocity is achieved with cross ventilation and highlights the significant contribution made by the stairwell to enhance ventilation.

In figure A.5-11 temperature hourly values are plotted for the living room in the hottest period (from March 03 to 21) for air velocity ≤ 0.2 m/s and = 0.5 m/s; temperatures are also plotted for the least hot period (from July 07 to 21), with air velocity ≤ 0.2 m/s. The adaptive ASHRAE comfort zone is overlaid, to show the comfort achieved. It can be noted that there is a temperature drop starting at 18:00 hrs, due to the opening of windows and doors[117]. In this way, during the day-time indoor temperature is lower than outdoors and during night-time the house cools down.

The interior surface of walls and ceiling is between 26 and 28 °C, as shown by the mean radiant temperature plotted in figure A.5-11, allowing an acceptable operative temperature for most of the time. If a fan is used (air velocity 0.5 m/s), 90% comfort is reached all the time.

117 The graph shows also that by delaying the opening of the windows by a couple of hours, i.e. to when outdoor air temperature becomes lower than indoors, better comfort conditions could be achieved.

FIGURE A.5-9 **HOUSE IN HOT ARID CLIMATE (SHADING AXONOMETRIC VIEWS)**

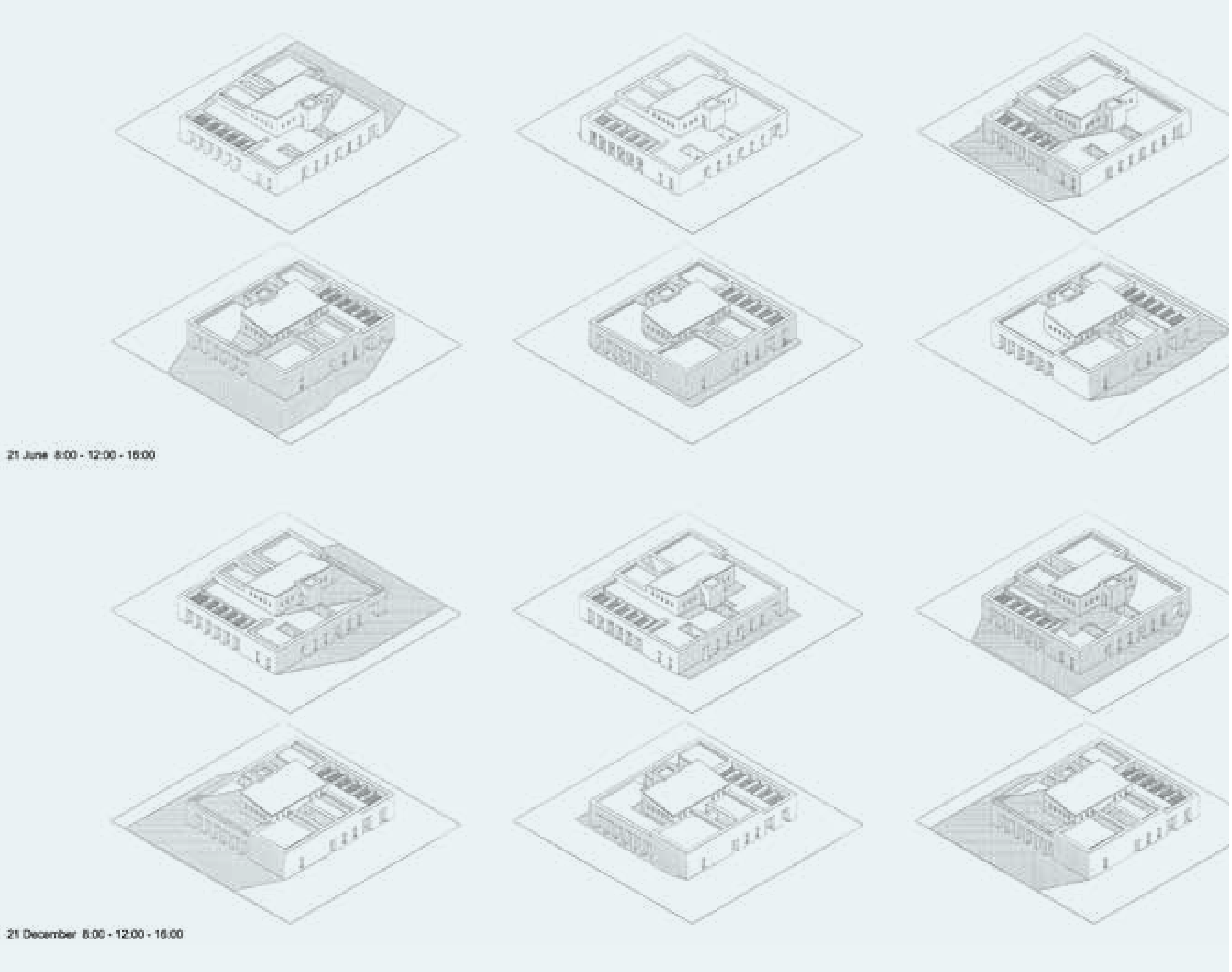
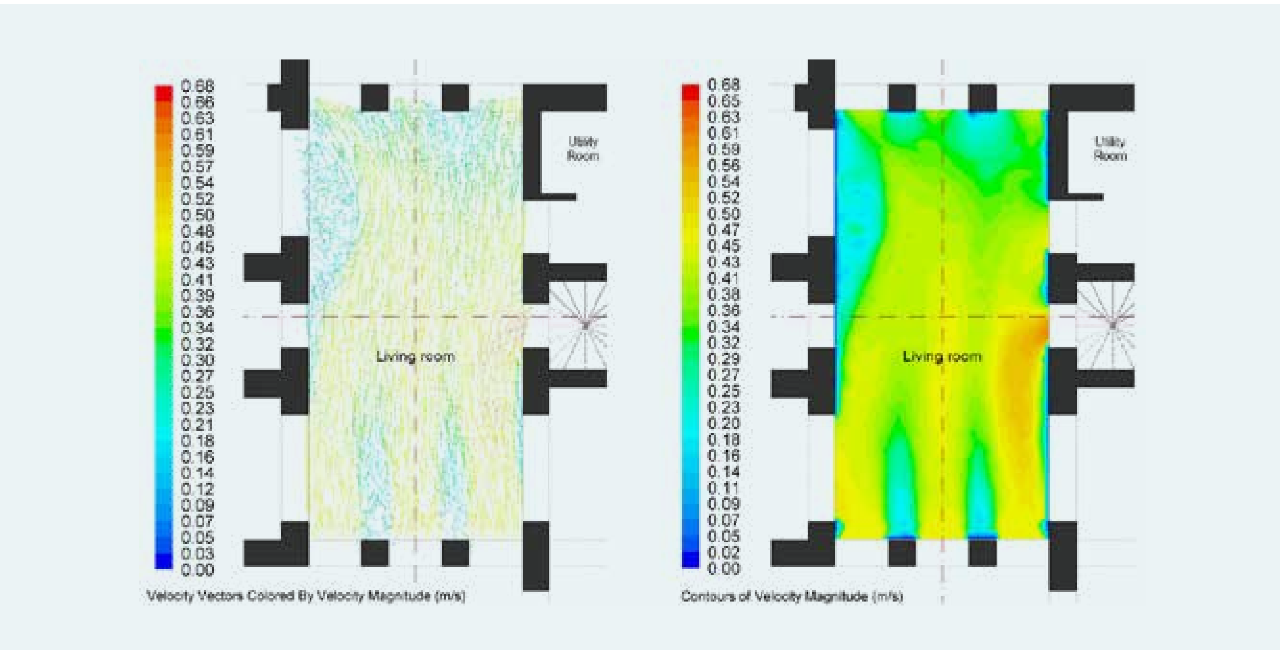


FIGURE A.5-10 **CFD SIMULATION OF THE LIVING ROOM WITH OUTDOORS WIND SPEED = 1.3 M/S FROM EAST**



During the least hot period, comfortable conditions are reached all the time, even without the need of a fan. In the bedroom, night comfort is always achieved even in the hottest period with air velocity 0.2 m/s (Fig. A.5-12).

Table A.5-3, the percentage of hours in which comfort is reached in the hottest month (March) and in the least hot month (July) is reported, both for living room and bedroom. Note that, some hourly operative temperatures falling below the comfort range lower limit were considered comfortable, because it is assumed that the occupants would use heavier clothing when needed. In the evaluation of bedroom comfort only night time hours are considered.

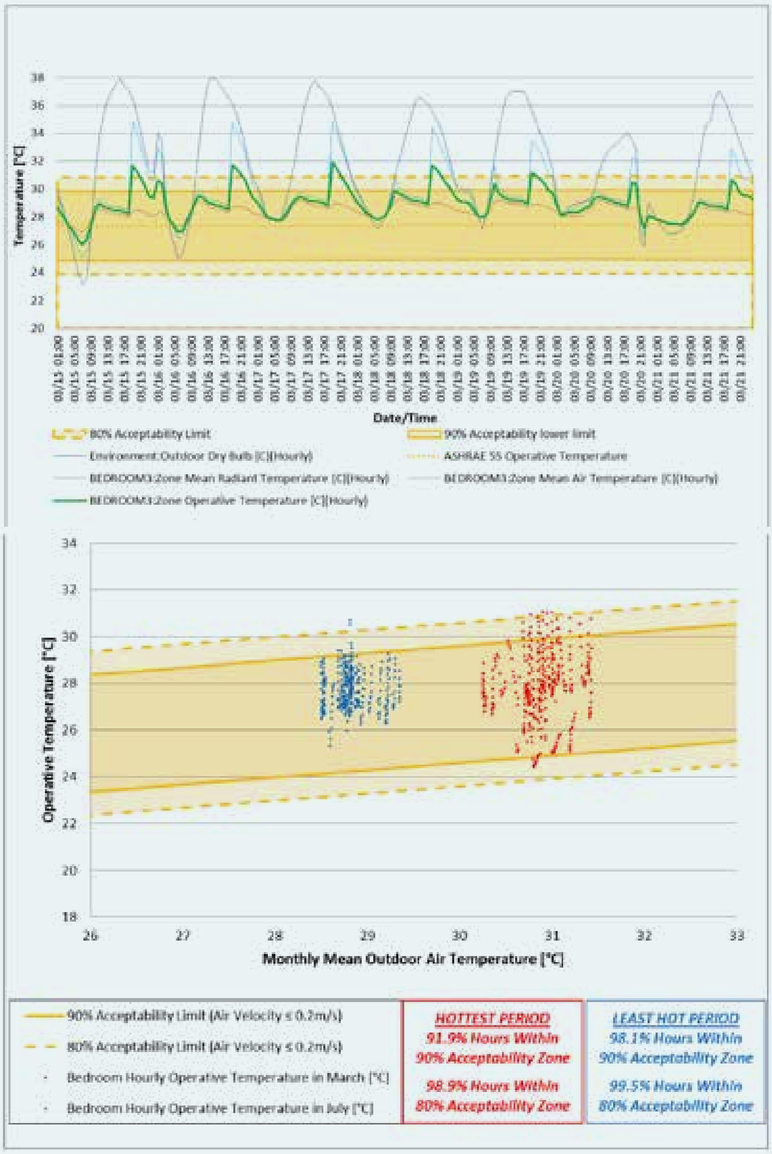
FIGURE A.5-11 **LIVING ROOM HOURLY TEMPERATURES IN THE HOTTEST (03/15 TO 03/21) AND LEAST HOT (07/07 TO 07/21) PERIOD AND ASHRAE 55 ADAPTIVE COMFORT BAND FOR INDOOR AIR VELOCITY ≤ 0.2 M/S AND 0.5 M/S**

Figure A.5-13, bottom, shows, for the living room, the plot of indoor hourly operative temperatures corresponding to the simultaneous outdoor air temperature, with the adaptive ASHRAE comfort zone overlaid, for the periods of hottest and least hot months of the year and for indoor air velocity ≤ 0.2 m/s and 0.5 m/s. The same kind of information is provided for the bedroom (air velocity ≤ 0.2 m/s) in figure A.5-12.

TABLE A.5-3 **PERCENTAGE OF HOURS THROUGH THE HOTTEST (MARCH) AND THE LEAST HOT (JULY) MONTH IN LODWAR IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS REACHED IN THE SIMULATED ROOMS. BEDROOM EVALUATION ONLY IN NIGHT TIME HOURS.**

Indoor Air Velocity	% hours in 90% acceptability Zone				% hours in 80% acceptability Zone			
	Living Room		Bedroom		Living Room		Bedroom	
	March	July	March	July	March	July	March	July
≤ 0.2 m/s	89.4%	94.9%	91.9%	98.1%	97.9%	99.7%	98.9%	99.5%
= 0.5 m/s	100%	100%	100%	100%	100%	100%	100%	100%

FIGURE A.5-12 **BEDROOM HOURLY TEMPERATURES FROM 03/15 TO 03/21 (LEFT) AND HOURLY OPERATIVE TEMPERATURES DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN LODWAR, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL (RIGHT). INDOOR AIR VELOCITY ≤ 0.2 M/S**



A.5.2.4 ADDITIONAL EVALUATIONS

A second set of simulations was run of the same geometrical model, assuming a different natural ventilation strategy and a less massive envelope.

In the first one (“Case 1”), nothing was changed in the original house (labelled as “Case 0”), but it was assumed that external doors and windows were left open for 24 hours, instead of being kept closed during the day-time.

In “Case 2”, the thermal mass of the envelope was more than halved by removing the soil layer on the roof and halving the thickness of the walls.

The results of the simulations carried out are summarised in Table A.5-4, where the percentage of 90% and 80% comfort hours achieved are given for the hottest period; for bedrooms only the night-time hours are considered, assuming an indoor air velocity ≤ 0.2 m/s.

Case 0 had the best performance. Case 1 shows a significant worsening. Case 2 outputs show that by halving the thermal mass of the envelope, the evaluated parameter decreases by 5.7 points in the living room and 14.5 points in the bedroom in 90% comfort acceptability. The lower reduction in the living room compared to the bedroom is due to the fact that the former is surrounded by other rooms, so reduction of thermal mass is less effective.

The conclusion that can be drawn is that a wall thickness of 40 cm is a reasonable compromise, as the decrease of comfort, with respect to the 60 cm thickness, is limited and can be compensated by using fans for increasing the indoor air velocity; the advantage is a lower construction cost.

TABLE A.5-4 **COMPARISON OF OUTPUT OF SIMULATED CASES, REFERRING TO THE PERCENTAGE OF HOURS THROUGH THE HOTTEST MONTH (MARCH) FALLING INTO ASHRAE 55 ADAPTIVE COMFORT RANGE, ASSUMING AN INDOOR AIR VELOCITY LESS THAN OR EQUAL TO 0.2 M/S. EVALUATION OF BEDROOM COMFORT IS LIMITED TO NIGHT TIME.**

	% hours in 90% Acceptability Zone		% hours in 80% Acceptability Zone	
	Living Room	Bedroom	Living Room	Bedroom
Case 0	89.4%	91.9%	97.9%	98.9%
Case 1	59.1%	82.8%	70.3%	95.4%
Case 2	83.7%	77.4%	91.7%	92.7%

A.5.3 HOUSE IN UPLAND CLIMATE (NAIROBI)

The layout, the shape and the orientation of the house in Nairobi is basically the same as the one in Mombasa, with the addition of a sun-space obtained by enclosing with glass the part of the porch in front of the dining and living rooms, on the north side (Fig. A.5-14, A.5-15, A.5-16 and A.5-17). The glazed façade of the sun-space can be fully opened to avoid overheating on the hottest days, simply by moving the system along a rail and packing it alongside, as shown in figure A.5-36. Three glass doors allow airflow exchange between the sun-space and the dining and living rooms.

The other difference from the house in hot humid climate is a smaller window area and the roof, which is not ventilated.

FIGURE A.5-14 **SINGLE-STOREY RESIDENTIAL BUILDING IN UPLAND CLIMATE (PLAN)**

FIGURE A.5-15 **SINGLE-STOREY RESIDENTIAL BUILDING IN UPLAND CLIMATE (SECTIONS)**

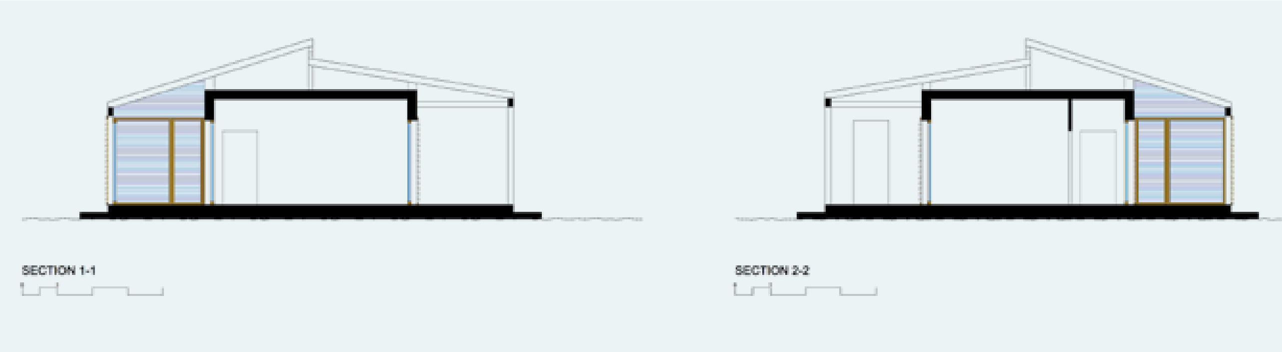
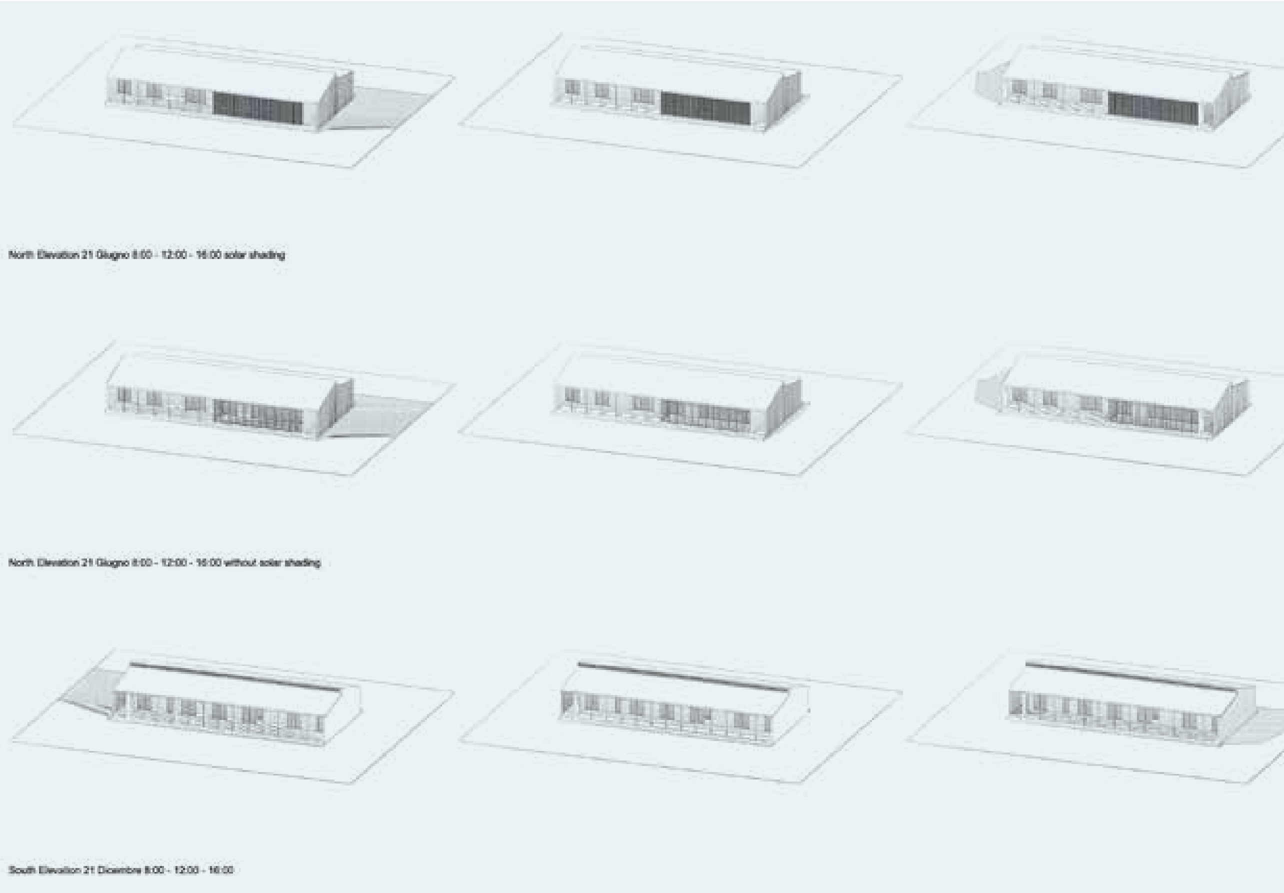


FIGURE A.5-16 **SINGLE-STOREY RESIDENTIAL BUILDING IN UPLAND CLIMATE (ELEVATIONS)**

FIGURE A.5-17 **SINGLE-STOREY RESIDENTIAL BUILDING IN UPLAND CLIMATE (SHADOWS AXONOMETRIC VIEWS)**



A.5.3.1 ENVELOPE COMPONENTS

Exterior envelope was designed as follows:

- exterior walls: medium weight walls made of 30 cm solid brick plastered masonry;
- floor: 20 cm concrete layer in contact with the ground;
- ceiling: 24 cm hollow block ceiling
- roof: aluminium sheet
- windows: casement-type with 3 mm single clear glass pane and timber frame; fly-screen

A.5.3.2 SIMULATION ASSUMPTIONS

Energy simulation was performed assuming:

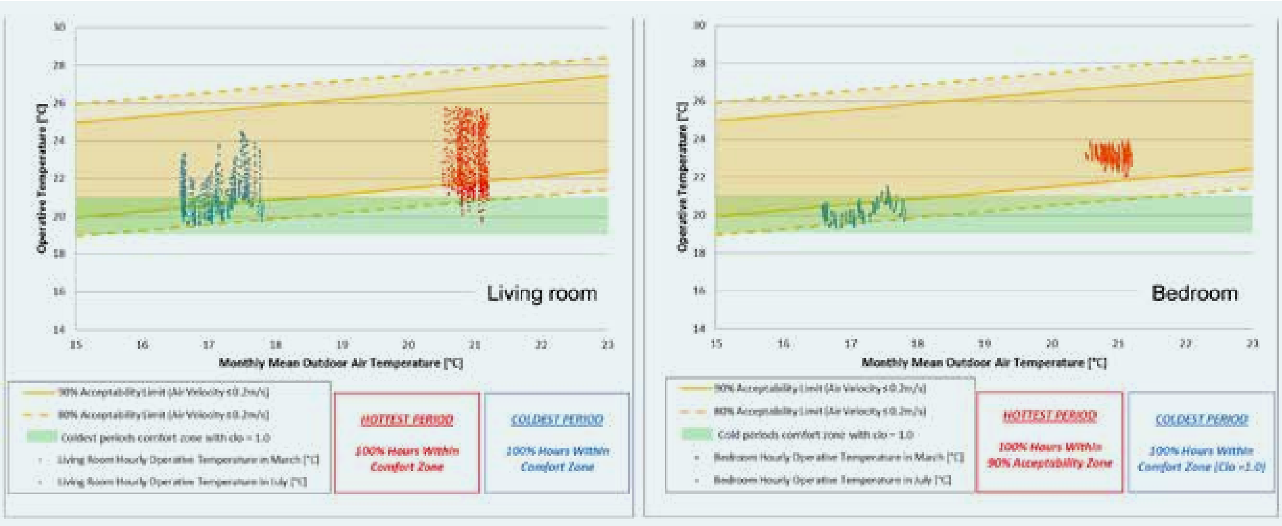
- clothing in hottest periods: 0.5 clo;
- clothing in coldest periods: 1.0 clo;
- occupancy constant during the simulation period, with 4 persons in the living room and two persons in bedroom;
- internal gains rate due to appliances, 2 W/m^2;
- glass doors between living room and sun-space closed in the cool season, to provide a buffer-zone;
- exterior glass doors of the sunspace open only in the hottest periods, to avoid overheating;
- no other exterior windows and doors were opened in coldest periods, assuming only infiltrations from outdoor environment equal to 0.5 air changes rate, while in hottest periods they were opened whenever outdoor airflow could provide comfort.

A.5.3.3 SIMULATION OUTPUTS

Indoor comfort conditions were analysed in the living room and in a bedroom (highlighted pale yellow in figure A.5-14). Figure A.5-18 shows the plot of the operative temperature in the living room and in the bedroom in conjunction with the outdoor air temperature at the same time for the hottest and the cool period, with the adaptive comfort band overlapped; the air velocity is ≤ 0.2 m/s. In many hours the operative temperature is below the comfort range, but this does not mean thermal discomfort, since the adaptive comfort temperature range is defined assuming summer clothing. If winter clothing is worn during these days and during all the cold period, as actually happens, the comfort range changes, as shown in green in figure A.5-18. Taking this into consideration, there is no need either for heating or for cooling, as shown in Table A.5-5.

Figure A.5-18 also shows in a very clear way the positive effect of the sunspace in front of the living room, that is definitively warmer than the bedroom in the cool period. An extension of the sunspace to the entire north façade could be helpful in improving comfort during the cool period.

FIGURE A.5-18 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM AND THE BEDROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN NAIROBI, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, FOR INDOOR AIR VELOCITY ≤ 0.2 M/S**



A.5.3.4 ADDITIONAL EVALUATIONS

In order to evaluate the appropriateness of the strategies used in the previously simulated case, two other variations were simulated. The first one (labelled "Case 1"), differs from the previous one (labelled "Case 0") only by the sun-space, which in Case 1 has been taken out. Only the coldest month was simulated. The second one (labelled "Case 2"), differs from "Case 0 "in the envelope construction, which is light-weight, the same as in "Case 0" in a hot humid climate.

The comparisons were limited to the living room. Table A.5-8 summarises the results of simulations and highlights the contribution to comfort given by the sunspace, without which in the coldest periods some heating is necessary. The same table shows that a lightweight envelope leads to discomfort both in the hot and in the cold periods.

TABLE A.5-5 **COMPARISON OF OUTPUTS OF SIMULATED CASES, REFERRING TO THE PERCENTAGE OF HOURS DURING THE HOTTEST MONTH (MARCH) AND THE COLDEST MONTH (JULY) FALLING INTO COMFORT RANGES, ASSUMING AN INDOOR AIR VELOCITY ≤ 0.2 M/S.**

	% hours in 90% Acceptability Zone		% hours in 80% Acceptability Zone	
	Living room		Bedroom	
	Hottest	Least hot	Hottest	Least hot
Case 0	100%	100%	100%	100%
Case 1	100%	93.3%	100%	93.3%
Case 2	92.5%	88.8%	99.0%	91.6%

A.5.4 MULTI-STOREY RESIDENTIAL BUILDINGS IN EAC

An apartment at the top floor of a multi-storey building (Fig. A.5-19, A.5-20, A.5-21) with the same plan as the single storey building would behave like the single-storey building (actually, a little better because the wind velocity will be higher, due to the height above the ground). All the other floors will show better performances than the single storey building because of absence of heat flow from the roof. Thus, the results of simulations carried out for the single-storey building can be applied to each apartment of the multi-storey building as a conservative evaluation, if the surrounding buildings do not obstruct the wind flow around it (see section 3.3 – Site planning).

FIG. A.5-19 **MULTI-STOREY SINGLE BANKED BUILDING – PLAN**

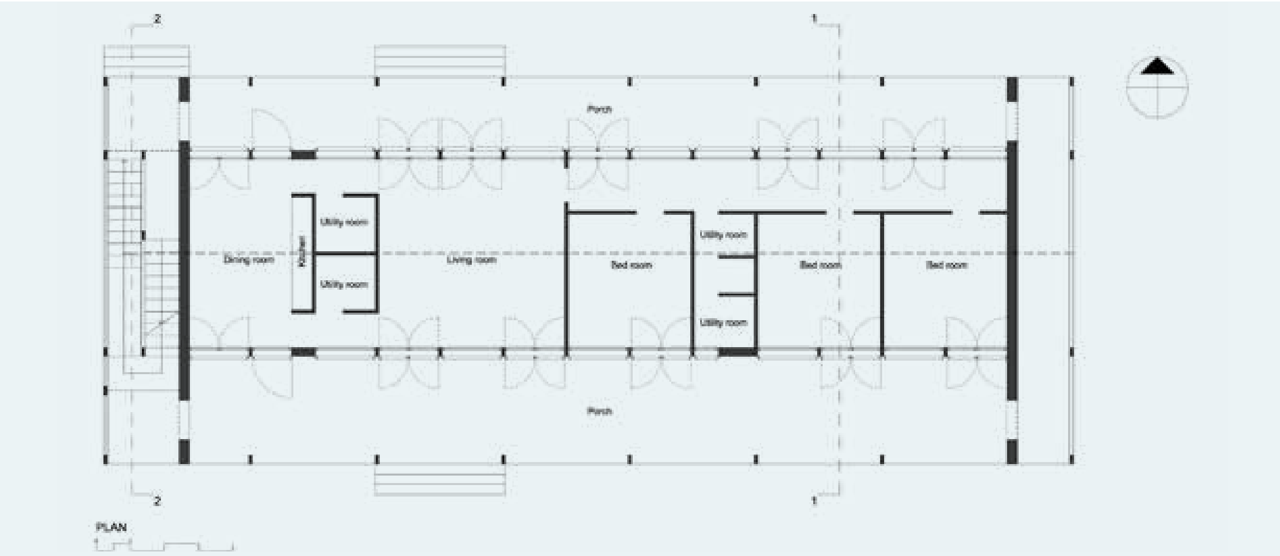


FIG. A.5-20 **MULTI-STOREY SINGLE BANKED BUILDING – SECTION 1-1 AND NORTH ELEVATION**

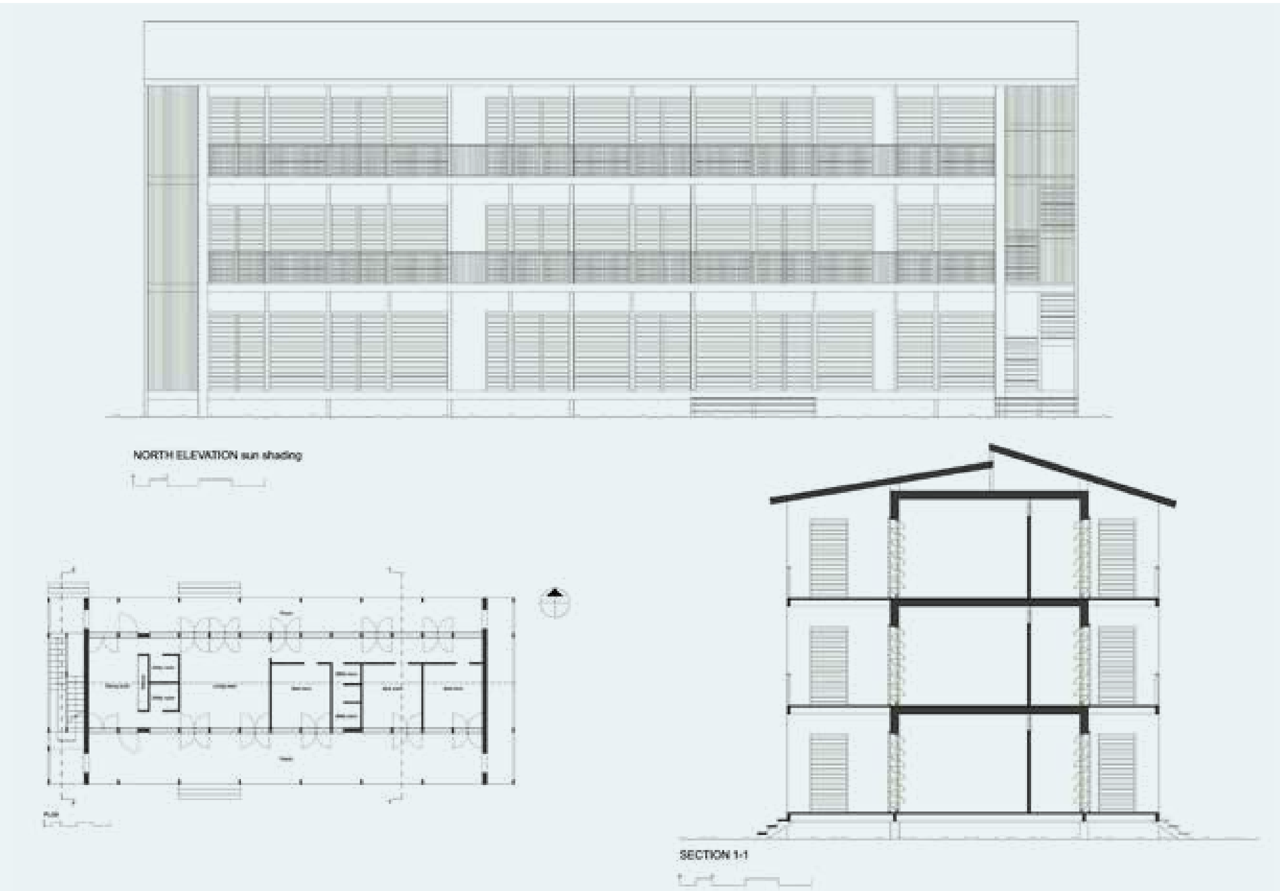
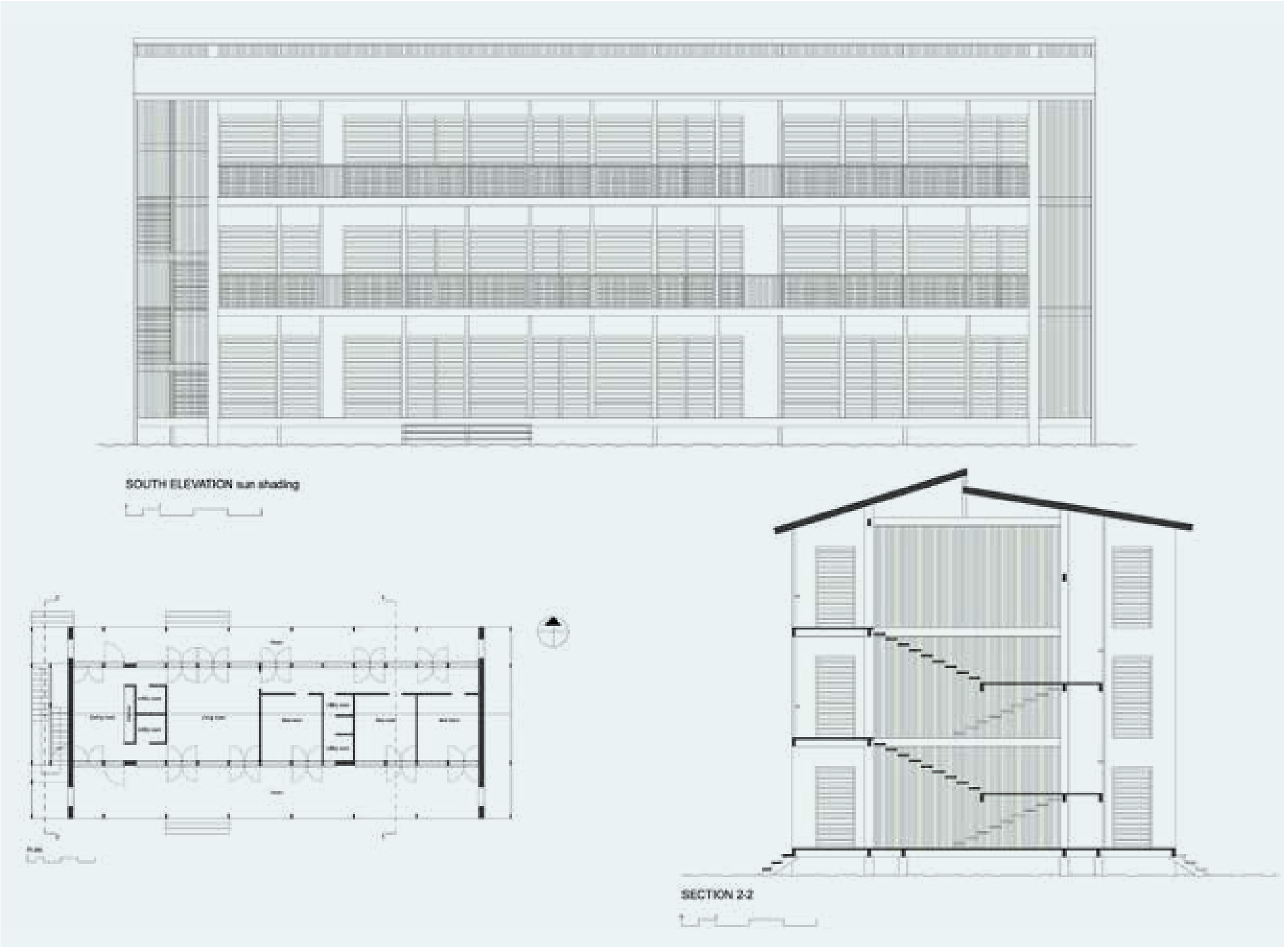


FIG. A.5-21 **MULTI-STOREY SINGLE BANKED BUILDING – SECTION 2-2 AND SOUTH ELEVATION**



Single banked buildings are the most appropriate for enhancing cross ventilation, but they need to be open to the wind, thus the distance between them and the reciprocal position is strongly constrained, and in contradiction with the need for a more compact urban layout.

For this reason, a different type of multi-storey building was designed, aiming to create a replicable architectural type which is adaptable to different climatic areas by changing only the envelope components. It is a four-storey building, with four apartments per floor and two courtyards separated by an atrium containing the staircase (figures A.5.21 to A.5.27). North and south façades are provided with balconies. Each apartment consists of a living room, a kitchen, two bedrooms and two bathrooms linked by a corridor, which faces the courtyard and a terrace mainly used as an outdoor kitchen. The openings are positioned in such a way as to allow some cross ventilation when needed; the depth of the balconies is optimised according to the solar path and provide shading most of the time. East and west openings are protected with a fixed outside egg-crate sunscreen. For each climatic zone, different envelope components were chosen. To evaluate the performances of the building, the simulation outputs relative to the living room and a bedroom in the north west apartment on the first floor (highlighted in pale yellow in figure A.5-22) were analysed.

A.5.4.1 HOT HUMID CLIMATE (MOMBASA)

A.5.4.1.1 **ASSUMPTIONS**

- exterior walls: 15 cm perforated brick plastered both sides
- internal partitions: 1.25 cm plasterboard enclosing a 10cm air gap
- floors: 1.5 cm plaster layer, 24 cm hollow brick, a 4cm sand and cement concrete layer and a ceramic tile finishing.
- windows and doors: jalousie-type with a single 3 mm clear glass pane and timber frame; fly-screen.
- occupancy: 4 persons in the living room and two persons in each bedroom;
- internal gains due to appliances: 2 W/m^2
- windows always open.
- inter-zone openings: always open

FIGURE A.5.22 **MULTI-STOREY RESIDENTIAL BUILDING (GROUND FLOOR AND FIRST FLOOR PLANS)**

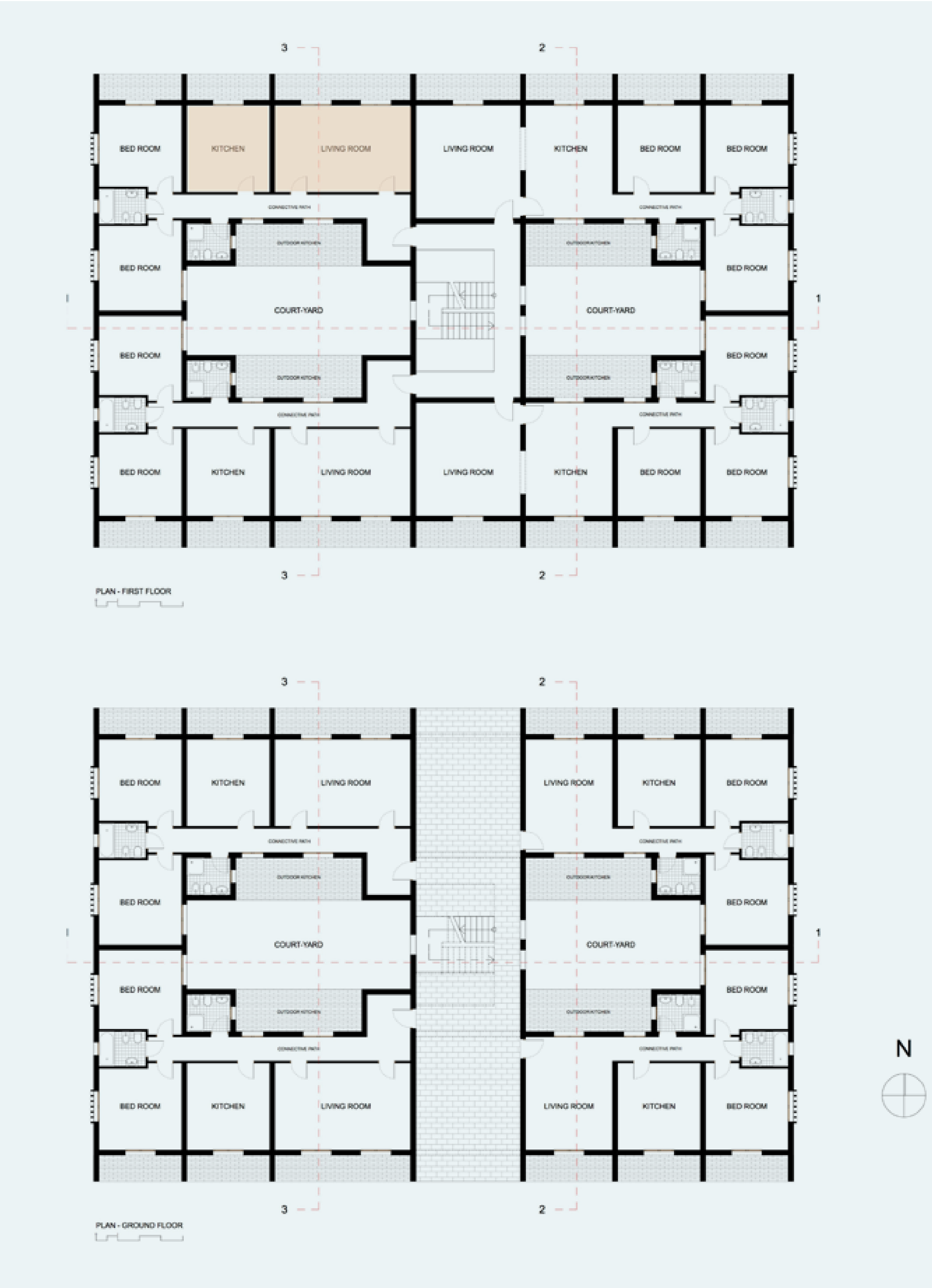


FIGURE A.5.23 **MULTI-STOREY RESIDENTIAL BUILDING (ROOF PLAN).**

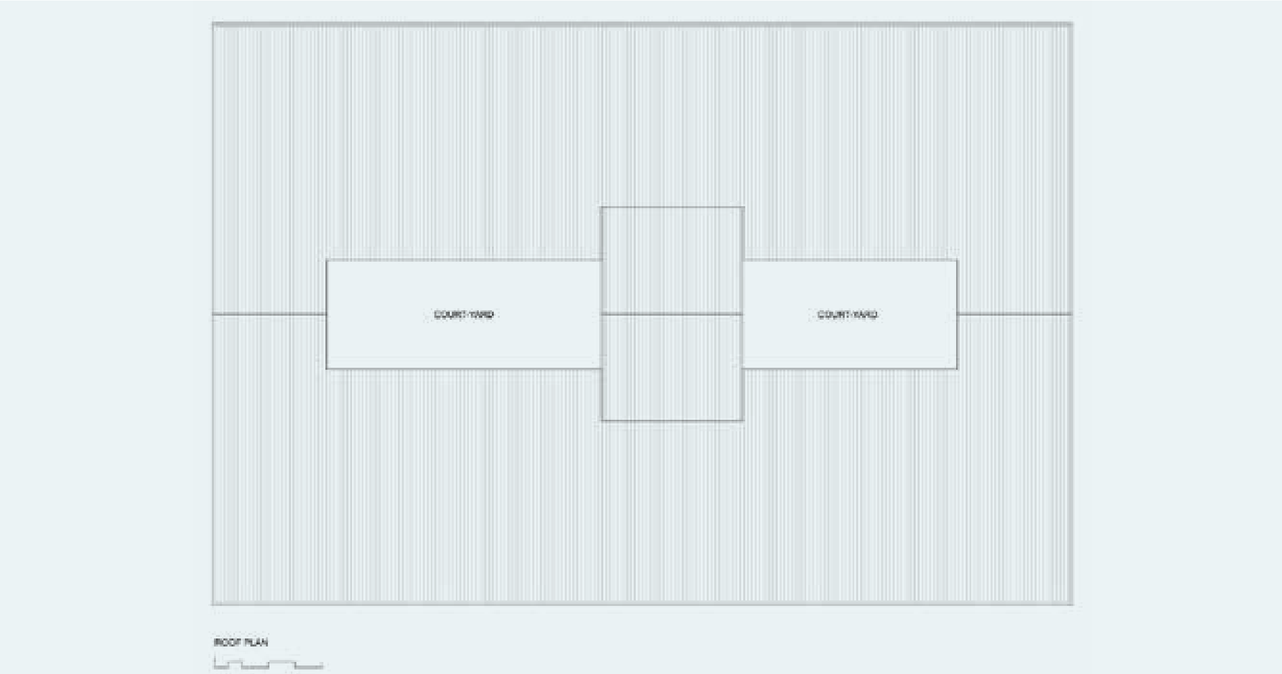


FIGURE A.5-24 **MULTI-STOREY RESIDENTIAL BUILDING (VERTICAL SECTION 1-1')**

FIGURE A.5.25 **MULTI-STOREY RESIDENTIAL BUILDING (VERTICAL SECTIONS 2-2' AND 3-3')**

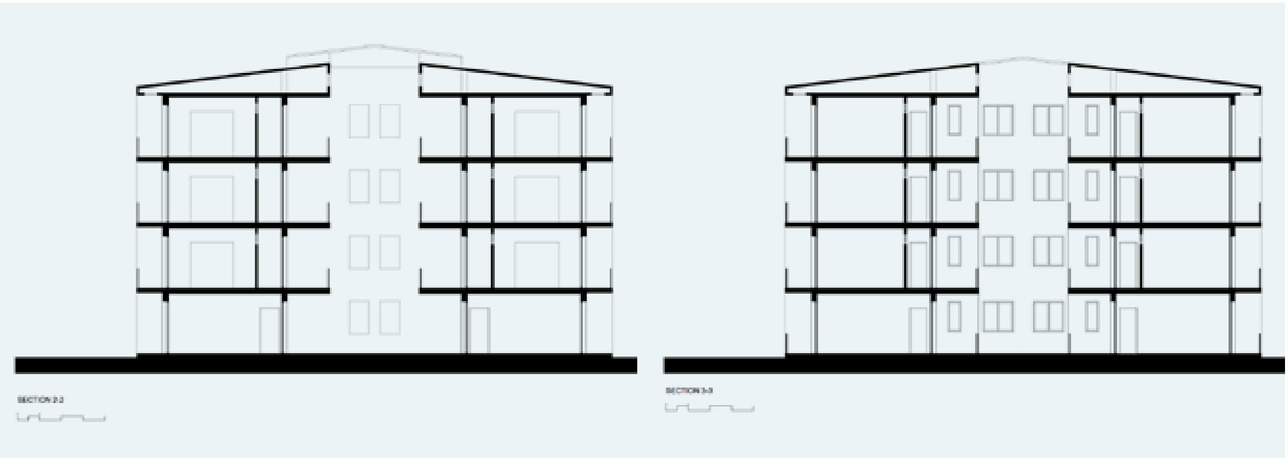
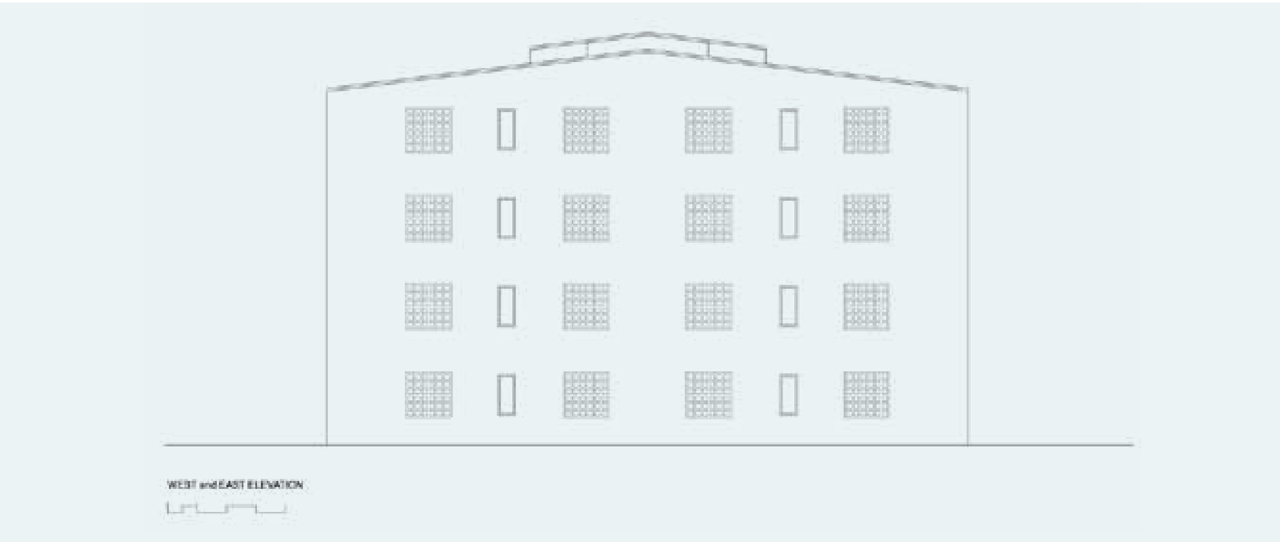


FIGURE A.5.26 **MULTI-STOREY RESIDENTIAL BUILDING (NORTH AND SOUTH ELEVATIONS)**

FIGURE A.5.27 **MULTI-STOREY RESIDENTIAL BUILDING (WEST AND EAST ELEVATIONS)**



A.5.4.1.2 **SIMULATION OUTPUTS**

Figure A.5-28 shows that during the hottest period (March 03-21) in the middle of the day in the living room the operative temperature is always above the comfort zone, but if a fan is used (air velocity = 0.5 m/s), comfort is achieved almost all the time; in the least hot period (July 07-21), comfort is always achieved.

In the bedroom, comfort conditions with air velocity ≤ 0.2 m/s are worse than in the living room (Fig. A.5-29, left), due primarily to the unshaded wall facing west, but the presence of two windows - even if not opposing - provides good ventilation, with consequent air velocity above 0.2 m/s. With air velocity = 0.5 m/s, which can be also obtained with a fan if outside wind is not sufficient, the operative temperature during the night is within the adaptive comfort range most of the time (Fig. A.5-29, right). Figure A.5-30 shows, for the living room, the plot of the operative temperature in conjunction with the outdoor air temperature at the same time, overlapped with the ASHRAE comfort band, for the hottest and the least hot month with 0.2 and 0.5 m/s air velocity, respectively. The same kind of information is provided in figure A.5-31 for the bedroom.

Table A.5-6 summarises the results as a percentage of the comfort hours in the living room and in the bedroom (calculated only for the night time) in the hottest period.

The simulation outputs show that in conditions of no wind (which is very unlikely in Mombasa and in general in all hot humid coastal locations in the EAC countries), during the hottest month for about 50% of time 90%

adaptive comfort is not reached. In normal conditions, i.e. with the typical wind velocity, the number of hours in which comfort is not attained is significantly smaller. In any case, if a fan is activated, air conditioning is necessary for only a few hours in the hottest period. Otherwise, adaptive comfort is always attained in least hot month.

TABLE A.5.6 **PERCENTAGE OF HOURS THROUGH THE HOTTEST (MARCH) MONTH IN MOMBASA IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS ACHIEVED**

Hottest month comfortable hours in hot humid climate (Mombasa)				
Indoor Air Velocity	**% Hours in 90% Acceptability Zone**		**% Hours in 80% Acceptability Zone**	
	Living Room	Bedroom	Living Room	Bedroom
≤ 0.2 m/s	56.5%	50.0%	88.2%	80.9%
0.5 m/s	99.5%	96.2%	100%	100%

FIGURE A.5.28 **LIVING ROOM HOURLY TEMPERATURES IN MOMBASA FOR DIFFERENT PERIODS (HOTTEST AND LEAST HOT) AND AIR VELOCITY (≤ 0.2 AND = 0.5 M/S)**

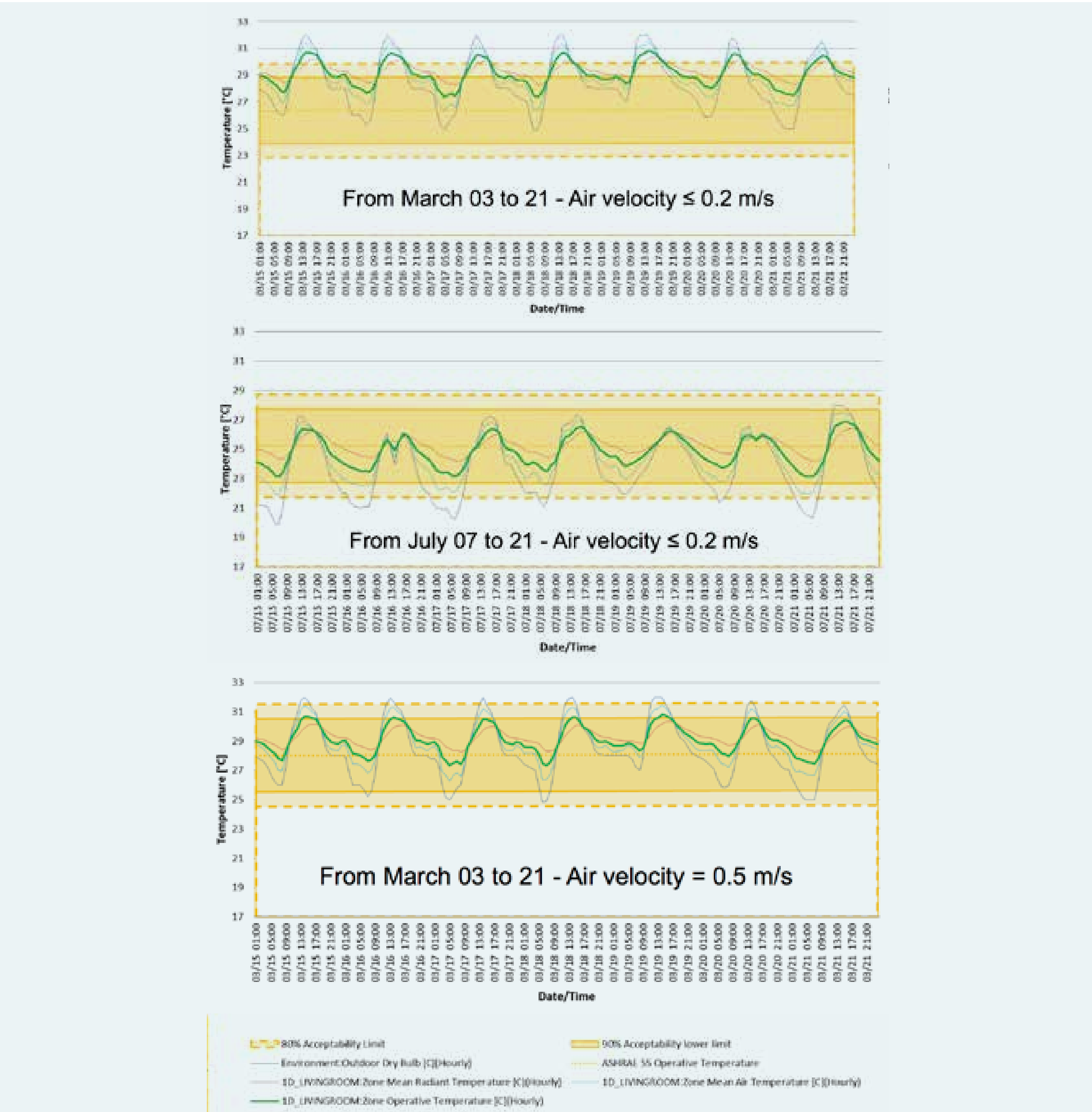


FIGURE A.5-29 **BEDROOM HOURLY TEMPERATURES IN MOMBASA FOR THE HOTTEST PERIOD (MARCH 03-21) AND DIFFERENT AIR VELOCITY (≤ 0.2 AND = 0.5 M/S)**

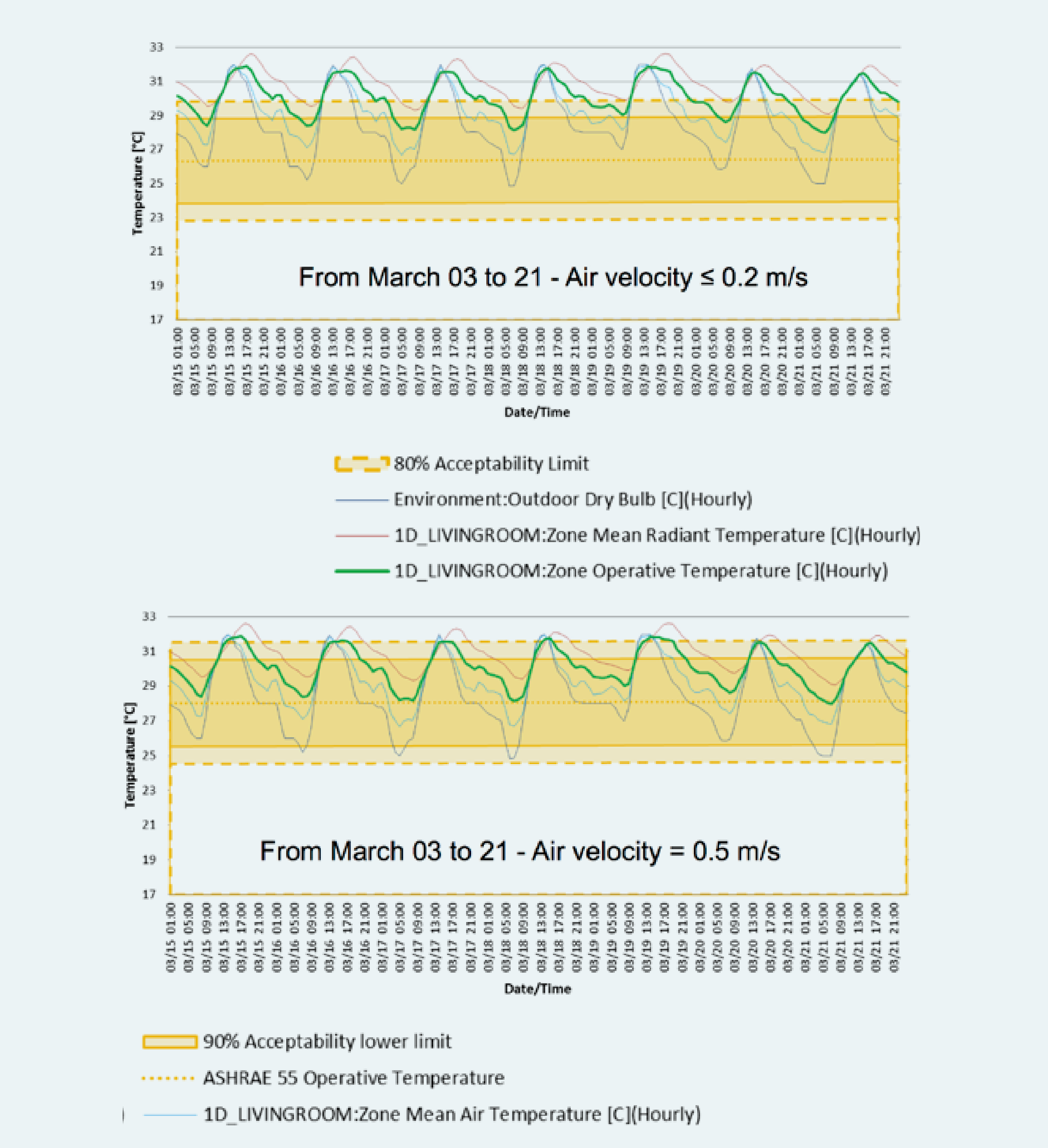


FIGURE A.5-30 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN MOMBASA, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING INDOOR AIR VELOCITY ≤ 0.2 M/S AND = 0.5 M/S**

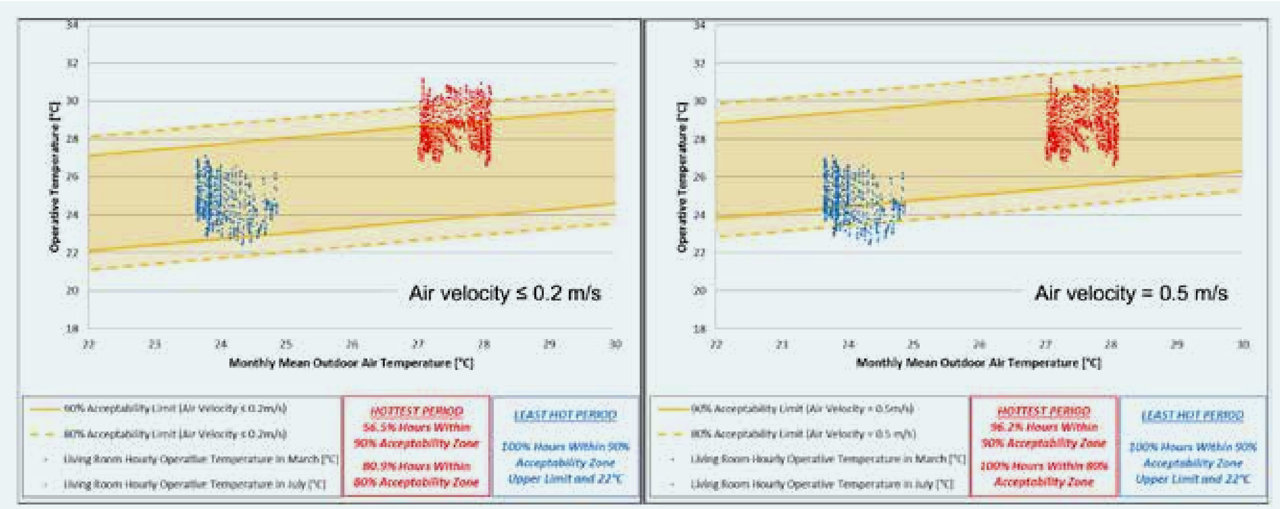
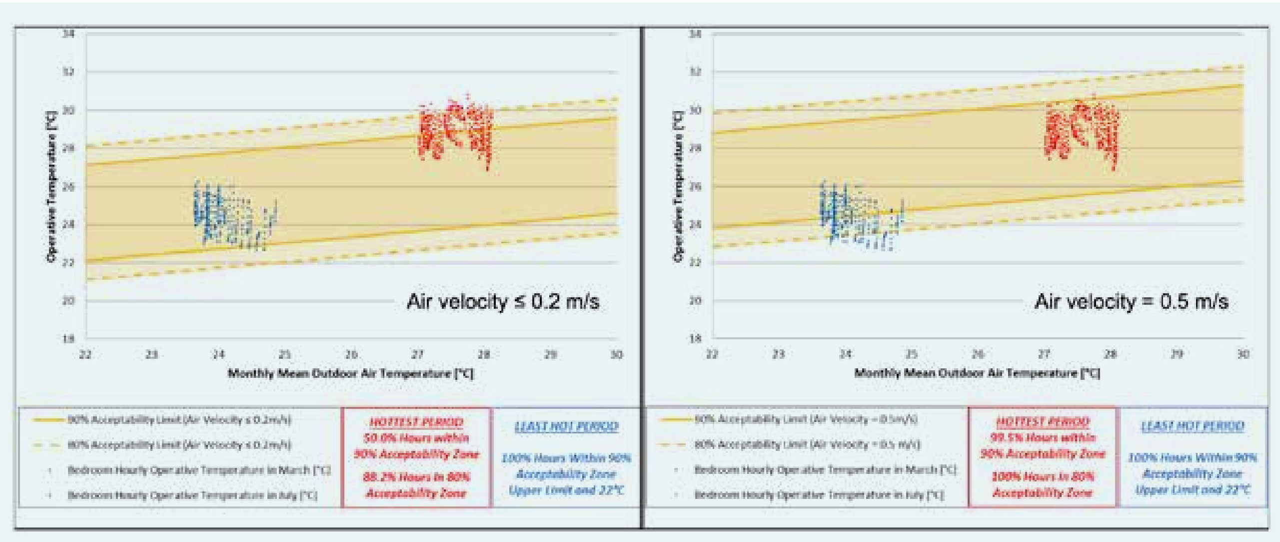


FIGURE A.5-31 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE BEDROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN MOMBASA, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING INDOOR AIR VELOCITY ≤ 0.2 M/S AND = 0.5 M/S**



A.5.4.2 UPLAND CLIMATE (NAIROBI)

A.5.4.2.1 **ASSUMPTIONS**

- exterior walls: 15 cm solid brick plastered both sides
- internal partitions: plasterboard.
- floors: 1.5 cm plaster layer, 24 cm hollow brick, a 4 cm sand and cement concrete layer and a ceramic tile finishing
- windows: casement
- occupancy: 4 persons in the living room and two persons in each bedroom
- internal gains due to appliances: 2 W/m^2
- exterior windows, with flyscreens, closed most of the time. Air infiltrations from outdoors: 0.5 ACH
- inter-zone openings: always open

A.5.4.2.2 **SIMULATION OUTPUTS**

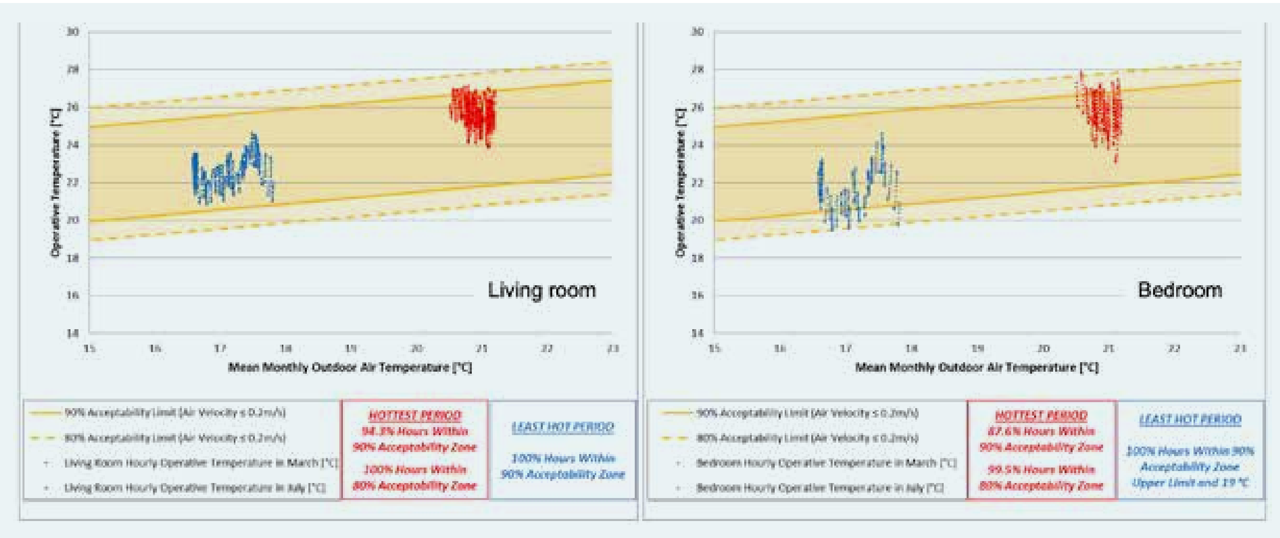
As shown in figure A.5-32 and summarised in Table A.5-7, comfort is achieved in all seasons if a fan is activated in the hottest hours.

Comparing these results with those of the single-storey case, without sunspace (Table A.5-8), the apartment in the multi-storey appears to be slightly more uncomfortable during the hot season, especially the bedroom, but slightly warmer during the cold one.

TABLE A.5.7 **PERCENTAGE OF HOURS THROUGH THE HOTTEST (MARCH) AND THE LEAST HOT (JULY) MONTH IN NAIROBI IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS REACHED**

Hottest and least hot month evaluation for upland climate (Nairobi)								
Indoor Air Velocity	**% Hours in 90% Acceptability Zone**				**% Hours in 80% Acceptability Zone**			
	Living Room		Bedroom		Living Room		Bedroom	
	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot
≤ 0.2 m/s	94.3%	100%	87.6%	100%	100%	100%	99.5%	100%

FIGURE A.5-32 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM AND IN THE BEDROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN NAIROBI, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING AN INDOOR AIR VELOCITY FOR COMFORT RANGE ≤ 0.2 M/S.**



A.5.4.3 SAVANNAH CLIMATE (TABORA)

A.5.4.3.1 **ASSUMPTIONS**

- Exterior walls: (from inside to outside) plaster, 15 cm solid brick, 15 cm perforated brick, plaster.
- Internal partitions: plastered 12 cm solid bricks
- Floors: 1.5 cm plaster layer, 24 cm hollow brick, a 4 cm sand and cement concrete layer and a ceramic tile finishing
- Windows: awning
- occupancy: 4 persons in the living room and two persons in each bedroom
- internal gains due to appliances: 2 W/m²
- exterior windows, with flyscreens, open every day, from 7:00 p.m. to 8:00 a.m. and closed in the remaining time
- inter-zone doors: always open

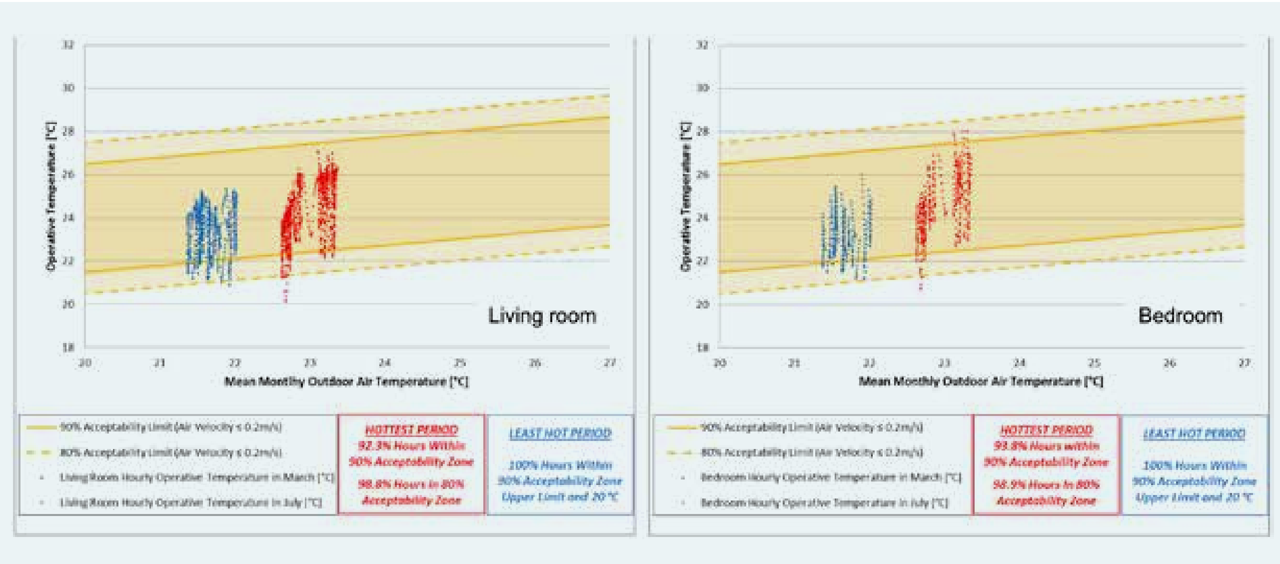
A.5.4.3.2 **SIMULATION OUTPUTS**

As shown in figure A.5.33 and summarised in Table A.5-8, the building seems appropriate for the savannah climate, as there is need to activate a fan in the hottest period, both in the living room and the bedroom in less than 10% of the hours. During the cool period and in the usually cool nights comfort can be reached by the occupants' wearing heavier clothing.

TABLE A.5.8 **PERCENTAGE OF HOURS THROUGH THE HOTTEST (MARCH) AND THE LEAST HOT (JULY) MONTH IN TABORA IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS REACHED**

Hottest and least hot month evaluation for savannah climate (Tabora)								
Indoor Air Velocity	**% Hours in 90% Acceptability Zone**				**% Hours in 80% Acceptability Zone**			
	Living Room		Bedroom		Living Room		Bedroom	
	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot
≤ 0.2 m/s	92.3%	100%	93.8%	100%	98.8%	100%	98.9%	100%

FIGURE A.5-33 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM AND IN THE BEDROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN TABORA, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING AN INDOOR AIR VELOCITY FOR COMFORT RANGE ≤ 0.2 M/S.**



A.5.4.4 GREAT LAKES CLIMATE (KAMPALA)

A.5.4.4.1 **ASSUMPTIONS**

- exterior walls: (from inside to outside) plaster, 15 cm solid brick, 15 cm perforated brick, plaster internal partitions: plastered 12 cm solid bricks floors: 1.5 cm plaster layer, 24 cm hollow brick, a 4cm sand and cement concrete layer and a ceramic tile finishing windows: awning with movable exterior shading
- occupancy: 4 persons in the living room and two persons in each bedroom
- internal gains due to appliances: 2 W/m^2
- exterior windows, with flyscreen, closed at night. Infiltrations: 0.5 ACH
- inter-zone doors: always open

A.5.4.4.2 **SIMULATION OUTPUTS**

As shown in figures A.5-34 and A.5-35 and summarised in Table A.5-9, the building's performances are good, providing full (almost full in the bedroom) adaptive comfort by using a fan for a limited number of hours.

A.5.5 IMPROVED MULTI-STOREY BUILDING

Simulation outputs show that in all the climates examined the bedroom is less comfortable than the living room during the day and at night does not always provide acceptable comfort conditions without the use of a fan. This is primarily due to the fact that there is a wall facing west that accumulates solar heat. The problem can be solved with a sunscreen protecting all the east and west facades, as shown in in figures A.6-36, A.6-37 and A.6-38.

TABLE A.5-9 **PERCENTAGE OF HOURS THROUGH THE HOTTEST (MARCH) AND THE LEAST HOT (JULY) MONTH IN KAMPALA IN WHICH ASHRAE 55 ADAPTIVE COMFORT IS REACHED**

Hottest and least hot month evaluation for great lakes climate (Kampala)								
Indoor Air Velocity	% hours in 90% Acceptability Zone				% hours in 80% Acceptability Zone			
	Living Room		Bedroom		Living Room		Bedroom	
	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot	Hottest	Least hot
≤ 0.2 m/s	86.8%	96.5%	73.1%	89.7%	100%	100%	100%	100%
0.5 m/s	100%	100%	98.4%	100%	100%	100%	100%	100%

FIGURE A.5-34 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE LIVING ROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN KAMPALA, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING INDOOR AIR VELOCITY ≤ 0.2 M/S AND = 0.5 M/S**

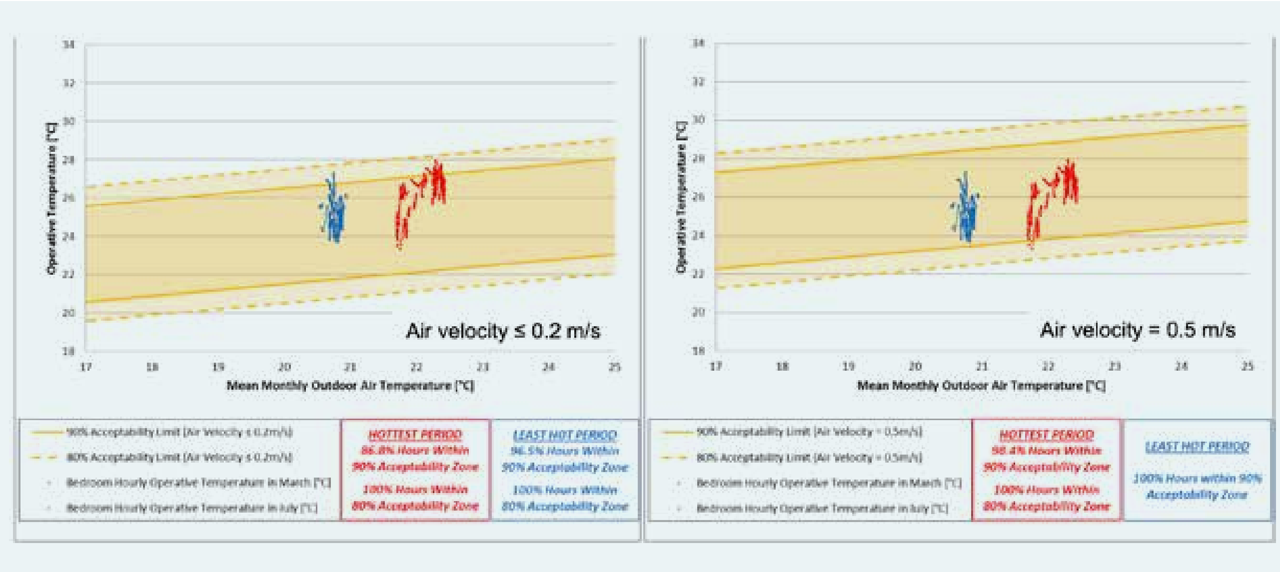


FIGURE A.5-35 **HOURLY OPERATIVE TEMPERATURES OCCURRING IN THE BEDROOM DURING THE HOTTEST (MARCH) AND LEAST HOT (JULY) MONTH IN KAMPALA, PLOTTED TOGETHER WITH COMFORT RANGE ACCORDING ASHRAE 55 ADAPTIVE MODEL, ASSUMING INDOOR AIR VELOCITY ≤ 0.2 M/S AND = 0.5 M/S**

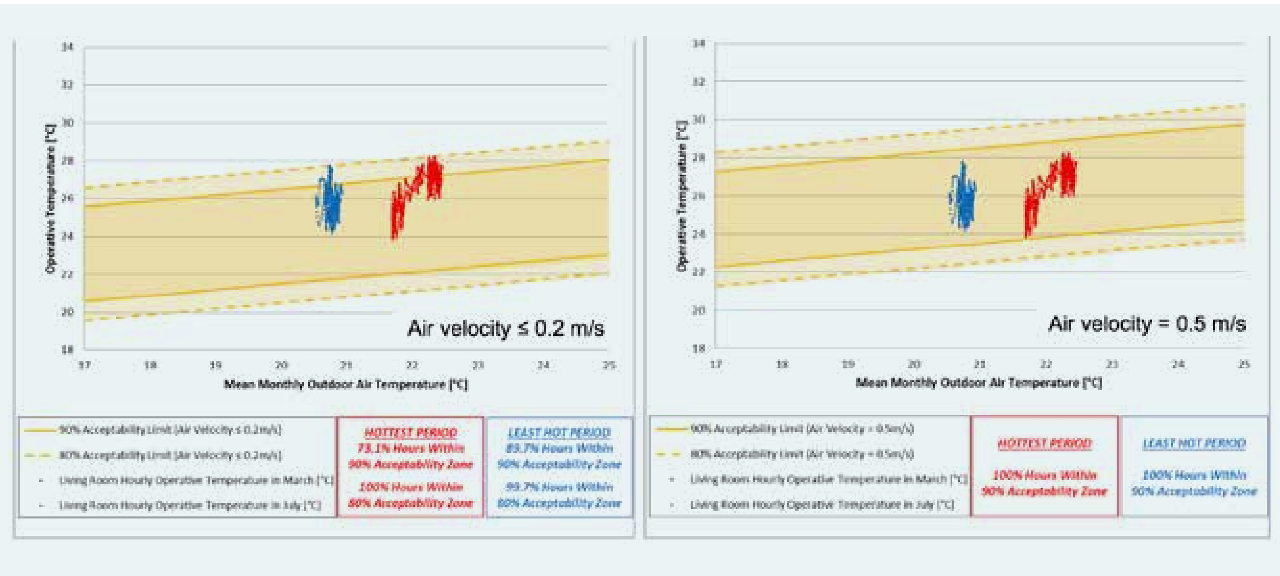


FIGURE A.5.36 **IMPROVED MULTI-STOREY RESIDENTIAL BUILDING (GROUND FLOOR AND FIRST FLOOR PLANS)**

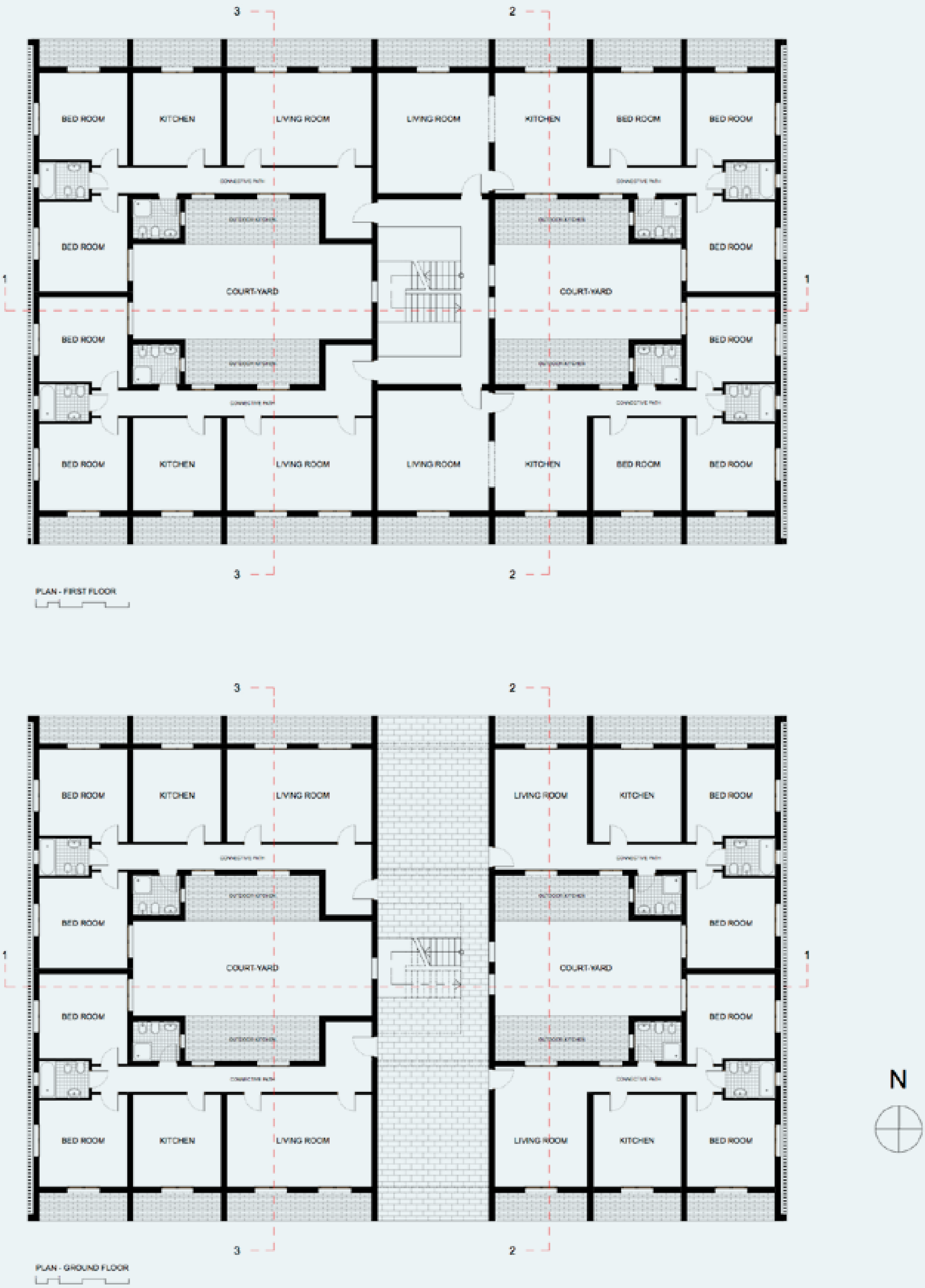


FIGURE A.5.37 **IMPROVED MULTI-STOREY RESIDENTIAL BUILDING (VERTICAL SECTION 1-1′)**

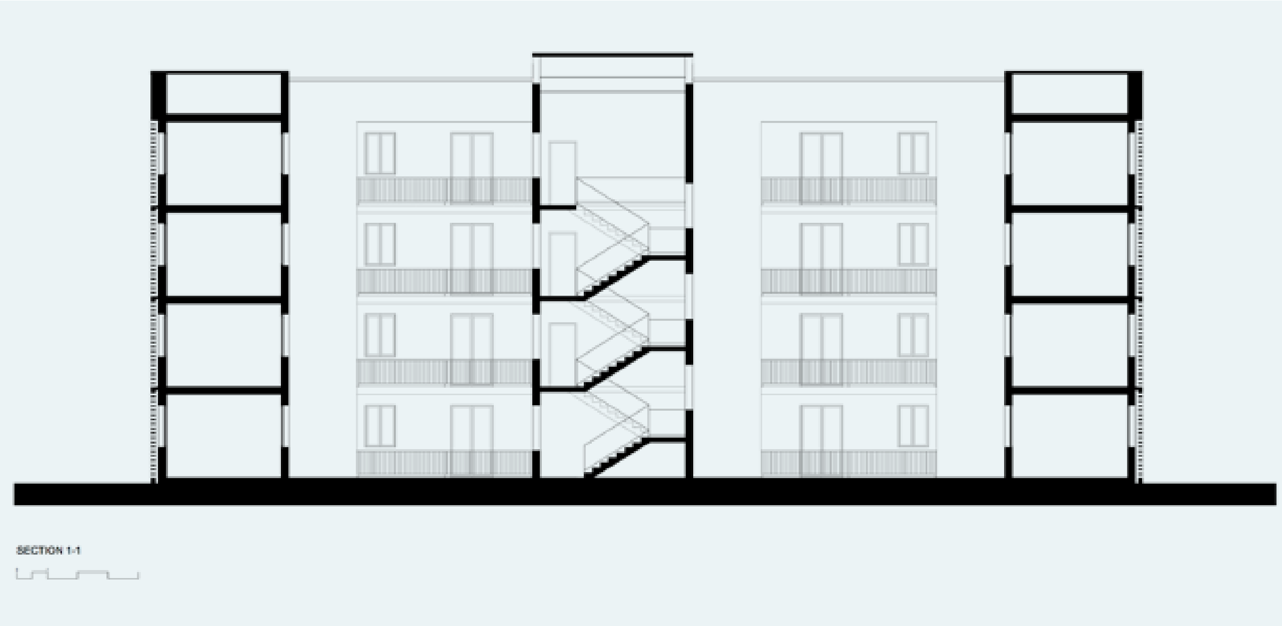
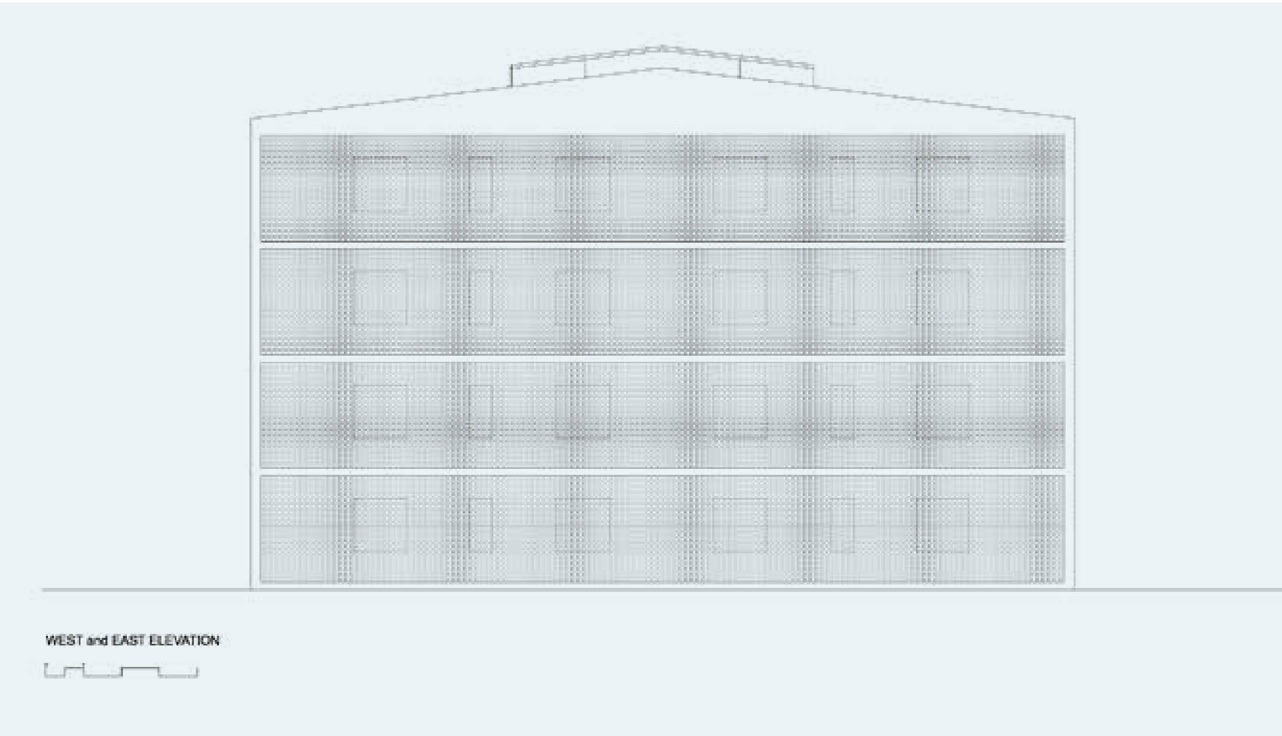


FIGURE A.5.38 **IMPROVED MULTI-STOREY RESIDENTIAL BUILDING (WEST AND EAST ELEVATIONS)**



GLOSSARY

Absolute humidity (humidity ratio) – the weight of water vapour per unit volume of dry air.

Absorber – the blackened surface in a solar collector that absorbs solar radiation and converts it to heat.

Absorptance – the ratio of the radiation absorbed by a surface to the total energy falling on that surface.

Active solar energy system – a system that requires auxiliary energy for its operation, e.g., energy to operate fans and pumps.

Air change – the replacement of a quantity of air in a volume within a given period of time. This is expressed in number of changes per hour. If a house has 1 air change per hour, all the air in the house will be replaced in a 1-hour period.

Air change per hour [ach] – a unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour.

Air pressure – the pressure exerted by air. This may refer to static (atmospheric) pressure, or dynamic components of pressure arising from airflow, or both acting together.

Air tightness – the degree to which unintentional openings have been avoided in a buildings structure.

Air, ambient – surrounding air.

Air, saturated – moist air in which the partial pressure of water vapour equals the vapour pressure of water at the existing temperature. This occurs when dry air and saturated water vapour co-exist at the same dry-bulb temperature.

Altitude angle – the angular height of a point above the horizontal plane, i.e. solar altitude – the angle between the line joining the centre of the sun and its projection on the horizontal plane.

Anemometer – an instrument for measuring the velocity of air.

Angle of incidence – the angle that the sun's rays subtend with a line perpendicular to a surface.

Atomize – reduce to fine spray.

Awning – an exterior, movable and usually flexible element. Protects detaining or diffusing solar radiation at certain angles.

Azimuth angle, solar – the angle on a horizontal surface between true south and the projection of sun's ray on the horizontal surface (negative before noon, positive after noon.)

Beam or direct radiation – radiation coming directly from the sun without its direction undergoing any change.

Berm – a man-made mound or small hill of earth.

Black body – a perfect absorber and emitter of radiation. A cavity is a perfect black body. Lampblack is close to a black body, while aluminium (polished) is a poor absorber and emitter of radiation.

Brightness – the subjective human perception of luminance.

Building orientation – the siting of a building on a plot, generally used to refer to solar orientation.

Calorific value – the energy content per unit mass (or volume) of a fuel, which will be released in combustion. [kWh/kg, MJ/kg, kWh/m^3, MJ/m^3]

Candela [cd] – an SI unit of luminous intensity . An ordinary candle has a luminous intensity of one candela .

Chimney effect – the tendency of air or gas in a duct or other vertical passage to rise when heated, due to its lower density in comparison with that of the surrounding air or gas. In buildings, the tendency towards displacement (caused by the difference in temperature) of heated internal air by unheated outside air, due to the difference in their densities.

Clear sky – A sky condition with few or no clouds, usually taken as 0-2 tenths covered with clouds. Clear skies have high luminance and high radiation, and create strong shadows relative to more cloudy conditions. The sky is brightest nearest the sun, whereas away from the sun, it is about three times brighter at the horizon then at the zenith.

Clerestory – a window that is placed vertically (or near vertical) in a wall above one's line of vision to provide natural light in a building.

Clo – clothing factor, a measure of the insulating value of clothing. For example, 0.3 clo is typical for light summer clothing and 0.8 is typical for heavy winter clothing.

Collector, flat plate – an assembly containing a panel of metal or other suitable material, usually a flat and black in colour on its sun side, that absorbs sunlight and converts it into heat. This panel is usually in an insulated box covered with glass or plastic on the sun side to take advantage of the greenhouse effect. In the collector, the heat transfers to a circulating fluid such as air, water, oil or antifreeze.

Collector, focusing – a collector that has a parabolic or other reflector which focuses sunlight onto a small area for collection. A reflector of this type can obtain considerably higher temperatures but will only work with direct beam sunlight.

Collector, solar – a device for capturing solar energy, ranging from ordinary windows to complex mechanical devices.

Comfort chart – a chart showing dry-bulb temperatures and humidities (and sometimes air motion) by which the effects of various air conditions on human comfort may be compared.

Comfort zone – on the bioclimatic chart , the area of combined temperatures and humidities that 80% of people find comfortable. People are assumed to be in the shade, fully protected from wind, engaged in light activity, and wearing moderate levels of clothing that increases slightly in winter.

Condensation – the process of vapour changing into the liquid state. Heat is released in the process.

Conditioned and unconditioned spaces - conditioned spaces need air treatment such as heat addition , heat removal, moisture removal, or pollution removal. Unconditioned spaces do not need such air conditioning , and no effort is made to control infiltration.

Conductance (C) - a measure of the ease with which heat flows though a specified thickness of a material by conduction. Units are W/m^2 °C.

Conduction – the process by which heat energy is transferred through materials (solids, liquids or gases) by molecular excitation of adjacent molecules.

Conductivity – the quantity of heat that will flow through one square metre of material, one metre thick, in one second, when there is a temperature difference of 1^{o}C between its surfaces.

Convection – the transfer of heat between a moving fluid medium (liquid or gas) and a surface, or the transfer of heat within a fluid by movements within the fluid.

Cooling load – a load with net cooling required.

Cross ventilation – ventilative cooling of people and spaces driven by the force of wind. When the outside air is cooler than the inside air, heat can be transferred from the space to the ventilation air. Cross ventilation also removes heat from people by convection and by increasing the rate of sweat evaporation . The cooling rate from cross ventilation is determined by wind speed , opening sizes and temperature difference between the inside and outside. See also, stack ventilation.

Daylight – illuminance from radiation in the visible spectrum from the diffuse sky, reflected light, and direct sun that lights a room.

Daylight factor (DF) – the proportion of interior horizontal illuminance (usually taken on the work plane) to exterior horizontal illuminance under an unobstructed sky . It is sum of the sky component and the internal reflected component. The range is 0-100%, but for most rooms it is usually limited to 1-10%.

Decrement factor – ratio of the maximum outer and inner surface temperature amplitudes taken from the daily mean.

Density – the mass of a substance, expressed in kilograms per cubic metre.

Diffuse radiation – radiation that has travelled an indirect path from the sun because it has been scattered by particles in the atmosphere such as air molecules, dust and water vapour. Indirect sunlight comes from the entire skydome.

Direct gain – the transmission of sunlight through glazing directly in to the spaces to be heated , where it is converted to heat by absorption on interior mass surfaces.

Direct sunlight – the component of visible spectrum radiation that comes directly from the sun without being diffused or reflected.

Direct radiation – the component of solar radiation that comes directly from the sun without being diffused or reflected.

Diffuse reflectance – reflectance is the ratio of reflected radiation to incident radiation. Diffuse reflectance spreads the incident flux over a range of reflected angles/directions.

Diurnal – relating to a 24-hr cycle. A diurnal temperature swing is the cycle of temperatures over the course of one 24-hr period.

Downdraft evaporative cooling tower - a cooling system that humidifies and cools warm dry air by passing it though a wetted pad at the top of a tower. The cooled air being denser, falls down the tower and into the occupied spaces below, drawing in more air through the pads in the process. Consequently, no distribution fans are required.

Dry bulb temperature – the temperature of a gas of mixture or gases indicated by an accurate thermometer after correction for radiation.

Emissivity – the property of emitting heat by radiation, possessed by all materials to a varying extent. "Emittance" is the numerical value of this property.

Envelope heat gain or loss – heat transferred through the skin of a building or via infiltration /ventilation.

Equinox – meaning equal light. The dates during the year when the hours of daylight are equal to the hours of darkness. On the equinox, the sun rises from the horizon at due east and sets due west. The equinoxes fall on March 21 and September 21.

Evaporation – phase change of a material from liquid to vapour at a temperature below the boiling point of the liquid. Cooling occurs during the process of evaporation.

Evaporative cooling - A heat removal process in which water vapour is added to air, increasing its humidity while lowering its temperature. The total amount of heat in the air stays constant, but is transferred from sensible heat in the air to latent heat in the moisture. In the process of changing from liquid to vapour (evaporating), the water must absorb large amount of heat.

Evaporative cooling, Direct – a cooling process where the warm and dry air moves through a wetted medium to evaporate moisture in the air. The cool humid air is then used to cool a place.

Evaporative cooling, Indirect – a cooling process where the evaporative process is remote from the conditioned space. The cooled air is then used to lower the temperature of the building surface, such as in a roof spray, or is passed through a heat exchanger to cool indoor air. The indirect process has the advantage of lowering temperatures without adding humidity to the air, thus extending the climate conditions and regions in which evaporate cooling is effective.

Glare – the perception caused by a very bright light or a high contrast of light, making it uncomfortable or difficult to see.

Glazing – Transparent or translucent materials, usually glass or plastic, used to cover an opening without impeding (relative to opaque materials) the admission of solar radiation and light.

Greenhouse effect – refers to the characteristic tendency of some transparent materials such as glass to transmit shortwave radiation and block radiation of longer wavelengths.

Heat exchanger – a device usually consisting of a coiled arrangement of metal tubing used to transfer heat through the tube walls from one fluid to another.

Heat gain – an increase in the amount of heat contained in a space, resulting from direct solar radiation and the heat given off by people, lights, equipment, machinery and other sources.

Heat island – the increased temperatures, relative to surrounding open load, found in the centre cities and areas of high development density. Heat islands are caused by concentrations of heat sources, decreased vegetation cover, increased massive and dark surfaces , decreased wind flows , and narrow sky view angles.

Heat loss – a decrease in the amount of heat contained in a space, resulting from heat flow through walls, windows, roof and other building envelope components.

Heat pump – a thermodynamic device that transfers heat from one medium to another; the first medium cools while the second warms up.

Humidity – water vapour within a given space.

HVAC – mechanical system for heating, ventilating and air-conditioning that controls temperature, humidity , and air quality.

Hygroscopic – absorptive of moisture , readily absorbs and retains moisture.

Illuminance – the measure of light intensity striking a surface . Specifically, the concentration of incident luminous flux, measured in foot –candle (I-P) or Lux (SI).

Illumination – lighting of the surface by daylight or electric light.

Infiltration – the uncontrolled movement of outdoor air into the interior of a building through cracks around windows and doors or in walls, roofs and floors. This may work by cold air leaking in during winters, or the reverse in summers.

Infrared radiation – Electromagnetic radiation having wavelength above the wavelength range of visible light. This is the predominant form of radiation emitted by bodies with moderate temperatures such as the elements of a passive building.

Internal gains – the energy dissipated inside the heated space by people and appliances. A portion of this energy contributes to the space heating requirement.

Isothermal – an adjective used to indicate a change taking place at constant temperature. A Jalousie window or louvre window (UK) is a window which consists of parallel glass, acrylic, or wooden louvers set in a frame. The louvers are locked together onto a track, so that they may be tilted open and shut in unison, to control airflow through the window. They are usually controlled by a crank mechanism.

Latitude – the angular distance north (+) or south (-) of the equator, measured in degrees of arc.

Latent heat – change of enthalpy during a change of state , usually expressed in J/kg (Btu per lb). With pure substances, latent heat is absorbed or rejected at constant temperature at any pressure.

Lighting, diffused – lighting in which the light on a working plane or on an object is not incident predominantly from a particular direction.

Longwave radiation – radiation emitted between roughly 5 and 30 m wavelength, as in thermal radiation from the surface of a room, or from the outside surface of the roof.

Longitude – the arc of the equator between the meridian of a place and Greenwich meridian measured in degrees east or west.

Louvre - an assembly of sloping vanes intended to permit air to pass through and to inhibit transfer of water droplets

Lumen – SI unit of luminous flux; it is the luminous flux emitted in unit solid angle by a uniform point source having a luminous intensity of 1 candela.

Lux – SI unit of illuminance; it is the illuminance produced on a surface of unit area (square metre) by a luminous flux of 1 lumen uniformly distributed over that surface.

Masonry – concrete, concrete block, brick, adobe, stone, and similar other building materials.

Negative pressure – a pressure below the atmospheric. In residential construction, negative pressure refers to pressure inside the house envelope that is less than the outside pressure. Negative pressure will encourage infiltration.

Night ventilation of mass - a cooling process whereby a building is closed during the hot daytime hours. Its heat gains are stored during that time in the building's structure or other thermal mass. At night, the building is opened and cooler outdoor air is used to flush heat from the mass, lowering its temperature, to prepare for another cycle.

Night sky radiation - a reversal of the day time insolation principle. Just as the sun radiates energy during the day through the void of space, so also heat energy can travel unhindered at night from the earth's surface back into space. On a clear night, any warm object can cool itself by radiating longwave heat energy to the cooler sky. On a cloudy night, the cloud cover acts as an insulator and prevents the heat from travelling to the cooler sky.

Opaque - not able to transmit light; for example, unglazed walls.

Passive system - a system that uses non-mechanical and non-electrical means to satisfy heating, lighting, or cooling loads. Purely passive systems use radiation, conduction, and natural convection to distribute heat, and daylight for lighting.

Pressure – the normal force exerted by a homogenous liquid or gas, per unit area, on the wall of container.

Pressure difference – the difference in pressure between the volume of air enclosed by the building envelope and the air surrounding the envelope.

Pressure , vapour – the pressure exerted by the molecules of a given vapour.

Radiant heat transfer – the transfer of heat by radiation. Heat radiation is a form of electromagnetic radiation. Radiant heating due to infrared radiation is commonly employed in passive systems.

Radiant temperature - the average temperature of surfaces surrounding a person or surface, with which the person or surface can exchange thermal radiation.

Reflectance - the ratio of radiation reflected by a surface to the radiation incident on it. The range is 0-1.0.

Reflection – process by which radiation is returned by a surface or a medium, without change of frequency of its monochromatic component.

Relative humidity - the percentage of water vapour in the atmosphere relative to the maximum amount of water vapour that can be held by the air at a given temperature.

Resistivity – the thermal resistance of unit area of a material of unit thickness to heat flow caused by a temperature difference across the material.

Selective coating – finishes applied to materials to improve their performance in relation to radiation of different wavelengths. Those applied to solar absorbers have a high absorptance of solar radiation accompanied by a low emittance of long wave radiation, while those for glazing have a high transmittance to solar radiation and high reflectance of long wavelengths.

Selective surface - a surface used to absorb and retain solar heat in a solar heating system such as a solar collector. Selective surfaces have high absorptance and low emittance.

Sensible heat - heat that results in a change in air temperature, in contrast with latent heat.

SI units - Standard International units; the metric system.

Sky component - the portion of the daylight factor (at a point indoors) contributed by luminance from the sky, excluding direct sunlight.

Sky cover - a measure of the fraction of the sky covered in clouds. Range is 0-10 tenths.

Sol-air temperature – an equivalent temperature which will produce the same heating effect as the incident radiation in conjunction with the actual external air temperature.

Solar absorptance - the fraction of incident solar radiation that is absorbed by a surface. The radiation not absorbed by an opaque surface is reflected. The range is 0-1.0.

Solar gain - heat transferred to a space by solar radiation through glazing.

Solar heat gain coefficient (SHGC) - the fraction of incident solar radiation (for the full spectrum) which passes though an entire window assembly, including the frame, at a specified angle. Range is 0-0.85. A higher SHGC is preferred in solar heating applications to capture maximum sun, whereas in cooling applications, a low SHGC reduces unwanted solar heat gain.

Solar load - the demand for energy required at any moment to compensate for the difference between desired indoor conditions and heat gains from solar radiation.

Solar radiation - radiation emitted by the sun, including infrared radiation, ultraviolet radiation, and visible light. The radiation received without change of direction is called beam or direct radiation. The radiation received after its direction has been changed by scattering and reflection is called diffuse radiation. The sum of the two is referred to as global or total radiation.

Specific heat – a measure of the ability of a material to store heat. Specifically, the quantity of heat required to raise the temperature of unit mass of a substance by one degree. [kJ/kg °C]

Stack ventilation - the cooling process of natural ventilation induced by the chimney effect, where a pressure differential occurs across the section of a room. Air in the room absorbs heat gained in the space, loses density, thus rising to the top of the space. When it exits through high outlet openings, a lower pressure is created low in the space, drawing in cooler outside air from low inlets.

Sunlight - beam daylight from the sun only, excluding diffuse light from the sky dome.

Surface resistance – the surface resistance is the resistance to heat flow at the surface of a material. It has two components , the surface resistance for convection and for conduction.

Task light - lighting on a specific area used for a specific task. Task lighting is usually from an electric source and is of a higher illuminance level than the surrounding ambient light level. It is a good strategy to combine task light with ambient daylight.

Temperature swing – the range of indoor temperatures in the building between the day and night.

Thermal break (thermal barrier) – an element of low thermal conductivity placed within a composite envelope construction in such a way as to reduce the flow of heat across the assembly.

Thermal conductivity (k) - a measure of the ease with which heat flows though a unit thickness of a material by conduction; specifically, the heat flow rate in Watt per metre of material thickness, and degree of temperature difference. Units is W/m°C

Thermal radiation - energy transfer in the form of electromagnetic waves from a body by virtue of its temperature, including infrared radiation, ultraviolet radiation, and visible light.

Thermal resistance - a measure of the insulation value or resistance to heat flow of building elements or materials; specifically, the reciprocal of the thermal conductance.

Thermal storage mass - high-density building elements, such as masonry or water in containers, designed to absorb solar heat during the day for later release when heat is needed.

Thermocirculation - the circulation of a fluid by convection. For example, the convection from a warm zone (sunspace or Trombe wall air space) to a cool zone through openings in a common wall.

Thermosyphon – the convective circulation of a fluid which occurs in a closed system where warm fluid rises and is replaced by a cooler fluid in the same system.

Tilt – the angle of a plane relative to a horizontal plane.

Time-lag – the period of time between the absorption of solar radiation by a material and its release into a space. Time-lag is an important consideration in sizing a thermal storage wall or Trombe wall.

Transmittance – the ratio of the radiant energy transmitted through a substance to the total radiant energy incident on its surface.

Ultraviolet radiation – electromagnetic radiation having wavelengths shorter than those of visible light. This invisible form of radiation is found in solar radiation and plays a part in the deterioration of plastic glazing materials, paint and furnishing fabrics.

U-value (coefficient of heat transfer) - the number of Watts that flow through one square metre of building component (e.g. roof, wall, floor, glass), in one second, when there is a 1 °C difference in temperature between the inside and outside air, under steady state conditions. The U-value is the reciprocal of the resistance.

Ventilation load - the energy required to bring outdoor air to the desired indoor conditions. In this book, ventilation load refers to fresh air ventilation, which may be provided either naturally or by a mechanical system. The rate of required ventilation varies with the use of the space and the number of occupants. Ventilation load depends on the rate of fresh air ventilation and on the temperature difference between inside and outside. It may be reduced by pre-tempering or the use of heat exchangers.

Ventilation losses – the heat losses associated with the continuous replacement of cool, stale air by fresh warm outdoor air.

Ventilation (natural) - air flow through and within a space stimulated by either the distribution of pressure gradients around a building, or thermal forces caused by temperature gradients between indoor and outdoor air.

Visible spectrum – that part of the solar spectrum which is visible to the human eye; radiation with wavelength roughly between 380 and 700 nm.

Visible transmittance (VT or τ_{vis}) - the fraction of incident visible light that passes though glazing.

Watt [W] - a measure of power commonly used to express heat loss or heat gain, or to specify electrical equipment. It is the power required to produce energy at the rate of one joule per second.

Wet-bulb temperature - the air temperatu
using a thermometer with a wetted bulb mc
through the air to promote evaporation. The
moisture and changing phase lowers the ten
measured relative to that measured with a d
bulb temperature accounts for the effects of
air. It can be used along with the dry-bulb te
psychrometric chart to determine relative hu

Zenith - the top of the sky dome. A point di... overhead 90° in altitude angle above the horizon.

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