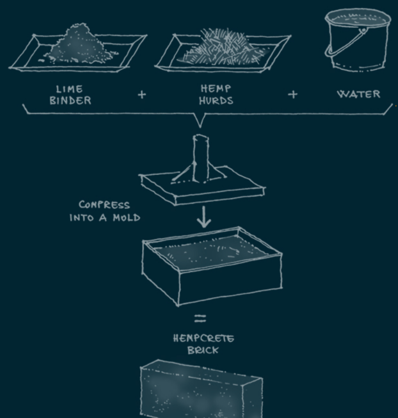
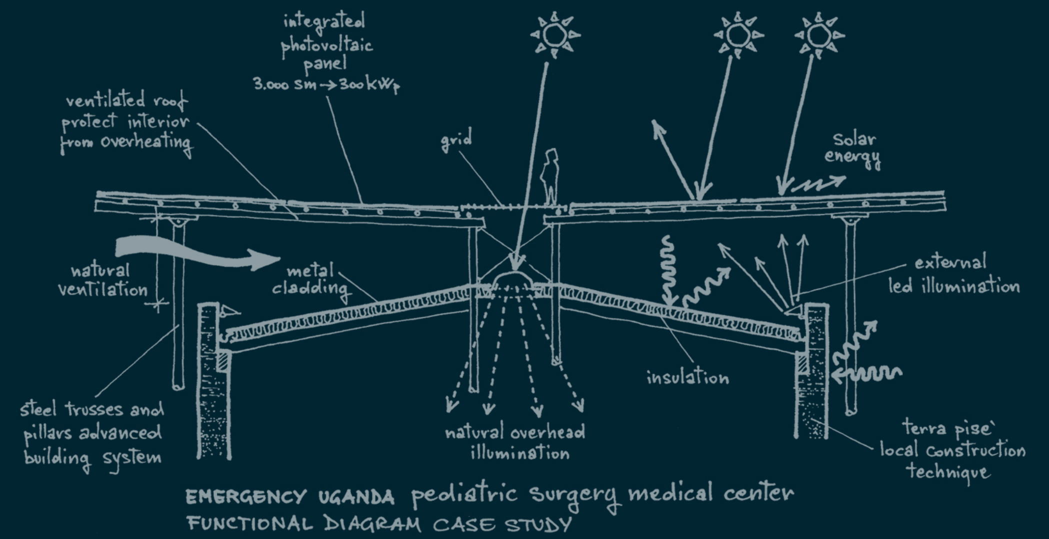
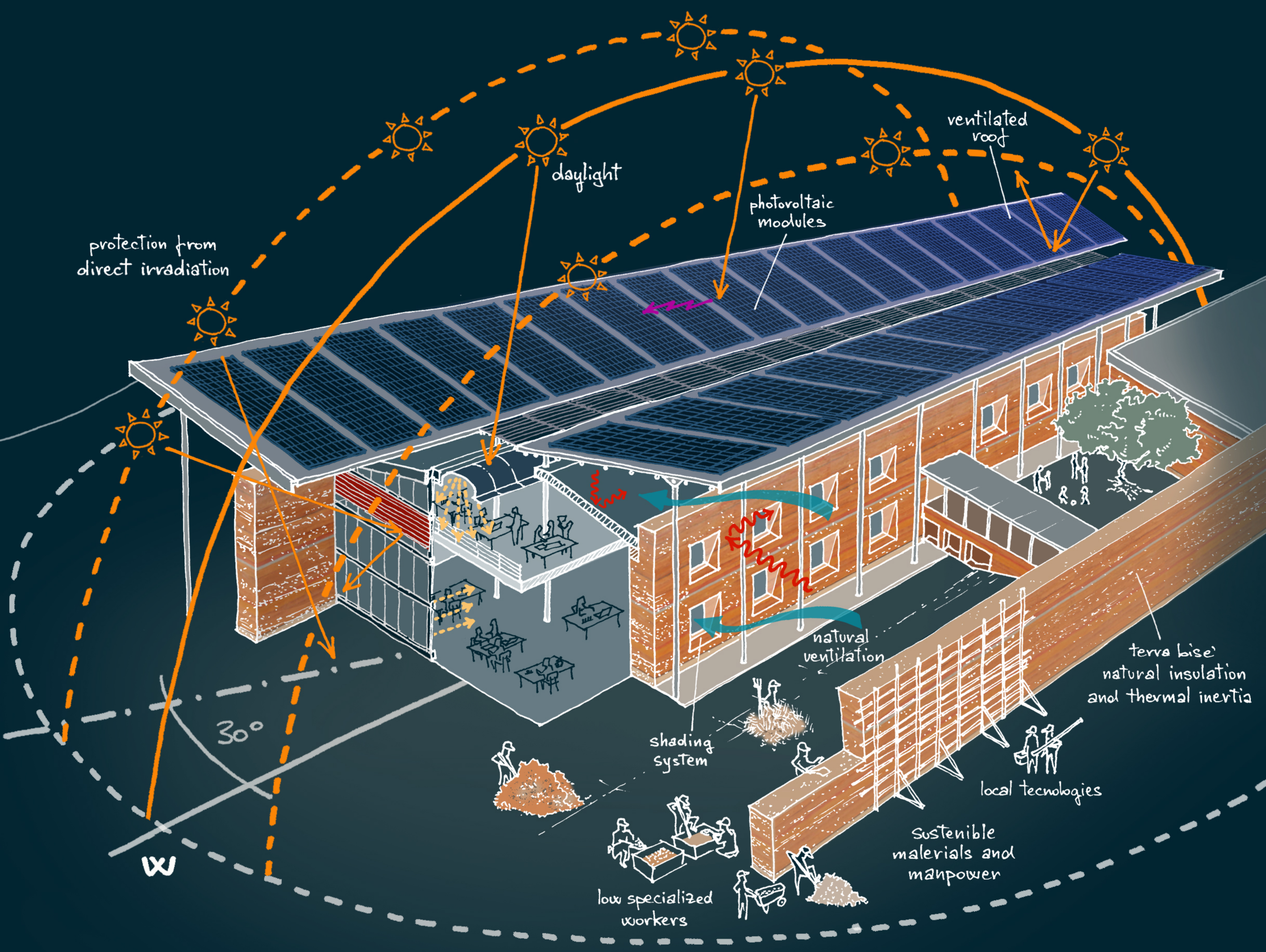




SUSTAINABLE BUILDING DESIGN FOR AFRICA



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UN-HABITAT

Africa-Europe Bioclimatic Collaboration 21

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FOREWORD

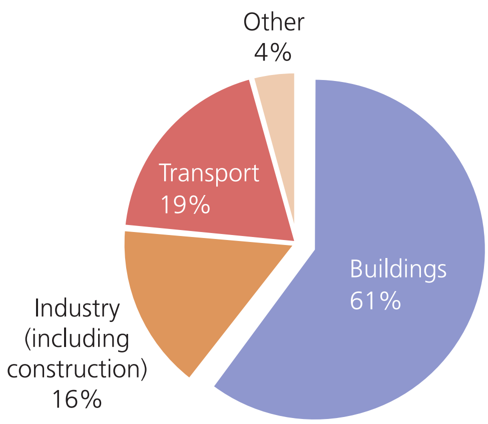
According UNEP[1] and IEA[2], the buildings sector is responsible directly and indirectly for more than one-third of global energy-and process-related CO_2 emissions. Much of this contribution is due to space heating and hot water production in developed countries, and in China.

In developed countries, the path towards a decarbonised building sector is quite clearly defined, as the building stock is already largely built up and population and urbanisation are no longer growing. Thus, most of the effort has to be put in making existing buildings' envelopes more efficient, in substituting boilers with heat pumps, and in producing electricity with renewable energy. Not easy, but by far more challenging is what has to be done in Africa to reach the same result, i.e. a decarbonized building sector. More challenging for several reasons:

2. Bioenergy represents the vast majority of energy use in African buildings (around 80 per cent), with almost all (95 per cent) being traditional biomass (70% of the population, almost a billion people, lacks access to clean cooking) – explaining the large difference between energy consumption and CO_2 emissions[4].

3. Since 2010, growth in emissions has been driven by a 23% rise in regional population and a 25% increase in wealth (gross domestic product), which has increased the demand for floor area and for energy consuming services; these pressures will continue as Africa's population is expected to grow and could more than double its economic wealth by 2040, thus floor area is expected to double between now and 2050, over 90% of which will be in the residential sector[3].

Buildings' share of total **final energy consumption** Africa, 2018



Buildings' share of total **CO_2 Emissions** Africa, 2018

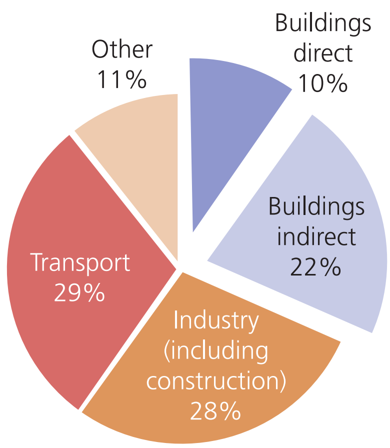


Fig.1 – Share of buildings final energy and emissions in Africa, 2018

1. The share of energy consumption of the building sector in Africa is much higher, as in 2018 it was already 61% of final energy use, while the CO_2 emission share is comparable (32%), excluding emissions from manufacturing building materials and products such as steel, cement and glass (Figure 1)[3].

4. With more than 238 million people in sub-Saharan Africa living in slums or informal settlements, the role of the informal construction sector is an important aspect of future buildings across the region[5].

1 *United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector – Executive Summary - https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34572/GSR_ES.pdf?sequence=3*

2 *IEA (2022), Buildings, IEA, Paris https://www.iea.org/reports/buildings, License: CC BY 4.0*

3 *GlobalABC/IEA/UNEP (Global Alliance for Buildings and Construction, International Energy Agency, and the United Nations Environment Programme) (2020): GlobalABC Regional Roadmap for Buildings and Construction in Africa: Towards a zero-emission, efficient and resilient buildings and construction sector, IEA, Paris. - https://iea.blob.core.windows.net/assets/d60403aa-6fae-4365-bcd5-8af5daf22193/GlobalABC_Roadmap_for_Buildings_and_Construction_in_Africa_2020-2050.pdf*

4 *United Nations Environment Programme (2021). 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi*

5 *GlobalABC/IEA/UNEP (Global Alliance for Buildings and Construction, International Energy Agency, and the United Nations Environment Programme) (2020): GlobalABC Regional Roadmap for Buildings and Construction in Africa: Towards a zero-emission, efficient and resilient buildings and construction sector, IEA, Paris. - https://iea.blob.core.windows.net/assets/d60403aa-6fae-4365-bcd5-8af5daf22193/GlobalABC_Roadmap_for_Buildings_and_Construction_in_Africa_2020-2050.pdf*

Over the next few decades Africa will be a huge construction site where millions of buildings will be built. Africa is currently home to 1.3 billion people, equal to roughly 17 percent of the world's total population. The expected population and urbanisation growth is such that if African building stock will not be decarbonized by 2050, the limit of 1.5 °C of global temperature rise will be out of target. Thus, Africa is one of the tipping points of the global energy transition: its buildings need to witness a fundamental shift in the way they are designed, constructed and how they function.

Decarbonising buildings across the entire life cycle would require a transformation of the buildings and construction sector. Reaching net-zero operational and embodied carbon emission buildings is possible, but requires clear and ambitious policy signals to drive a range of measures including passive building design, material efficiency, low-carbon materials, efficient building envelope measures, and highly efficient lighting and appliances.

In order to design sustainable buildings, consistent with a zero-emission world, it is not enough to have laws and regulations, which are a sine qua non, but above all it is necessary to have the skills, i.e. it is necessary to promote capacity building.

This need is addressed by this handbook, which builds on another handbook we produced previously, and which only covered tropical African climates. In this handbook, building design recommendations are extended to the other climates of the African continent.

TABLE OF CONTENT

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 biodiversity loss are the main challenges that mankind has to face in the 21st century, and they will affect all countries. The two phenomena are interconnected, and both negatively affect something we absolutely cannot do without: food, with the aggravating circumstance that food production, in turn, is the main cause of biodiversity loss and one of the causes of climate change.

Nobody will be immune to the consequences of this double challenge. However, some countries and people are more vulnerable than others. In the long term, the whole of humanity faces risks but more immediately, the risks and vulnerabilities are skewed towards the world's poorest people.

Let's consider climate change, first. We know that the world is warming and that the average global temperature has increased by around 1°C since the advent of the industrial era[1]. We know also that the trend is accelerating[2]: earth's temperature has risen by 0.08° C per decade since 1880, and the rate of warming over the past 40 years is more than twice that, 0.18° C per decade since 1981.

With the global rise in temperature, local rainfall patterns are changing, ecological zones are shifting, the seas are warming and ice caps are melting.

Future climate-related risks depend on the rate, peak and duration of warming[3]. In the aggregate, they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C). Essentially, the lower the rise in global temperature above preindustrial levels, the lower the risks to human societies and natural ecosystems. Put another way, limiting warming to 1.5°C can be understood in terms of 'avoided impacts' compared to higher levels of warming. Many of the impacts of climate change assessed have lower associated risks at 1.5°C compared to 2°C (Figure 1.1-1). In order to reach in a clean way (i.e. without the use of Carbon Capture and Storage) the target of 1.5 °C warming in 2050 we should halve our emissions by 2030. While transitions towards lower greenhouse gas emissions are underway in some cities, regions, countries, businesses and communities, there are few that are currently consistent with limiting warming to 1.5°C.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address

1 *IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. - https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf*

2 *R. Lindsey, L. Dahlman, Climate Change: Global Temperature, NOAA, March 2021 - https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature*

3 *IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. - https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf*

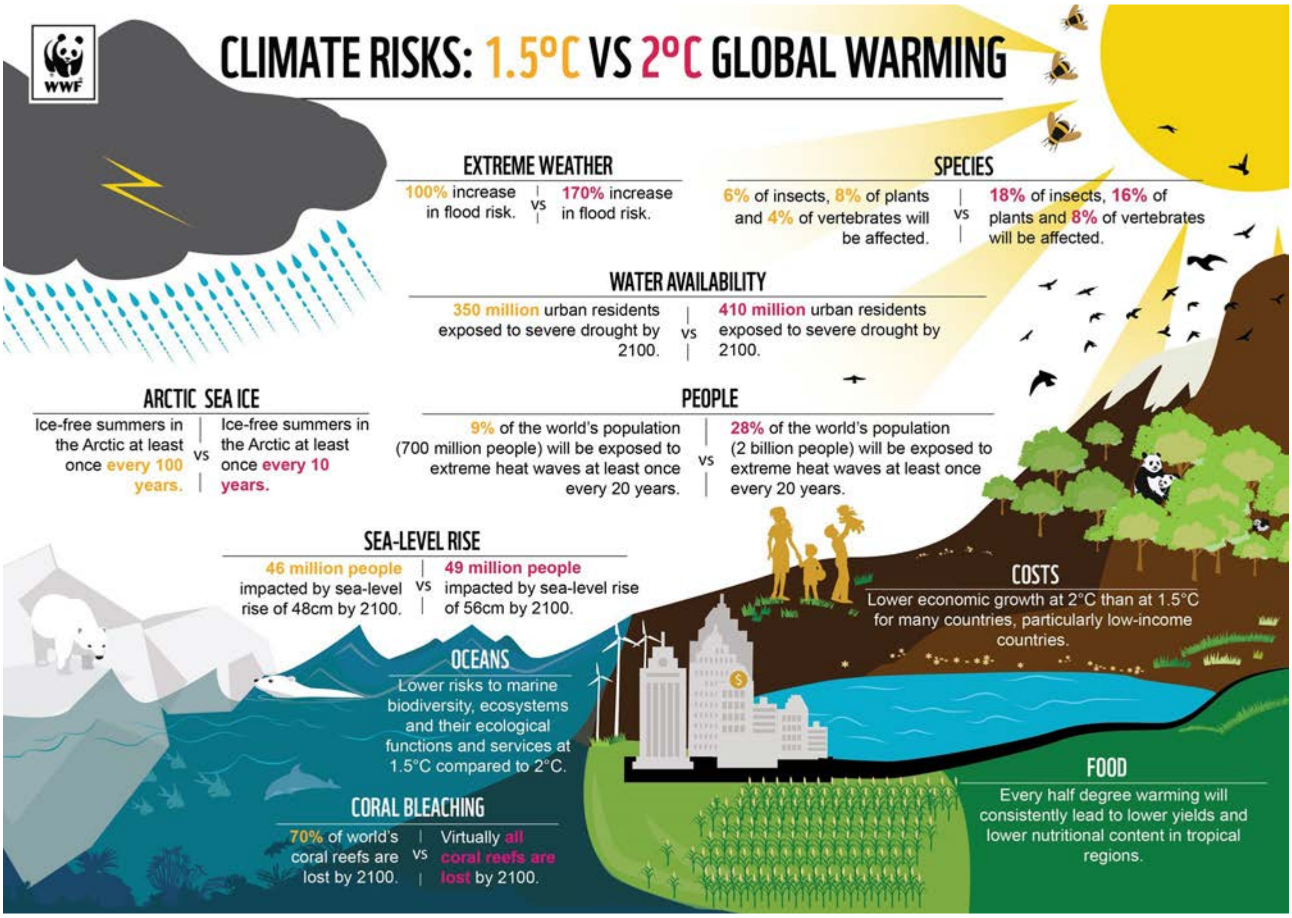


Fig. 1.1-1 - 1.5 vs 2° global warming impact

Source: *WWF, https://wwfint.awsassets.panda.org/downloads/1_5c_infographic___final__high_res__final.jpg*

climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C.

A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade (Figure 1.1-2), with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.

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

Even more critical is the perspective for all those materials used in the technologies connected to the transition to renewable energy sources, such as lithium, copper, nickel, cobalt, manganese, rare earths, because their demand will be rocketing and most of them are concentrated in a few places of the Earth, with consequent geopolitical problems. These materials are used in batteries, electric motors and generators, wiring.

Biological resources are also rapidly depleting: the ecological footprint is growing and the planet's biocapacity is shrinking. Since the 1970s, humanity's annual demand on the natural world has exceeded what the Earth can renew in a year. (Fig. 1.1-4)

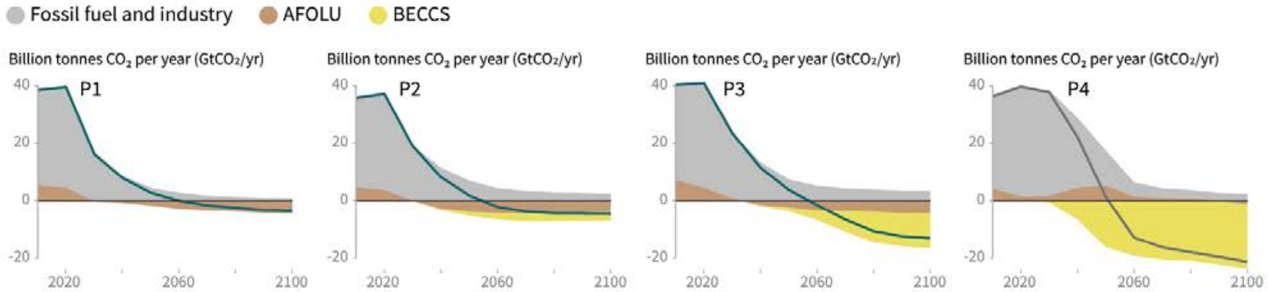
This "ecological overshoot" has continued to grow over the years, reaching a 75% per cent deficit in 2018. This means that it takes 1.75 years for the Earth to regenerate the renewable resources that people use, and absorb the waste they produce in one year[4]. Developed countries

4 Earth Overshoot Day - https://www.overshootday.org/how-many-earths-or-countries-do-we-need/

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
↳ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
↳ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
↳ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
↳ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
↳ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
↳ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
↳ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
↳ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
↳ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
↳ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
↳ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km²)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Fig. 1.1-2 - Four illustrative model pathways to reach 1.5 °C target

Source: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SPM3b.png - https://www.ipcc.ch/sr15/chapter/spm/

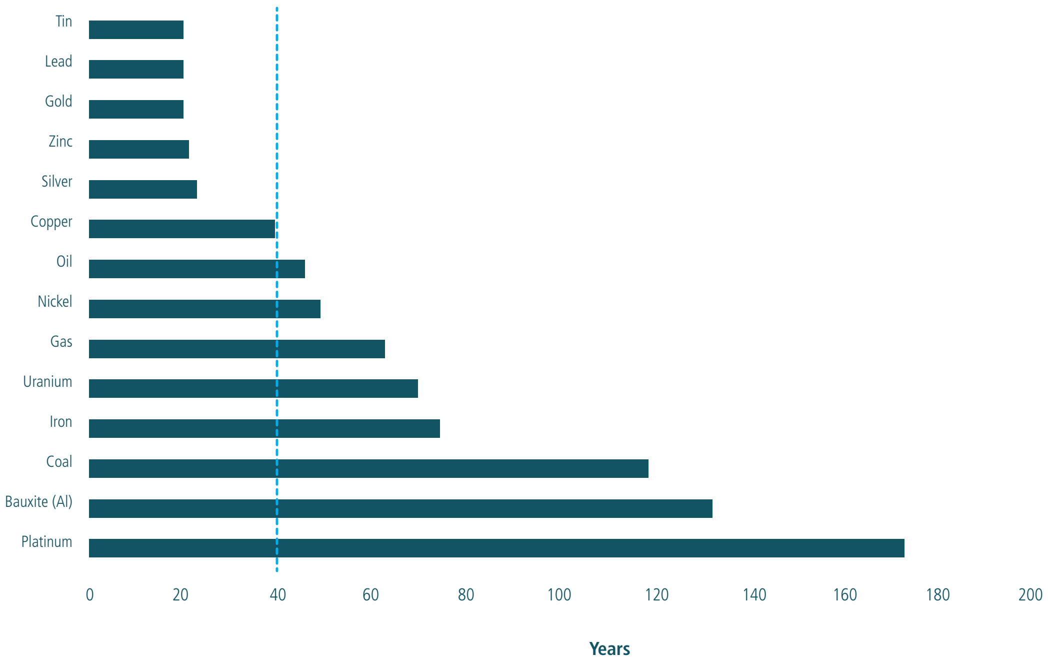


Fig. 1.1-3 - Potential shortage of materials – Reserves (2010 production)

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

have very high per capita ecological footprint, higher than developing countries.

1.2 The building sector

The building sector, is a major CO_2 emitter, second only to the industry sector, accounting for 27% of global emissions[5], deriving both by the fossil fuel burnt for space heating, hot water production and cooking and by the one burnt for producing the electricity consumed.

If the present trend is not changed, the impact of the building sector on global warming is set to grow, because of the combination of factors such as the population growth, the urbanization process, and the improvement of the economic conditions in developing countries.

Thus, any chance to meet the 1.5 °C target goes through a significant change in building design and construction. This is even more true considering that most of the energy presently consumed in buildings of developing countries is biomass and that the expected improvement of living conditions would 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).

Developing countries are going to play a decisive role in

5 NEW BUILDINGS: EMBODIED CARBON, Architecture 2030 - https://architecture2030.org/new-buildings-embodied/

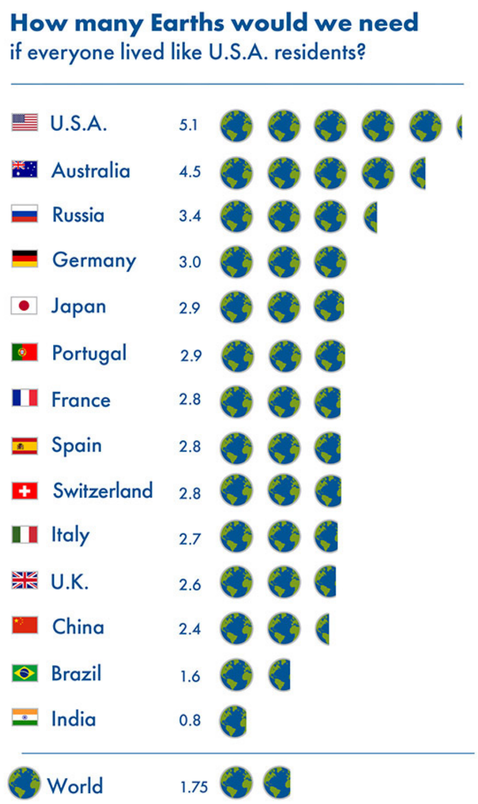


Fig. 1.1-4 - How many earths would we need

Source: *National Footprint and Biocapacity Accounts 2022* the future world energy scenario, as a consequence of their economic development. Industrial energy consumption will grow, and a dramatic increase of transport energy consumption can be expected, with the growth of the circulating cars stock - if the present worldwide accepted approach to mobility will not change.

The energy consumption increase in the building sector can be expected 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 of the number of buildings.

The building sector must therefore do its part, and the long-term goal is to transform the buildings to consumers in net energy producers. This, of course, will be possible for the new buildings, which will have the task to compensate for the inevitable - even if they have to be greatly reduced - consumption of existing ones.

The challenge is unprecedented and will require (it requires it by now) a radical transformation of the ways to design and build. The reduction of CO_2 emissions by reducing energy consumption is the top priority with which the construction industry has to face.

1.2.1 Construction materials

Almost 40% of the raw materials and energy produced worldwide are used in the building sector[6].

The production of cement, steel, glass, aluminium and baked bricks, which are the basic building materials for most of modern constructions, have very high environmental impacts, consumes the most energy and causes the majority of the GHG emissions in the construction sector[7] because their production requires the processing of mined raw materials at a very high temperature.

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.

The production process of building materials, as for any othe product, implies GHG emissions. These emissions are called embodied emissions of a product. If the embodied emissions of building materials and construction are added, then the contribution of the building sector jumps to 37% of global CO_2 emissions, far above industry and transport. This is mainly due to the contribution of concrete, steel and aluminum, as the production of these three materials alone (used also in sectors other than buildings) contributes for 23% of global CO_2 emissions.

6 *Circularity Gap Report 2022, Circle Economy - https://drive.google.com/file/d/1NMAUtZcoSLwmHt_r5TLWwB28QJDghi6Q/view*

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

The global environmental impact of the materials' use in buildings is going to be very high: it is estimated that 46% of the world building stock that will exist in 2050 will have been built between 2015, i.e. the world building stock in 2050 will have almost doubled[8].

If in all these new buildings will be used the same materials we presently use, it will be impossible to meet the target of curbing CO_2 emissions to zero in 2050.

The intelligent use of natural available materials like inorganic materials (e.g, natural stones and clay) and especially the utilisation of building materials out of organic raw materials, made from biomass which is renewable, can lead to a significant reduction of the GHG emissions and the environmental impacts caused by the production of building materials.

Developing countries need not to 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[9].

The innovation in sustainable building materials, construction methods and architectural design can be orientated on traditional knowledge and practice, which are in general relatively well adapted to local climates (see chapter 4) and using locally available materials. Anyhow the development has to be also adapted to specific ecological, economic and social basic conditions to meet the present and future needs and requirements. Although the majority of people wants to use "modern" and "fashioned" building materials, like e.g. metal sheets as roofing material and cement blocks and cement plaster as wall building material, 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; especially politicians, investors, city planners and architects should leave abandon the vision of the architecture and town planning of 20° century, which has proved to be unsustainable.

1.3 Integrated design

Building envelope design, aiming to the maximum comfort with the minimum primary energy consumption (and thus to minimum GHG emissions), requires that the parameters of comfort and energy be integrated in each of the critical steps of the design process (Fig. 1.3-1). Factors such as climate, master plan, building shape, facade design, thermo-physical characteristics of the material,

8 *Global Alliance for Buildings and Construction/UNEP, Global Status Report 2016 –Towards zero-emission, efficient and resilient buildings - http://www.buildup.eu/en/practices/publications/towards-zero-emission-efficient-and-resilient-buildings-global-status-repor-0 -*

9 *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*

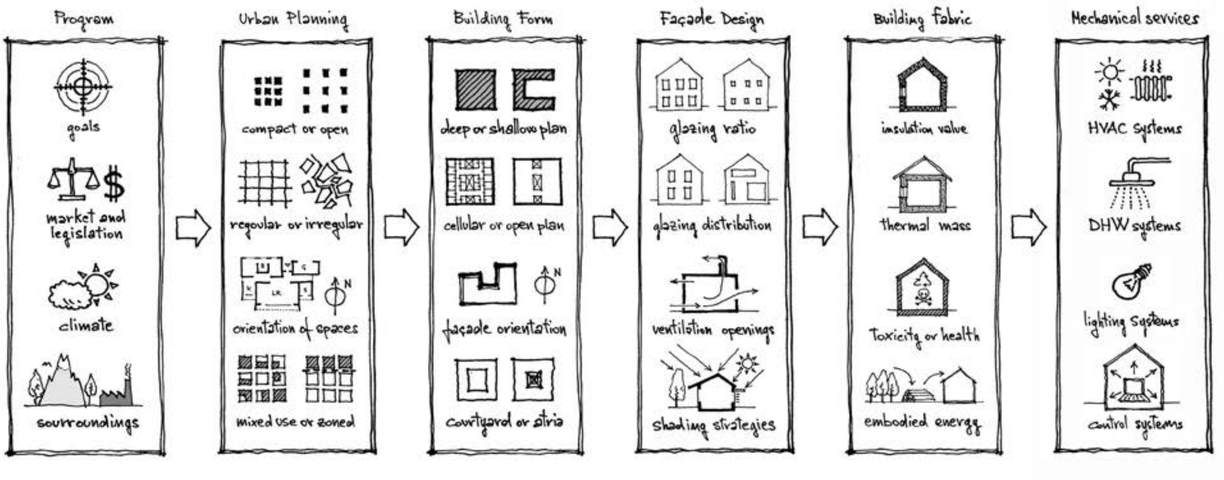


Fig. 1.3-1 - The phases of the design process in which choices have an influence on building's energy performance and comfort

and finally the building plan, must have a role in decisions.

To achieve this result, 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 the mechanical systems design (when the building is equipped with an air conditioning system), and the construction (Fig. 1.3-2). The architect – because of his training – usually little or nothing knows about building physics; the consequence is that architectural choices very often have a negative impact on the building's energy performance, and on the occupants' comfort.

If the architect is constrained by building regulations limiting energy consumption, his lack of competence in building physics will have an impact not on energy consumption but on the overall cost of the building.

The reason is that in order to reduce energy consumption the architect will use the simplest but not the most appropriate approach: increase walls insulation and use high performance glazing, when more clever and cheaper solutions are available for reaching the same energy consumption target. Moreover, very often also thermal and visual comfort are very poor.

Fig. 1.3-2 - Usual design process

Thus the usual design process is incompatible with low energy, high comfort buildings. It is necessary to change the design methodology, making use of the integrated design model that includes, inter alia, the introduction of a new professional expertise: the energy expert (Fig. 1-8).

The energy expert must have a deep knowledge of building physics; he must be able to interact with the architect and with the mechanical engineer; he must be not only capable to manage rules of thumb, but also able to use sophisticated simulation tools for evaluating energy performances of the building, thermal comfort, daylighting, natural ventilation and all the passive means to reduce energy demand. The energy expert should also evaluate the embedded emissions of materials used, especially when the building is approaching the condition of zero energy, as in this case the only contribution to climate change would come from them. From these evaluations the energy expert derives recommendations for the architect and the mechanical engineer which, in turn, modify accordingly their design choices, proposing new solutions that have to be re-evaluated. This circular

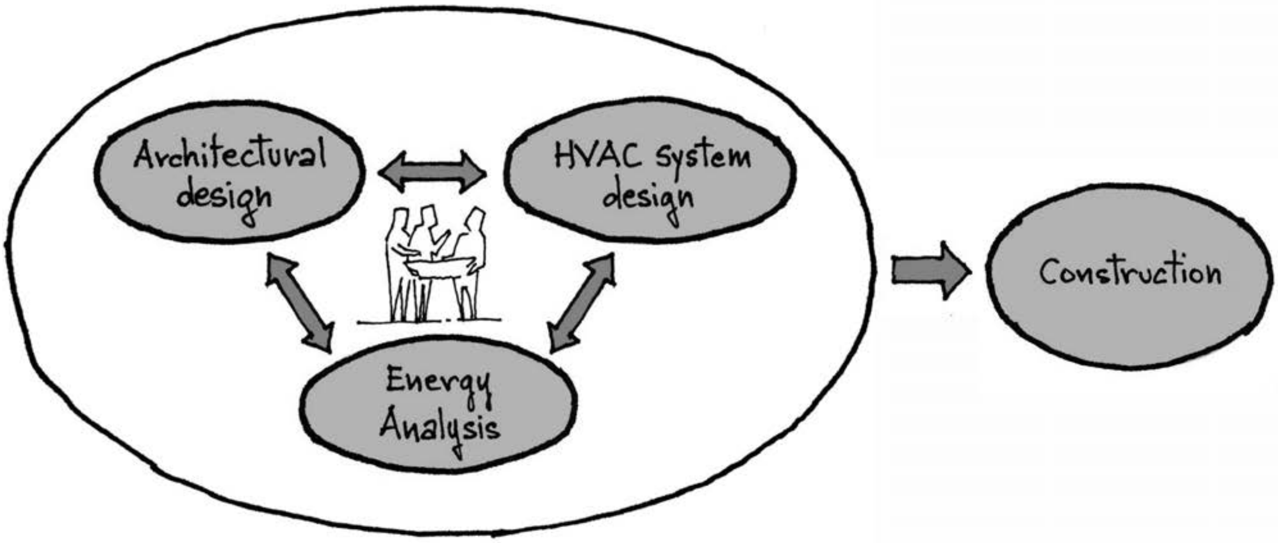


Fig. 1.3-3 - Integrated design

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).

It is also crucial that these skills are integrated since the earliest stages of the process. Indeed, it is in these phases that most critical decisions are taken, having a high weight on 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 outbalanced not only by the lower energy bill and the higher comfort, but also by the lower construction cost, compared with the cost of a building with the same energy performances but designed with the usual design process; this also because the unfortunately common practice of oversizing building's components and HVAC systems can be avoided.

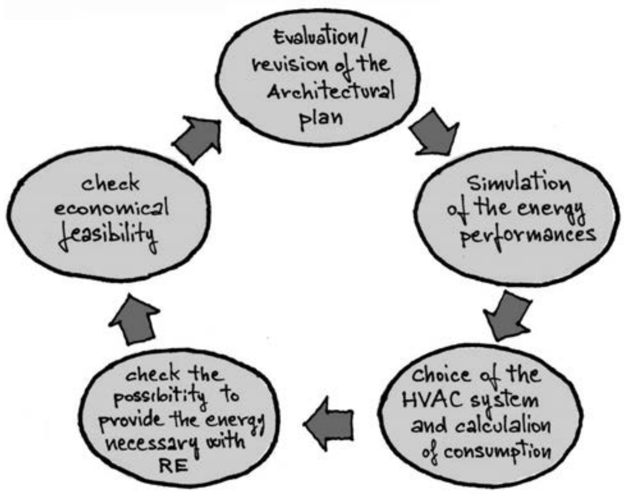


Fig. 1.3-4 - Sustainable design process

It is not sufficient, however, that the new design process integrates a new expertise, and that from linear it becomes circular; it is also necessary to define a planning strategy, the one characterising the low energy and comfortable building, that is not simply a "normal" building in which renewable energy is used instead of oil or gas; it is a building designed in a different way, whose planning strategy is depicted in figure 1.3-6, where it is pointed out that the 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, the issue of maximising the energy efficiency of mechanical systems and their appropriate control must be tackled.

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

1.4 Architecture in tropical climates

In developed countries, mostly located in cold climates, the main cause of energy consumption in buildings is due to space heating, and the efforts in the direction of curbing CO_2 emissions are in the direction of substituting – whenever possible – gas or oil boilers with heat pumps, that are far more efficient and are ready to be powered by solar or wind energy.

Heat pumps have double advantage: not only are the best technology for heating but, reversing the cycle, they provide cooling, and cooling, with global warming, is becoming an issue also in climates where it was not

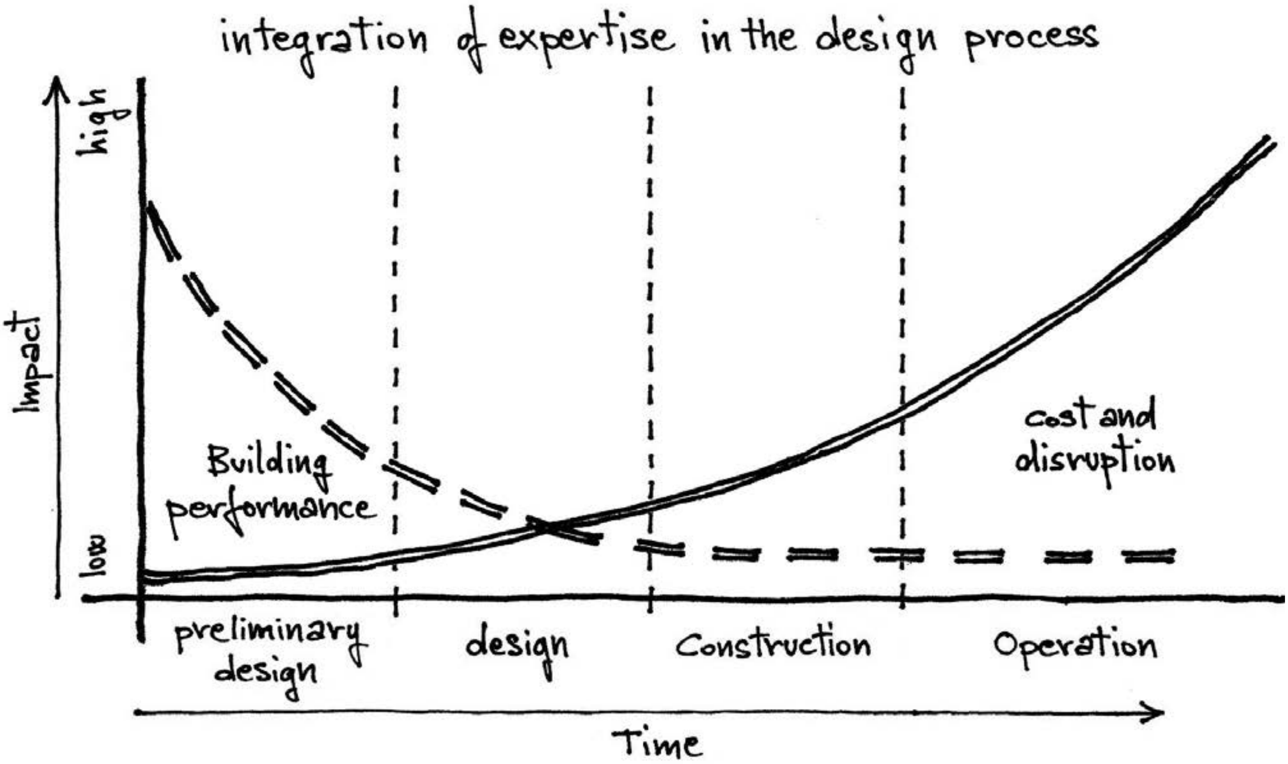


Fig. 1.3-5 - The earlier the integration of expertise in the design process, the greater the impact on performance, and the smaller the cost

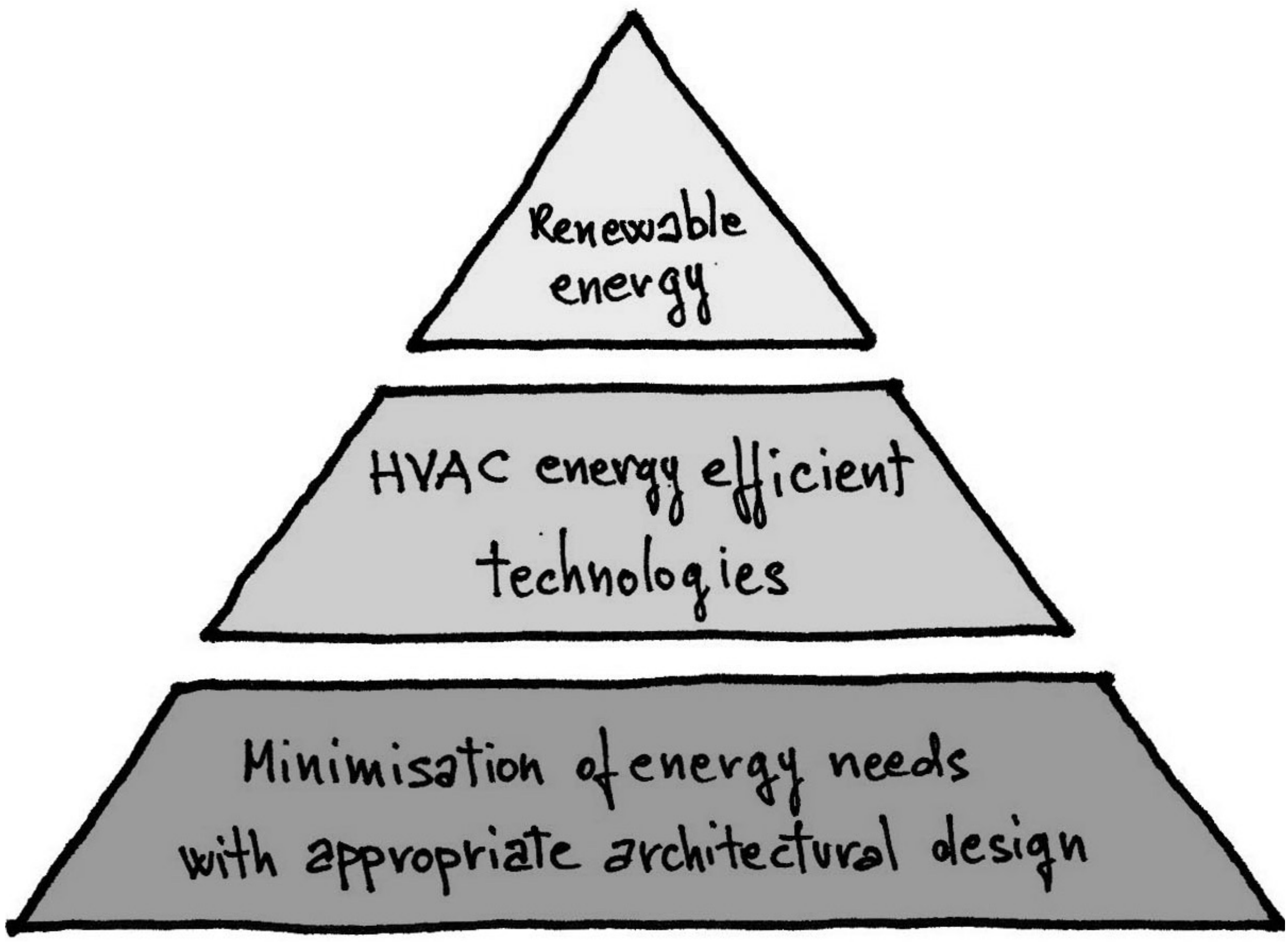


Fig. 1.3-6 - Towards low energy, high comfort buildings: design strategy

considered a need. Moreover, people's perception of comfort is changing, and environmental conditions in the past considered as acceptable, now they are not. Thus, the energy consumption growth (present and expected) for air conditioning is also due to the wish to live in more comfortable spaces, wish often exacerbated by two other drivers: inappropriate architecture and a wrong approach to thermal comfort. The former driver can be offset by following the principles of sustainable building design, but the latter requires a behavioural change.

Temperatures in northern American air-conditioned buildings and unfortunately also in most developing countries' buildings are far below the physiological requirements for thermal comfort. Set point temperatures below 24 °C are common in all commercial buildings, often requiring to wear a pull-over or a jacket and –in hotels – to use blankets. This usually does not happen in Europe, where temperatures in air-conditioned spaces usually do not fall below 25 °C.

In the African climates, thus, 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 exploited at best, and the adaptive comfort principles can dramatically reduce air conditioning energy consumption providing very good comfort conditions.

This approach is especially critical in tropical climates, and for this reason much attention is given to them – also because northern and southern African climates show close similarities with the southern European ones, for which much literature is available about energy efficient buildings design.

1.5 A new energy system for cities

When, about two centuries ago, the first gas networks started to be built in our cities, the basis for the present urban energy system was set up. At those times coal was the only fossil energy source used.

A little more than a century ago the urban electric grids appeared, and coal was slowly taken over 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 last century, the main cities of the western world were provided with a sewage system, a water network and a solid waste collection system. No more hard work to carry water from the fountains, no more epidemics, comfortable interiors with heating, cooling and electric lighting, easier life at home with domestic appliances, fast mobility. A revolution in quality of life. All thanks to cheap fossil fuels and to the technologies fed by them.

Cities slowly changed, and learnt to metabolise fossil fuels, building up either an urban energy system based on them and an overall metabolic system that left no room to recycling: the saturation of environment with wastes was not an issue. At the end of the process a new organism, the modern city, was born, fit to an environment supposed as an infinite source and an infinite sink.

Present urban energy system is designed on this assumption. Our task is to transform, with a sort of genetic engineering, the fossil energy based city – into the renewable energy based city. Unfortunately we do not have two centuries in front of us, we do not have so much time; we must do it in less than thirty.

Starting from the seventies of past century – after the first oil shock – the energy issue started to be introduced, by a few pioneers, in the architectural design. Guidelines for low energy building design were implemented, and now they are becoming compulsory practice in all European Union and in some other countries of the world.

Now it is the time of introducing the energy issue in the urban design, since the most significant energy savings can be obtained at this scale, by redesigning the energy system.This implies to change the priorities in the formal design of the urban layout and in the organization of the urban functions, but not only.

The Distributed Energy Resources (DER) approach must be introduced, made 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) capable to rely mostly on renewable energy sources, and implies an evolutionary jump towards a far more "intelligent" urban energy system, because it is needed also a distributed control system – made possible by the present development the information and communication technologies.

The change of the energy paradigm is the only chance we have to cope with the present world trend leading to either the economical or the ecological catastrophe, or both.It is not an easy task, because it is a technological change that implies a cultural change. It has to change the culture of architects and city planners, of citizens, of entrepreneurs, of city managers and politicians.

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, which mostly affects the building design, is generally related to an area ranging from a few square metres 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 it 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 sun on the horizon (and thus the lower the latitude) the more energy reaches the ground and the higher the air temperature.

The intensity of solar radiation is also related to the atmospheric composition and length of the atmospheric path traversed by the sun's rays as described in detail in paragraph 2.1.2.

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 1 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).

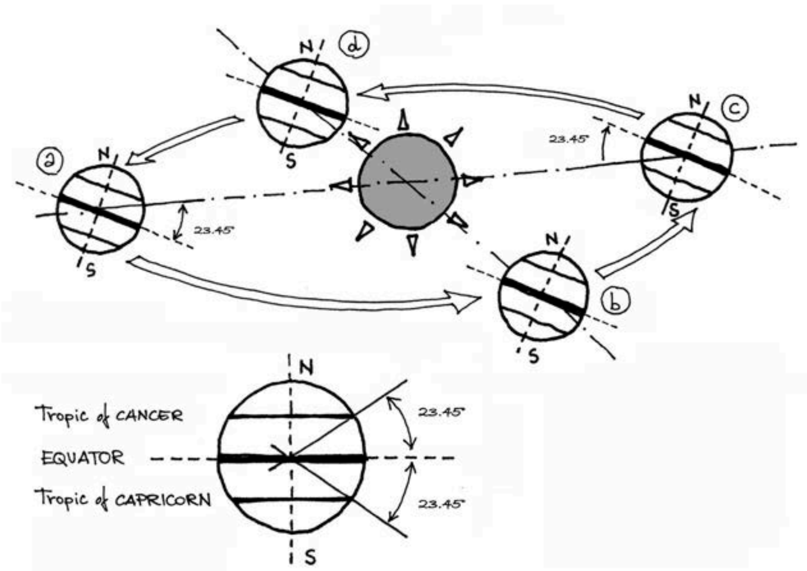


Fig. 2.1-1 - Solar declination angle. (a) Summer solstice; (b) Autumn equinox; (c) Winter solstice; (d) Spring equinox

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.

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[1] coordinate axis to the projection of the line of sight to the sun on the ground.

We assume 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 θz is used, which is its complementary; 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 thermal and visual 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.

On the other hand, for latitude > 30° (Figure 2.1-2b), when winter space heating may be welcome, the lower solar altitude favours beneficial sun penetration in buildings, improving themal comfort and reducing energy consumption for heating.

2.1.1.1 Solar and local time

Solar time, usually used in solar analysis, is a measure of the rotation angle of the earth with respect to the sun. This

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

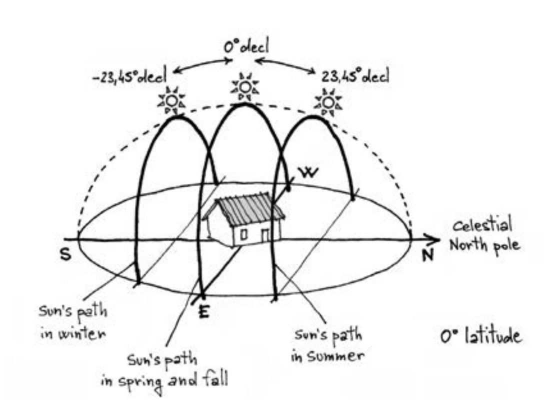


Fig. 2.1-2a - Apparent sun path (equator)

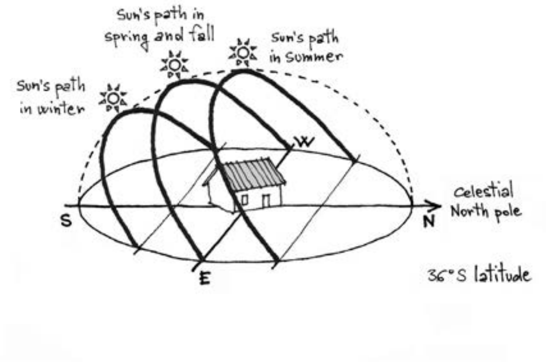


Fig. 2.1-2b - Apparent sun path (+35° Latitude)

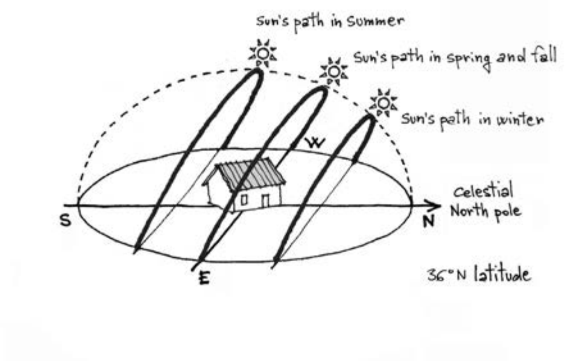


Fig. 2.1-2c - Apparent sun path (-35° Latitude)

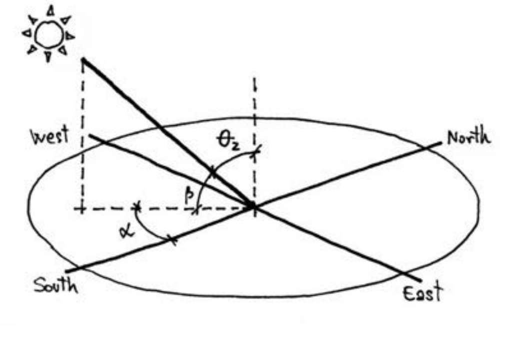


Fig. 2.1-3 - Angular coordinates of the sun

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[2]. 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, economic 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 at any reference longitude the local mean time deviates from solar time of the day[3] by up to -16 minutes in November and +14 minutes in February (Fig. 2.1-4) and its graphic representation is the analemma (Fig. 2.1-5).

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.

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[4] (cylindrical diagrams).

The most widely used is the stereographic (or radial) representation, which uses the theoretical nadir point (the point of the celestial sphere that is directly opposite the zenith and vertically downward from the observer) as the centre of projection (Fig. 2.1-6).

The alternative is to use a cylindrical representation in which, solar elevation is plotted on the Y-axis and the azimuth is plotted on the X-axis (Fig. 2.1-6b).

This provides a fairly accurate representation near the horizon circle, with an increasing distortion at higher altitudes. The zenith point is stretched into a line of the

2 *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.*

3 *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.*

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

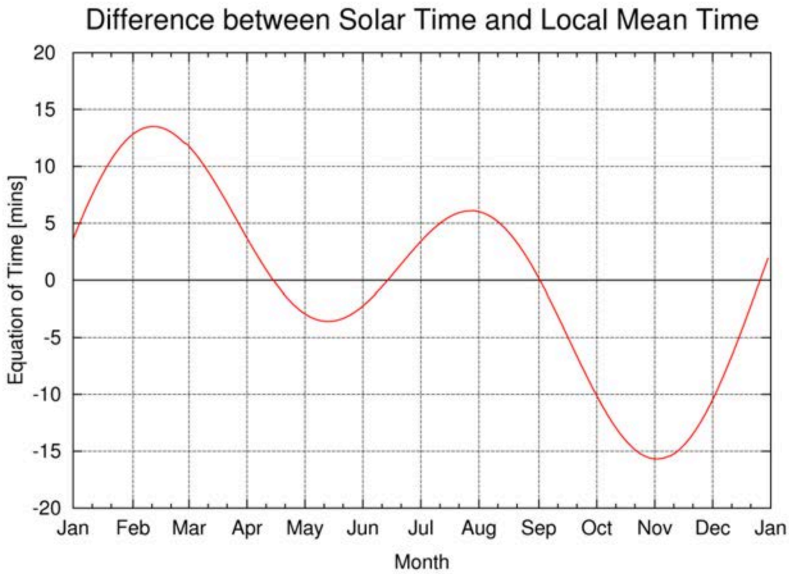
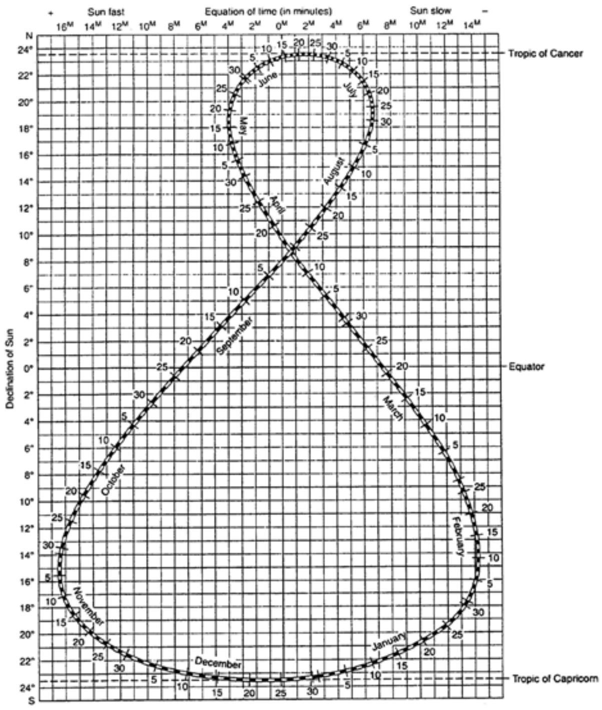


Fig. 2.1-4 - Equation of Time diagram



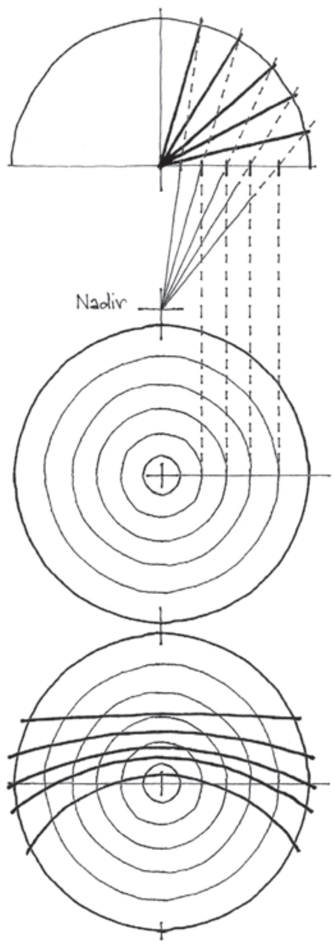


Fig. 2.1-5 - Local time analemma

Fig. 2.1-6a - Stereographic Polar diagram construction same length as the horizon circle. In these diagrams, the problem is that equal increments of altitude will be compressed towards the zenith.

For locations between the tropics two such charts are necessary, one facing south and another facing north. A modification of this cylindrical projection is the Waldram diagram, which represents equal areas for the purposes of daylighting design.

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).

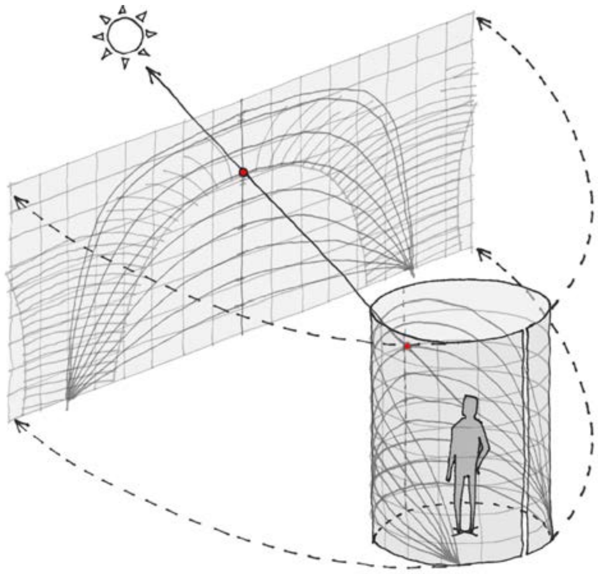


Fig. 2.1-6b - Cylindrical diagram construction

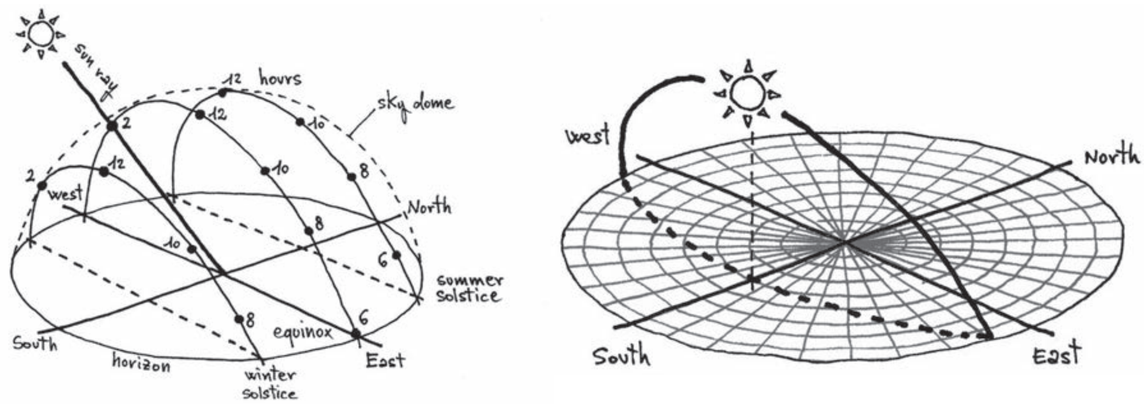


Fig. 2.1-7 - Projection of solar path on the polar chart

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

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.

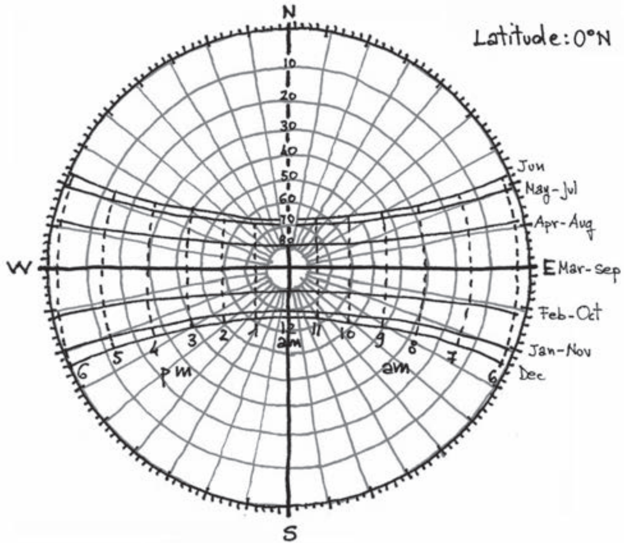


Fig. 2.1-8 - Polar sunpath diagram or sunchart at the equator

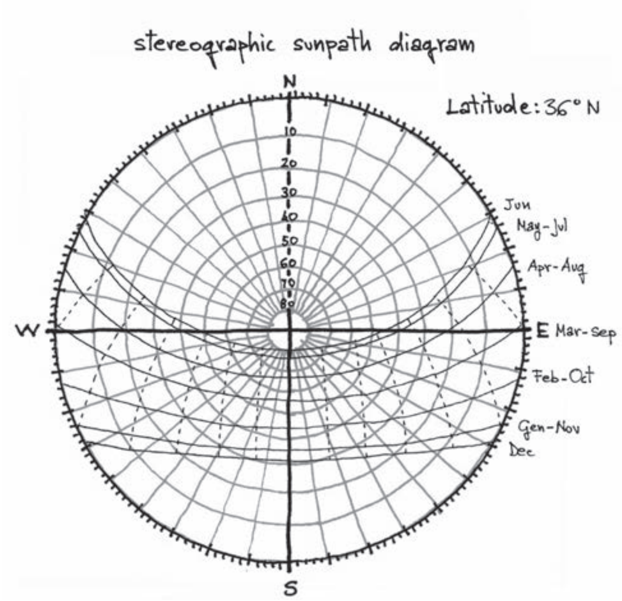


Fig. 2.1-8a - Use of sunchart example at 36° of latitude

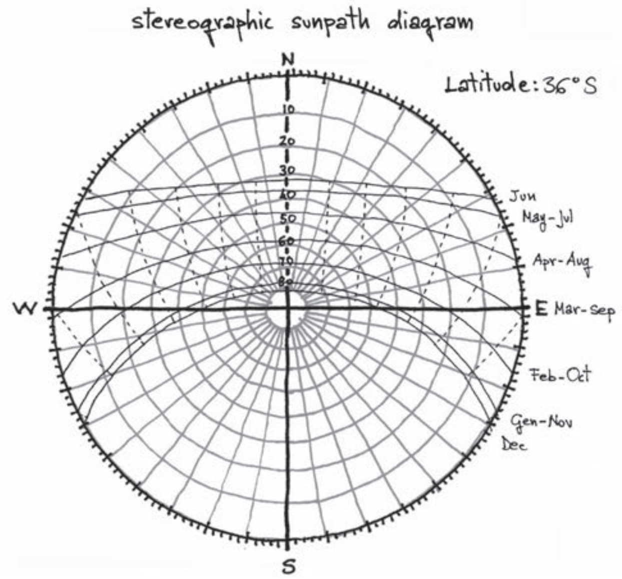


Fig. 2.1-8b - Polar sunpath diagram or sunchart at the equator

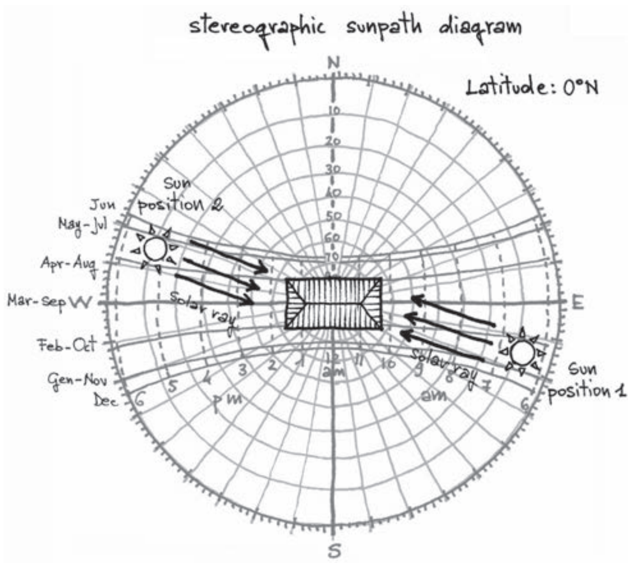


Fig. 2.1-8 - Polar sunpath diagram or sunchart at the equator

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 exactly perpendicular to the surface and 90° when they are parallel to it.

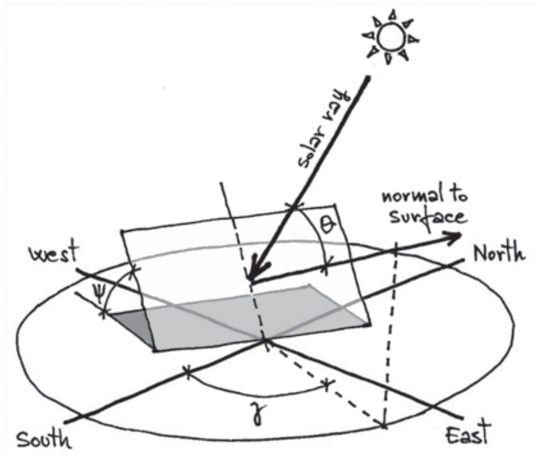


Fig. 2.1-10 - PSurface azimuth γ, tilt angle ψ and incidence angle θ

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 radiant energy that reaches the earth falls between 300 and 2400 nm wavelength. 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).

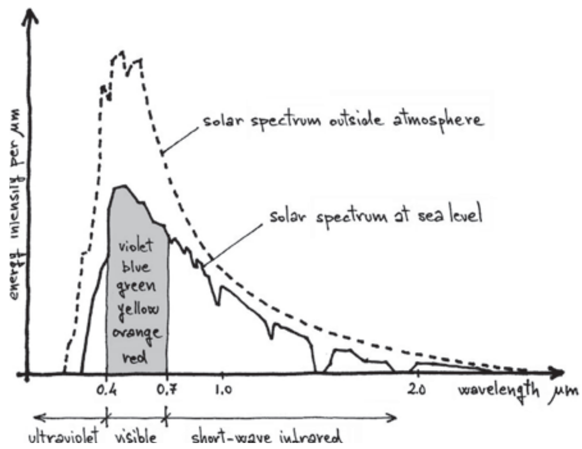


Fig. 2.1-10 - Solar spectrum

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).

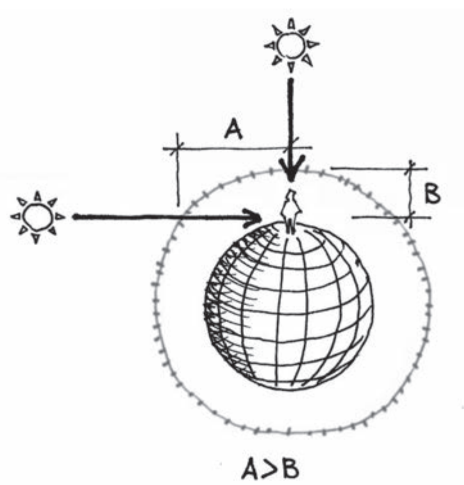


Fig. 2.3-12 - Sun path across the athmosphere

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%. In overcast sky condition, 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 (see paragraph 2.1.6)

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.

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. So, the horizontal surface without obstructions (no shadow) receives maximum diffuse radiation.

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 ground, façades, 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.

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

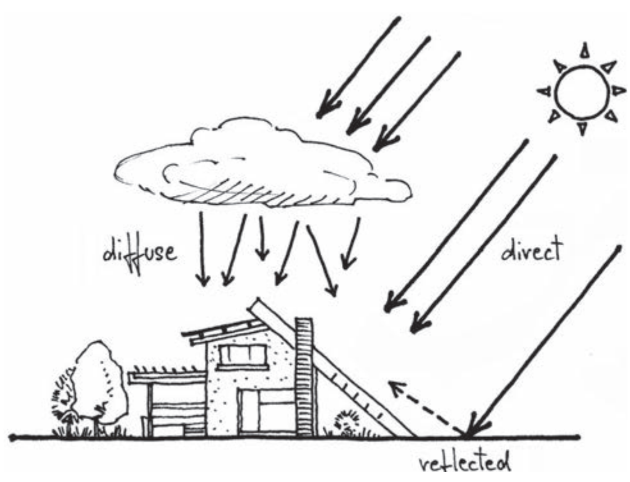


Fig. 2.1-13 - Direct, diffuse and reflected radiation

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. 2.1-2).

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.

In fact, in passing through the earth's atmosphere, the sun's radiation is reflected, scattered, and absorbed by particles, such as dust, gas molecules, ozone, water vapor, and water droplets (fog and clouds).

In particular, while the ultraviolet solar radiation is absorbed by the ozone in the upper atmosphere, the near and far infrared radiation are mostly absorbed by water droplets.

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.

Costal 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 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.

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

Table 2.1-1 - Albedo of surfaces

2.1.1.3 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/m^2];

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;

ρ is the albedo;

I is the total irradiance ($I = I_b + I_d$) on the horizontal plane [W/m²];

$F_c = 1 - F_s$ represents the view factor of the surrounding context, from which the reflected radiation reaches the surface considered.

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.

Solar radiation data are provided for selected African locations (see Appendix 4) 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 ($I = I_b + I_d$).

2.1.2.4 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, where solar radiation is plotted for two different locations, one equatorial (Mombasa with the latitude Φ = 4.04 ° South), and another one far from equator (Algiers with the latitude Φ = 36.69° North) 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.

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. 2.1-6) shows the overall trend of monthly irradiation on a horizontal surface for three locations: Mombasa (Φ: 4.04° South, hot-humid climate), Calvinia (Φ: 31.5° South, arid climate) and Algiers (Φ: 36.69° North, temperate climate).

As can be seen, there is a large variation in solar radiation which ranges between 75 and 270 kWh/m² per month, where the oscillations depend on the season and the specific climatic context.

Note that Algiers and Calvinia are characterized by higher solar radiation values during the summer period.

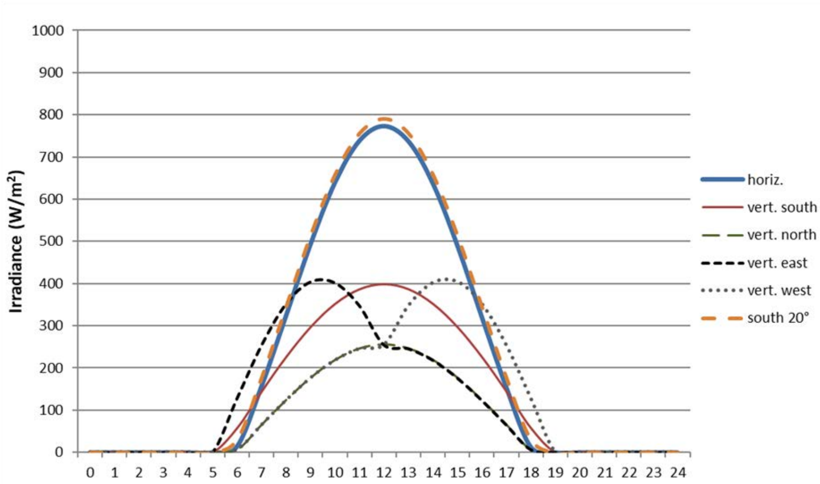


Fig. 2.1-14a - Mombasa, December solstice irradiance (albedo = 0.2)

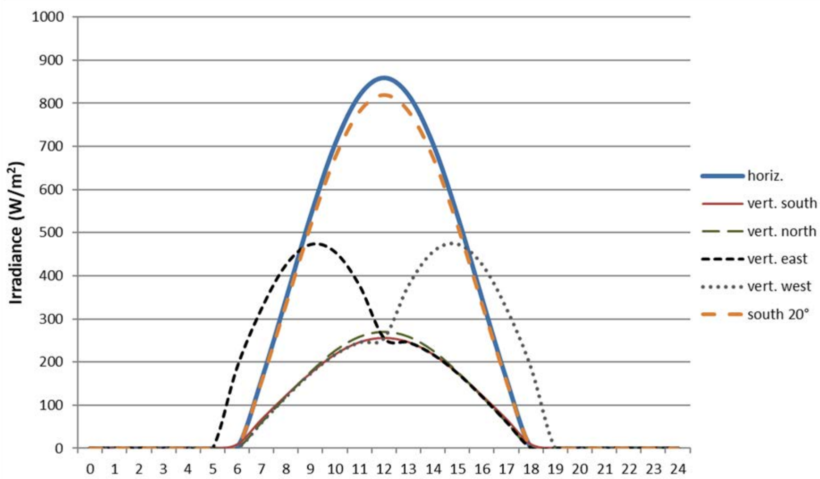


Fig. 2.1-14b - Mombasa, vernal equinox irradiance (albedo = 0.2)

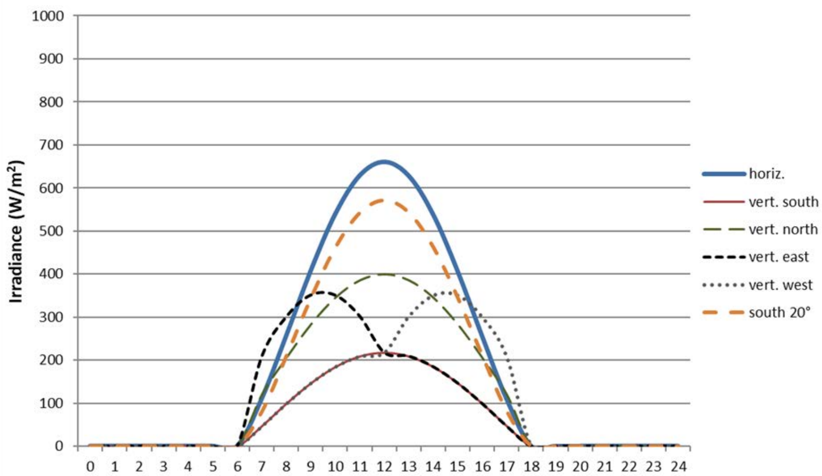


Fig. 2.1-14c - Mombasa, June solstice irradiance (albedo = 0.2)

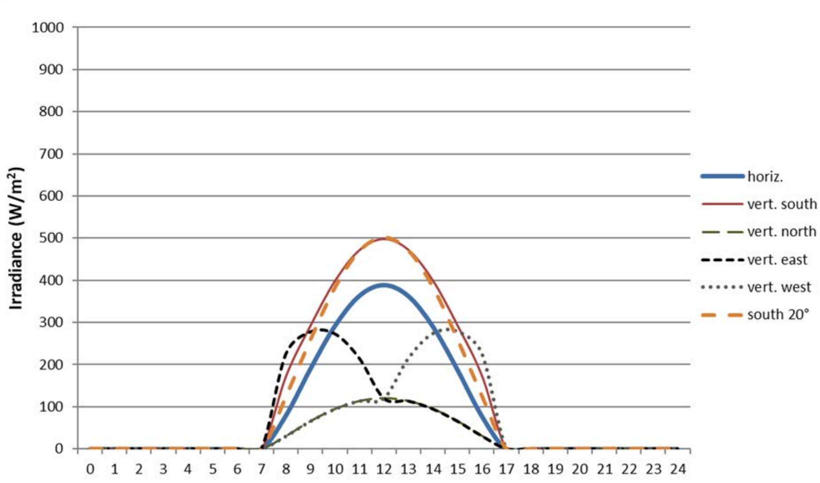


Fig. 2.1-15a - Algiers, December solstice irradiance (albedo = 0.2)

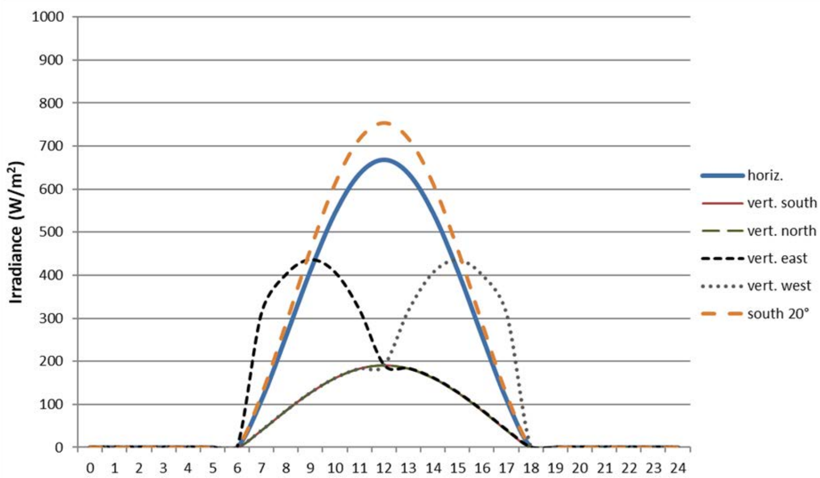


Fig. 2.1-15b - Algiers, vernal equinox irradiance (albedo = 0.2)

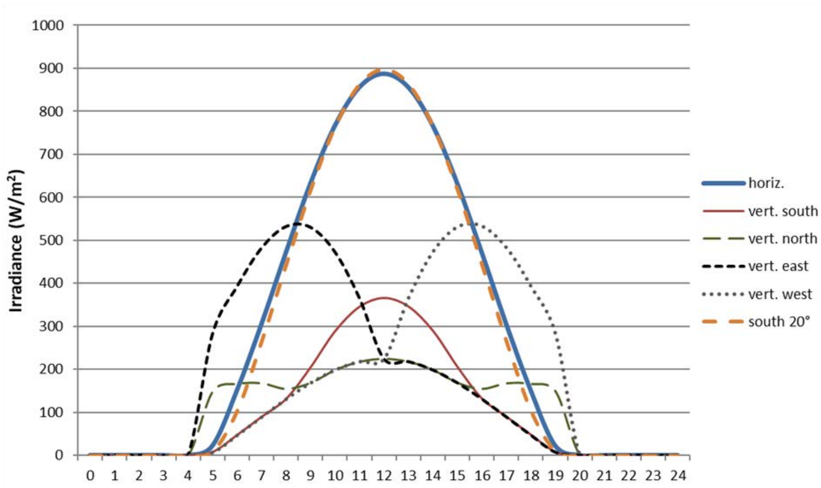


Fig. 2.1-15c - Algiers, June solstice irradiance (albedo = 0.2)

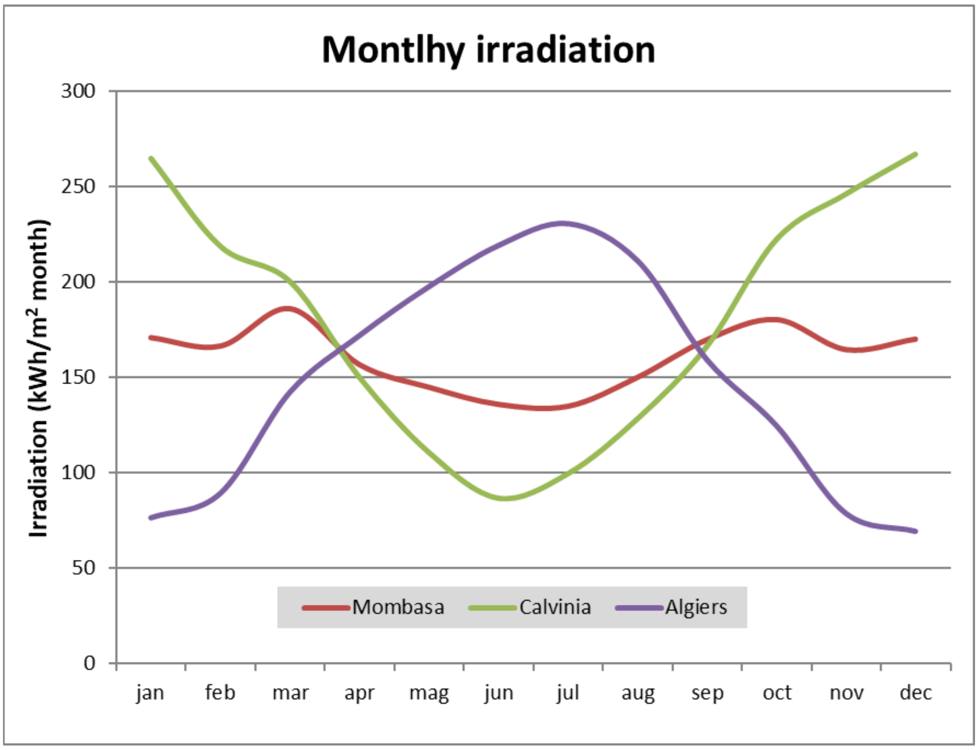


Fig. 2.1-16 - Monthly irradiation in three sites

	Jen		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	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	I_b
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.																								
6 a.m.	9	3	5	3	1	1													4	2	8	3	10	4
7 a.m.	98	57	91	72	88	71	88	46	75	41	72	38	80	26	86	36	87	61	93	66	100	54	100	56
8 a.m.	181	142	171	176	170	177	173	126	151	114	147	109	163	83	172	104	169	157	175	163	185	137	183	139
9 a.m.	252	242	240	294	240	300	246	223	217	203	212	195	235	156	246	189	240	269	246	276	258	234	255	237
10 a.m.	307	335	292	403	293	413	303	315	267	288	261	277	290	227	302	271	294	374	301	381	314	326	310	328
11 a.m.	341	402	325	480	327	493	338	381	299	348	293	336	324	279	338	329	328	448	335	455	349	391	345	393
12 a.m.	353	425	337	508	339	521	350	404	309	370	303	357	336	298	350	351	339	474	347	482	361	415	356	417
1 p.m.	341	402	325	480	327	493	338	381	299	348	293	336	324	279	338	329	328	448	335	455	349	391	345	393
2 p.m.	307	335	292	403	293	413	303	315	267	288	261	277	290	227	302	271	294	374	301	381	314	326	310	328
3 p.m.	252	242	240	294	240	300	246	223	217	203	212	195	235	156	246	189	240	269	246	276	258	234	255	237
4 p.m.	181	142	171	176	170	177	173	126	151	114	147	109	163	83	172	104	169	157	175	163	185	137	183	139
5 p.m.	98	57	91	72	88	71	88	46	75	41	72	38	80	26	86	36	87	61	93	66	100	54	100	56
6 p.m.	9	3	5	3	1	1													4	2	8	3	10	4
7 p.m.																								
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

Radiation square: Hourly irradiance [W/m2] on a horizontal surface, Mombasa, Kenya (Group A climates: Hot-Humid)

I < 300 W/m2 | 300 ≤ I ≤ 600 W/m2 | I > 600 W/m2

Table. 2.1-2 - Radiation square, Mombasa

	Jen		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	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	I_b
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.																								
6 a.m.	54	86	32	51	6	8													24	34	49	74	62	92
7 a.m.	114	218	93	178	65	117	34	57	12	14	1	1	6	6	27	31	56	80	85	149	111	199	124	220
8 a.m.	171	373	149	333	120	259	86	178	64	100	52	68	58	82	82	125	114	201	142	294	169	349	182	370
9 a.m.	219	531	197	495	167	412	131	315	108	206	96	156	103	179	130	237	163	334	191	447	219	504	232	522
10 a.m.	256	668	234	637	203	549	165	442	143	308	130	243	138	273	167	343	201	456	229	582	257	638	271	654
11 a.m.	280	762	258	734	226	644	186	531	164	380	151	306	159	340	190	418	225	541	252	675	281	730	295	744
12 a.m.	288	795	266	769	234	678	194	563	172	407	159	329	167	365	198	445	233	572	260	708	289	762	303	775
1 p.m.	280	762	258	734	226	644	186	531	164	380	151	306	159	340	190	418	225	541	252	675	281	730	295	744
2 p.m.	256	668	234	637	203	549	165	442	143	308	130	243	138	273	167	343	201	456	229	582	257	638	271	654
3 p.m.	219	531	197	495	167	412	131	315	108	206	96	156	103	179	130	237	163	334	191	447	219	504	232	522
4 p.m.	171	373	149	333	120	259	86	178	64	100	52	68	58	82	82	125	114	201	142	294	169	349	182	370
5 p.m.	114	218	93	178	65	117	34	57	12	14	1	1	6	6	27	31	56	80	85	149	111	199	124	220
6 p.m.	54	86	32	51	6	8													24	34	49	74	62	92
7 p.m.																								
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

Radiation square: Hourly irradiance [W/m2] on a horizontal surface, Calvinia, South Africa (Group B climates: Arid)

I < 300 W/m2 | 300 ≤ I ≤ 600 W/m2 | I > 600 W/m2

Table. 2.1-3 - Radiation square, Calvinia

	Jen		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dic	
	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	I_b
1 a.m.																								
2 a.m.																								
3 a.m.																								
4 a.m.																								
5 a.m.											11	12	4	6										
6 a.m.							32	22	62	48	64	87	54	89	34	54	7	6						
7 a.m.			25	12	58	52	100	93	128	125	118	187	104	200	84	163	68	82	33	31	3	1		
8 a.m.	53	44	89	65	120	138	163	188	189	219	168	304	151	328	131	294	126	186	92	115	65	45	45	35
9 a.m.	102	111	145	137	173	238	218	291	241	318	211	421	191	458	172	429	175	300	143	215	119	110	93	97
10 a.m.	140	179	188	208	214	331	260	383	281	405	244	523	221	569	203	548	213	404	182	310	160	177	130	161
11 a.m.	164	230	215	260	239	397	286	448	306	465	265	592	241	644	222	628	237	477	206	377	186	226	154	209
12 a.m.	172	249	224	279	248	420	295	471	315	486	272	616	247	671	229	657	245	503	214	402	195	244	162	227
1 p.m.	164	230	215	260	239	397	286	448	306	465	265	592	241	644	222	628	237	477	206	377	186	226	154	209
2 p.m.	140	179	188	208	214	331	260	383	281	405	244	523	221	569	203	548	213	404	182	310	160	177	130	161
3 p.m.	102	111	145	137	173	238	218	291	241	318	211	421	191	458	172	429	175	300	143	215	119	110	93	97
4 p.m.	53	44	89	65	120	138	163	188	189	219	168	304	151	328	131	294	126	186	92	115	65	45	45	35
5 p.m.			25	12	58	52	100	93	128	125	118	187	104	200	84	163	68	82	33	31	3	1		
6 p.m.							32	22	62	48	64	87	54	89	34	54	7	6						
7 p.m.											11	12	4	6										
8 p.m.																								
9 p.m.																								
10 p.m.																								
11 p.m.																								
12 p.m.																								

Radiation square: Hourly irradiance [W/m2] on a horizontal surface, Algiers, Algeria (Group C Climates: Temperate Hot Humid)

I < 300 W/m2 | 300 ≤ I ≤ 600 W/m2 | I > 600 W/m2

Table. 2.1-4 - Radiation square, Algiers

2.1.3 Air temperature

Air temperature is greatly influenced by context, depending primarily on geographical factors (latitude and hydrography), topography (altitude and orography), 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. 2.1-17).

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 preliminary 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. 2.1-18). For detailed evaluations, precise values with small intervals (e.g. hourly) of temperature are used.

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

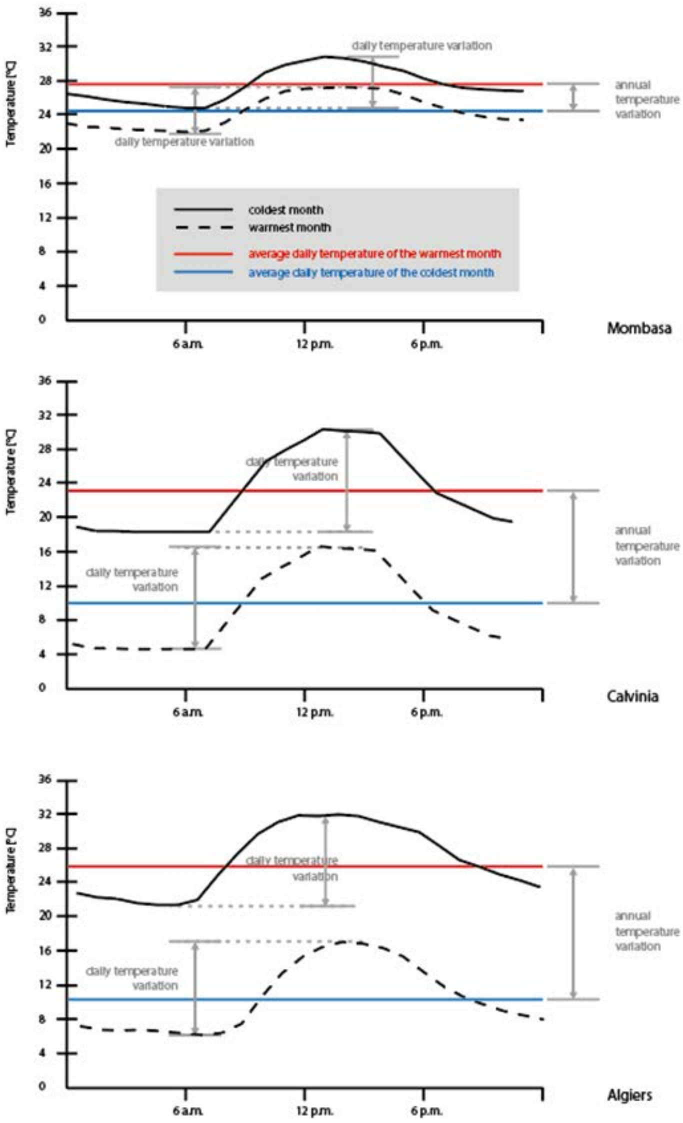


Fig. 2.1-17 - Typical temperature pattern (monthly average values)

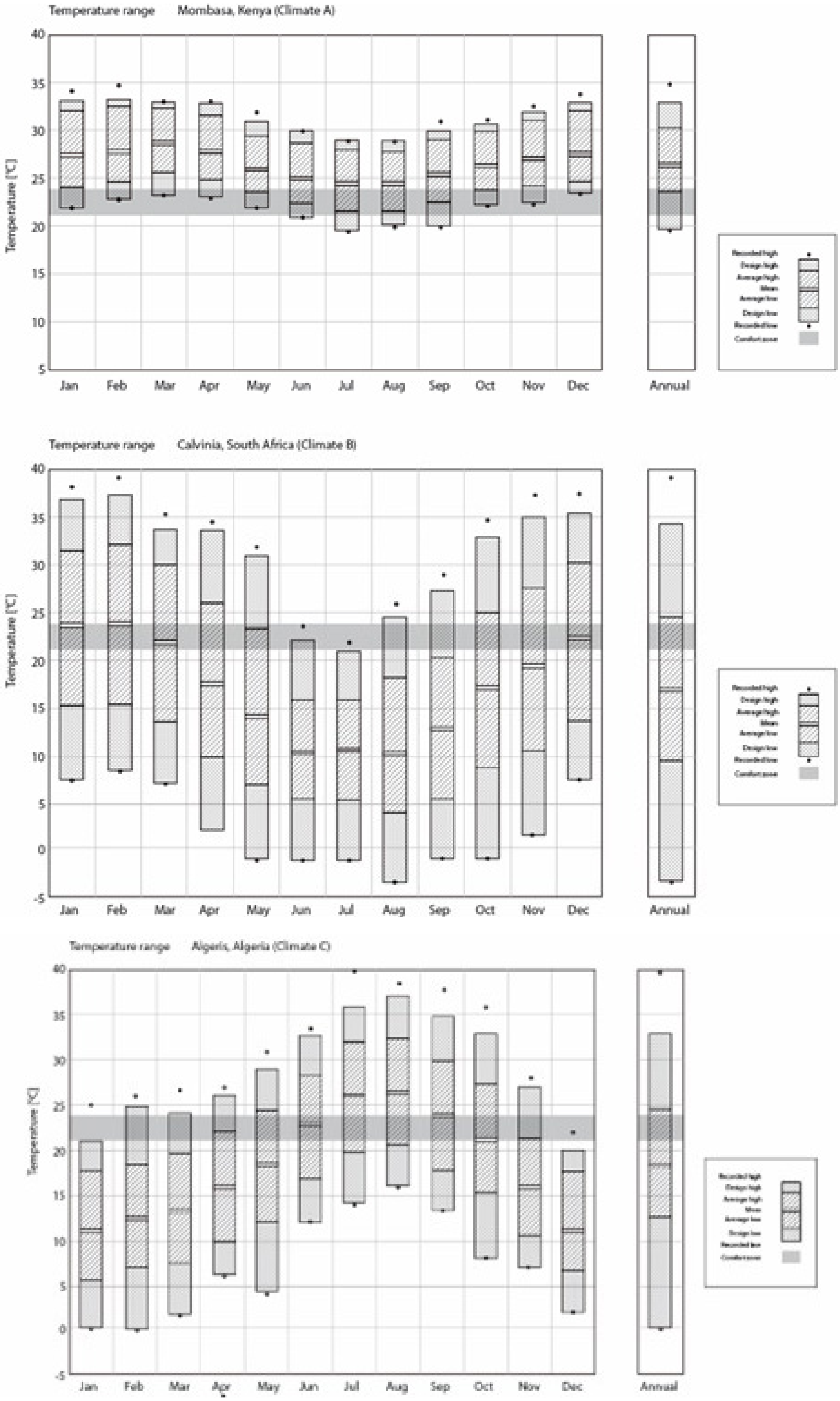


Fig. 2.1-18 - Monthly pattern and temperature variation (source: Climate Consultant)

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.

Orography 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. 2.1-10).

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. 2.1-11).

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.

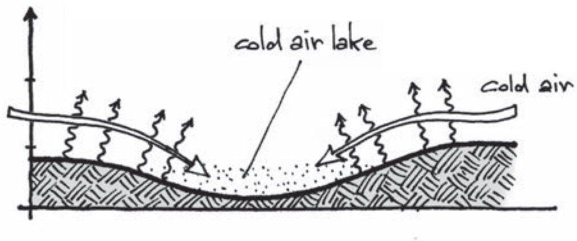


Fig. 2.1-10 - Cold air lake

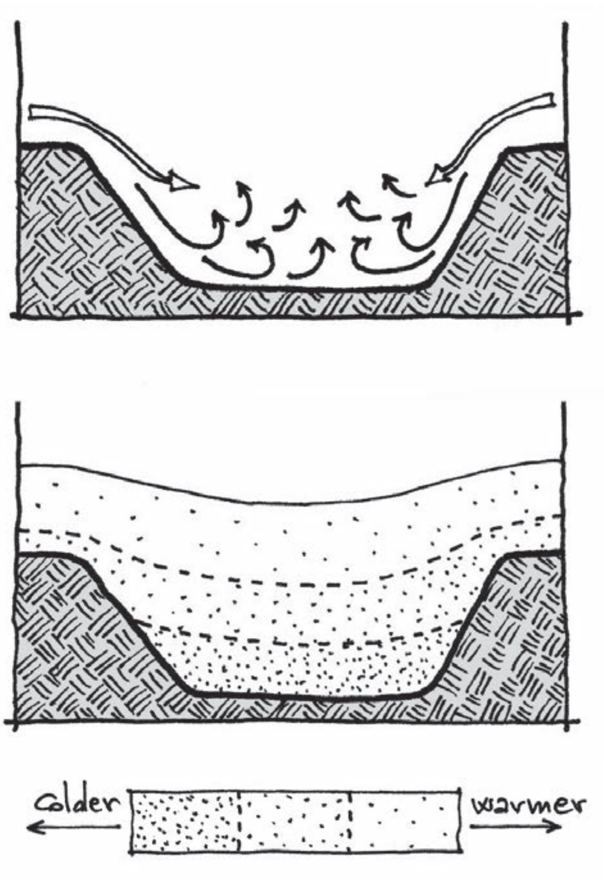


Fig. 2.1-11 - Cold air lake stratification

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 2.1.2.1), infrared emissivity and specific heat of the material the soil is made of, as shown in figure 2.1-21.

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. 2.1-22). 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. 2.1-23). 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 2.1-24, 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.

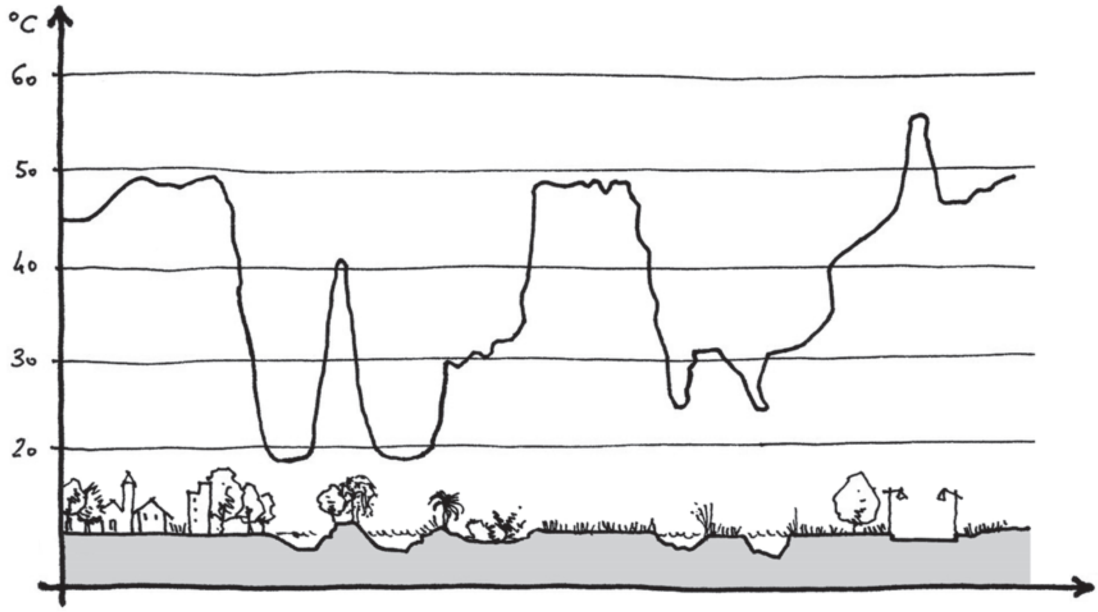


Fig. 2.1-21 - Soil nature and temperature

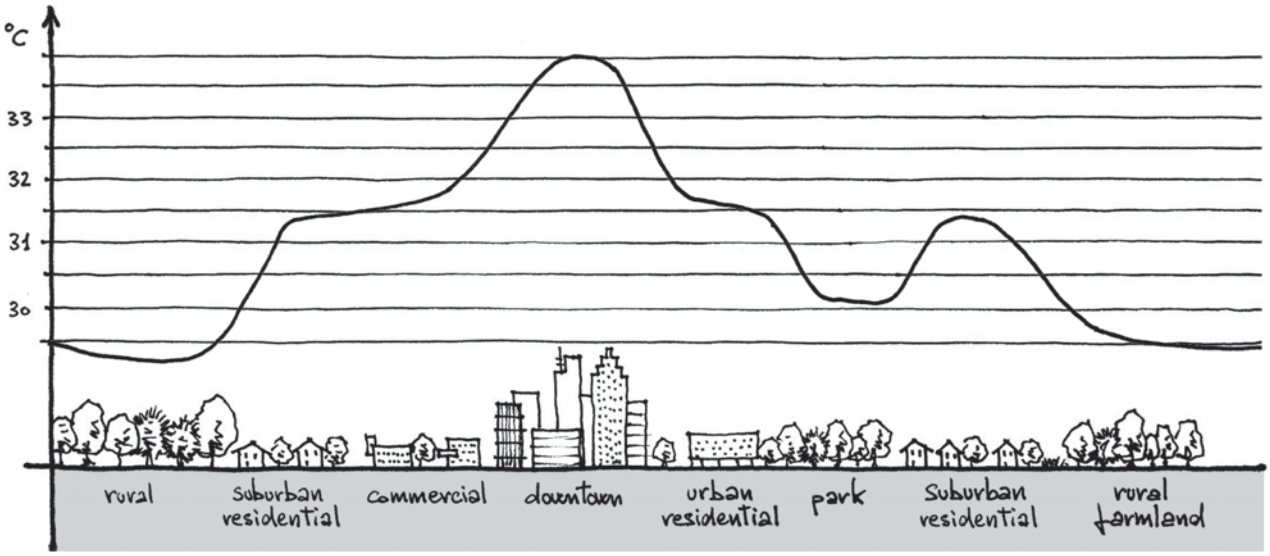


Fig. 2.1-22 - Effect on air temperature of the urban heat island

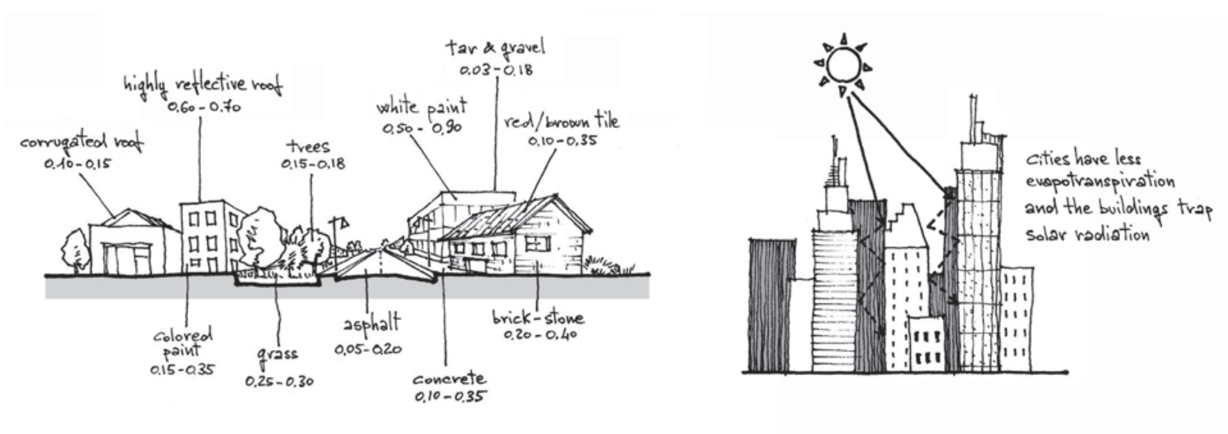


Fig. 2.1-23 - Various urban environment albedos (left) and heat trap or urban canyon effect (right)

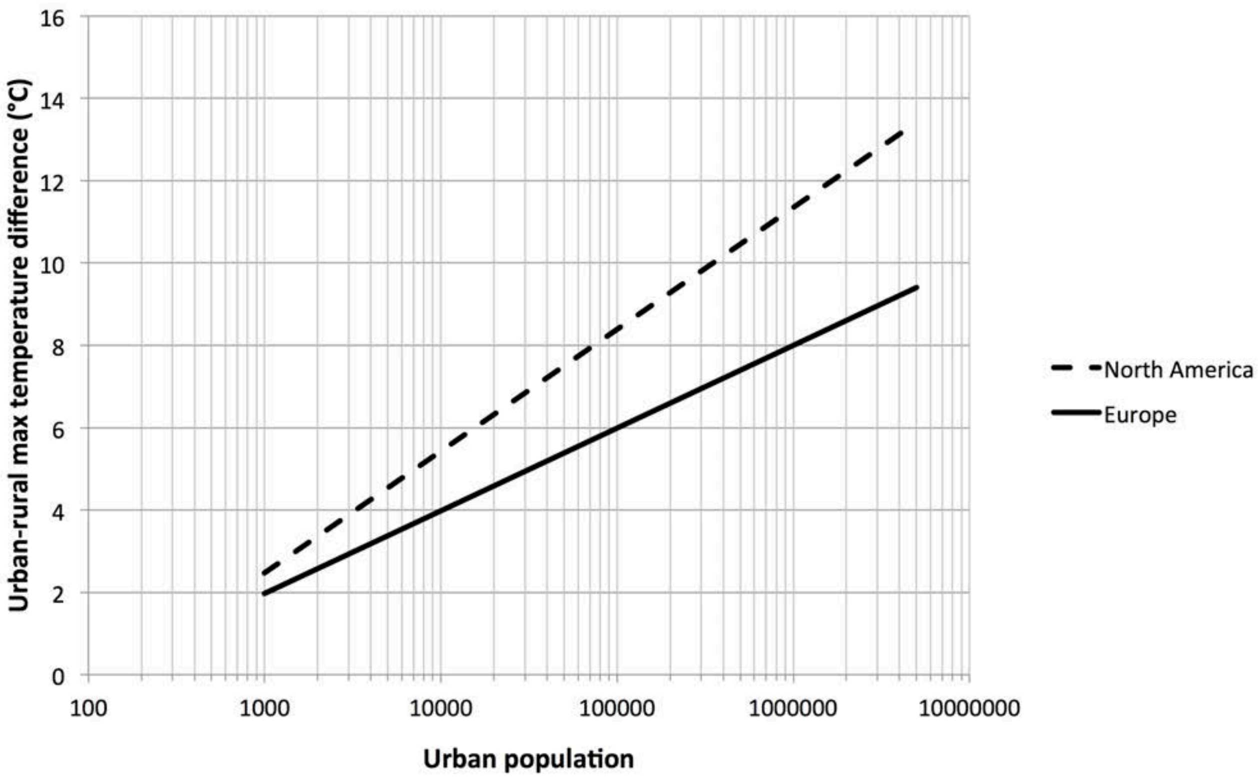


Fig. 2.1-24 - Effect of urban size on heat island (Adapted from: T.R. Oke, City size and the urban heat island. Atmospheric Environment 7:769-779,1973)

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. 2.1-16).

In fact, the amount of water that can be hold in air is directly related to the temperature: higher is the temperature, higher is the water that can be sink in air.

Due to the definition of relative humidity, if the maximum possible amount of water content in the air rise but the actual quantity present in the air remains the same, the ratio decreases.

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.

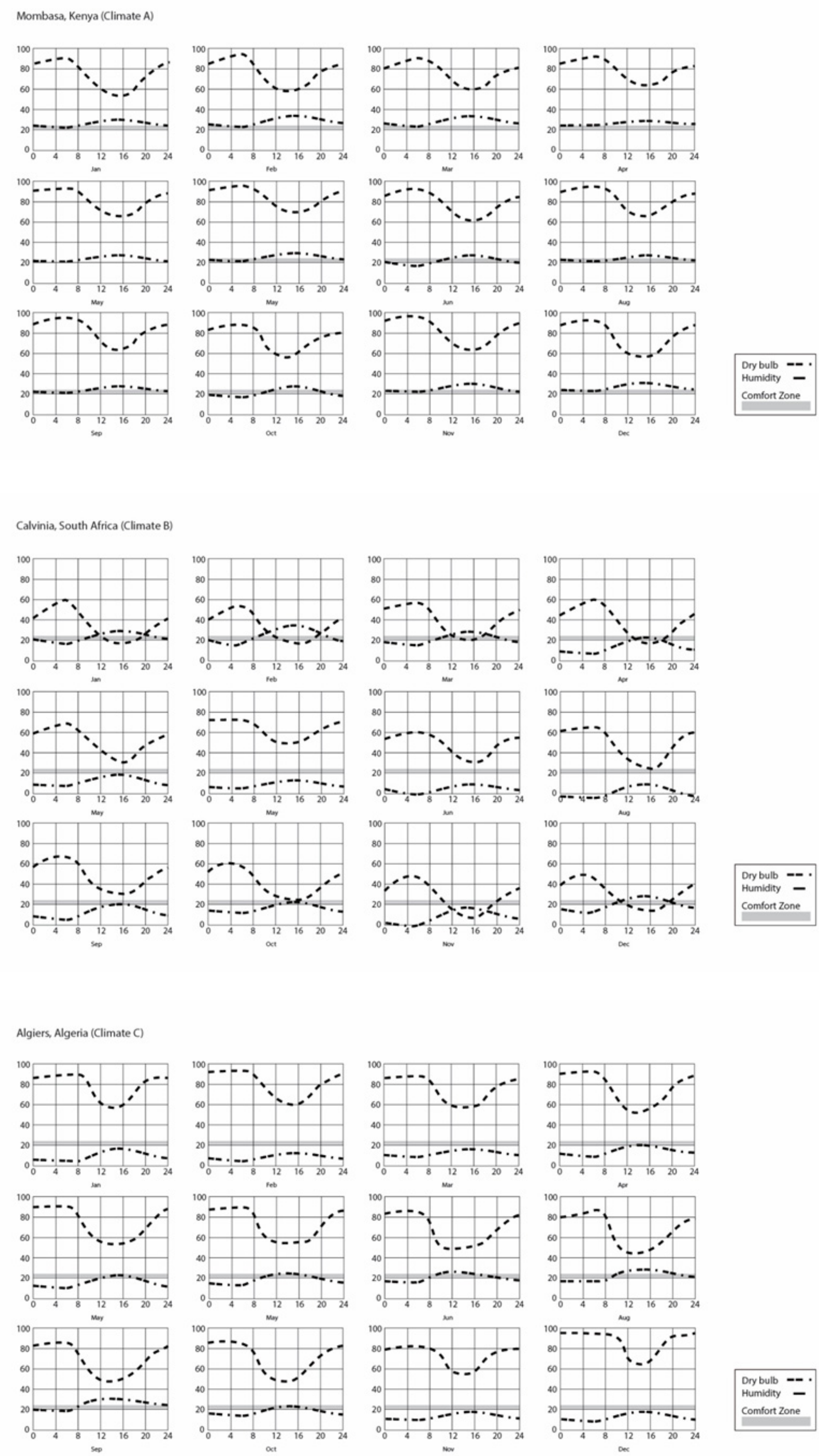


Fig. 2.1-16 - Relative humidity vs. dry bulb temperature (Source: Climate Consultant)

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. 2.1-26). Presented in a circular format, the wind rose shows the percentage of hours in which winds blowing from particular directions (the so called frequency).

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.

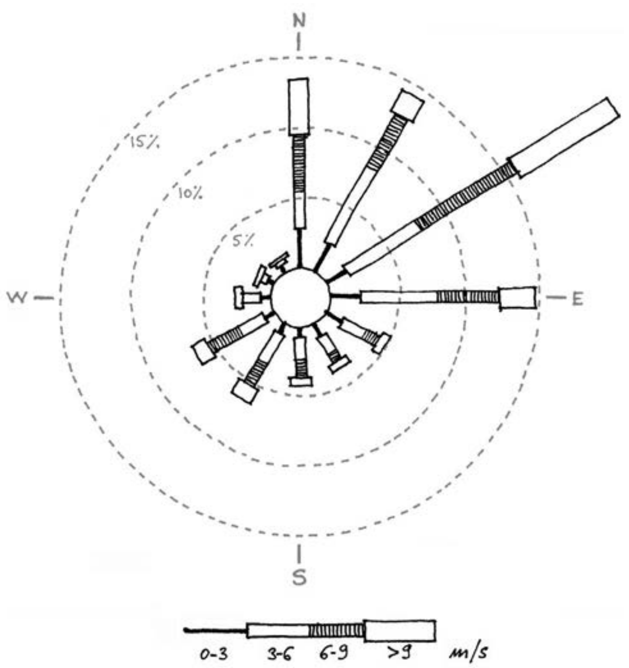


Fig. 2.1-26 - Wind rose

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 2.1-27 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:

Z = is the height [m]

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.

The graph shown in Fig. 2.1-28 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. 2.1-29.

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

Table 2.1-5 – Correction factors as a function of the height and roughness of the ground

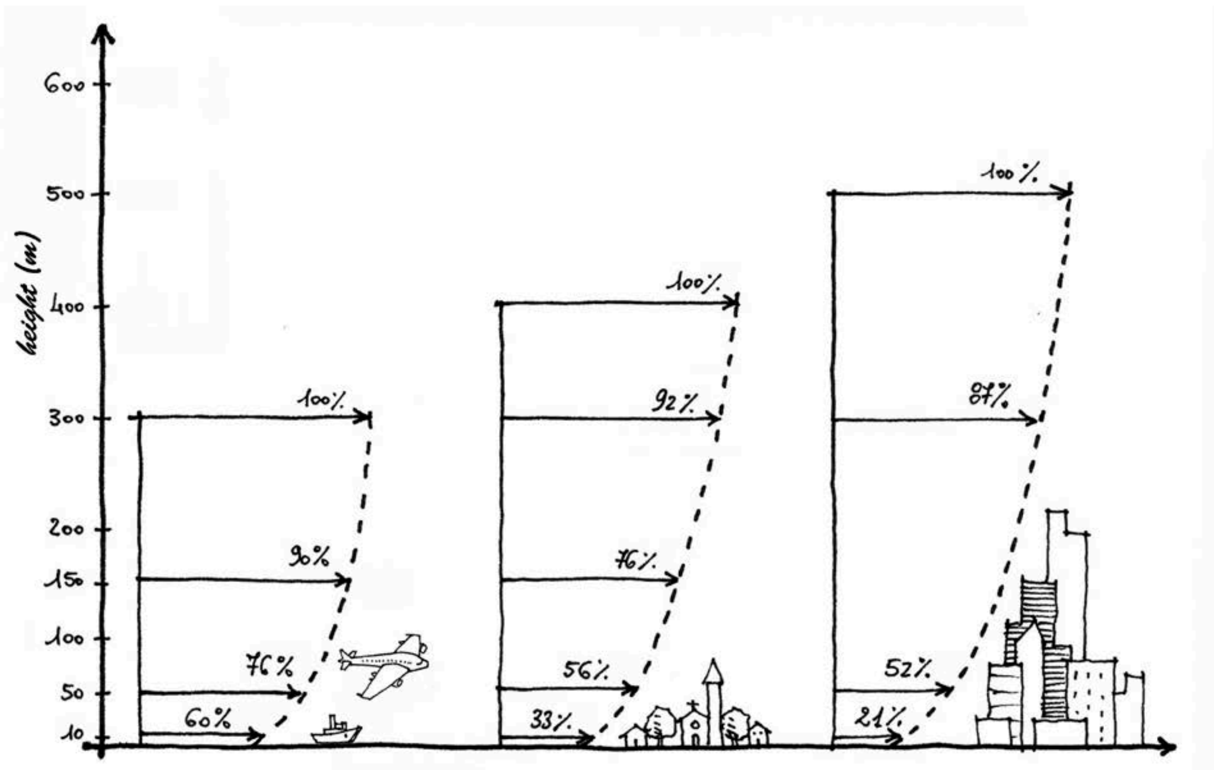


Fig. 2.1-27 - Wind speed profiles

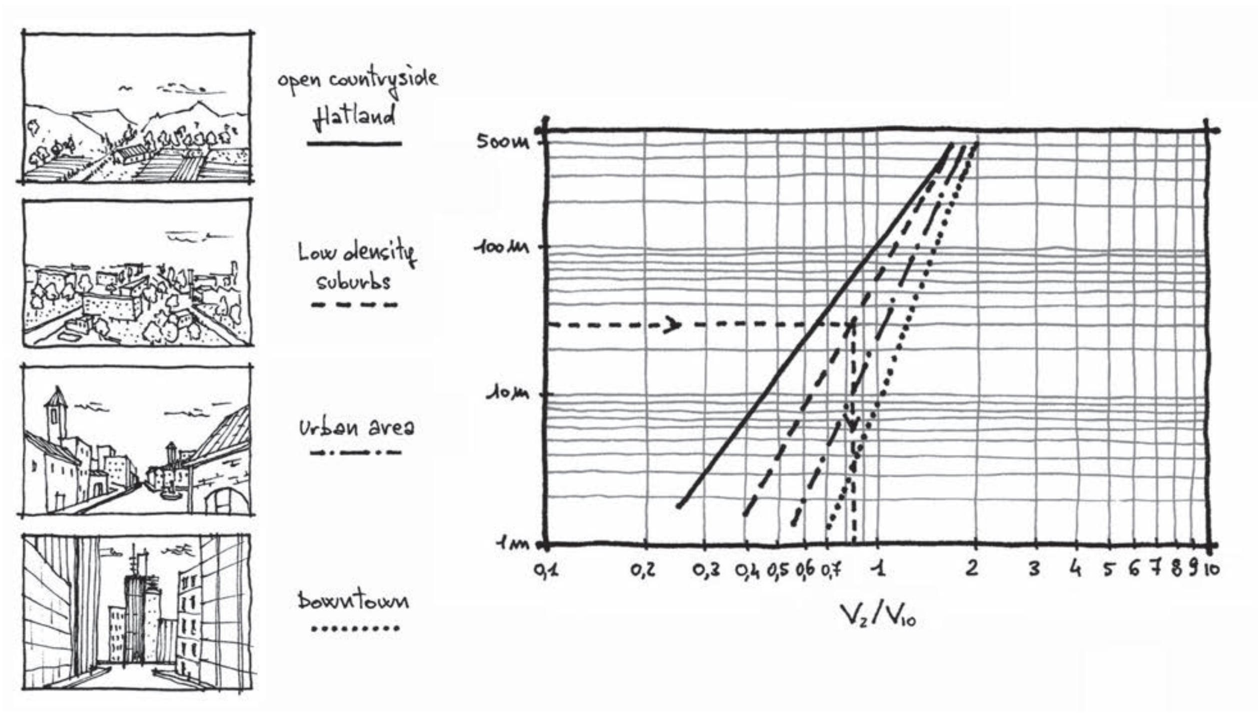


Fig. 2.1-28 - Wind speed variation according to type of ground

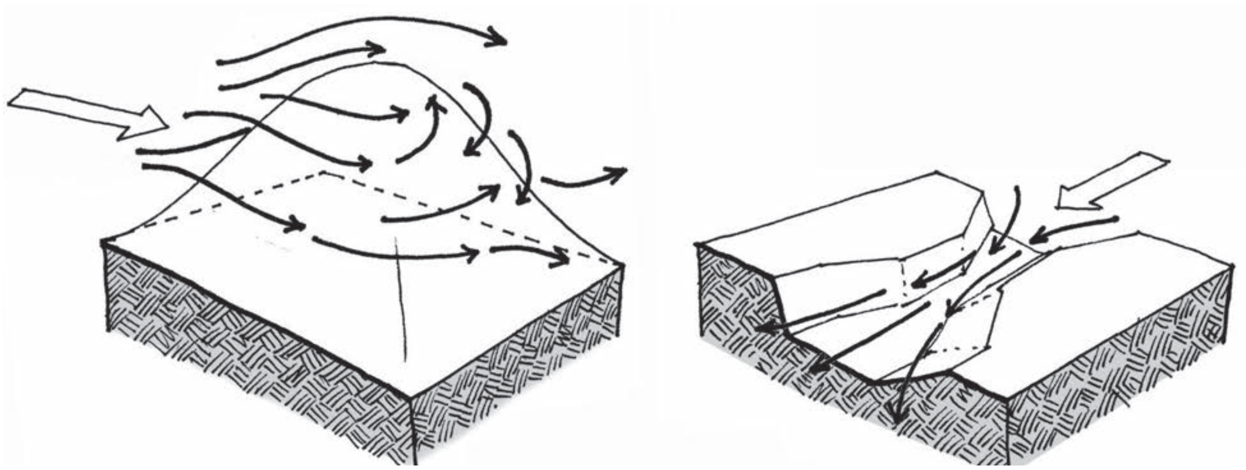


Fig. 2.1-29 - Effects of orography on wind; deviation (left), reinforcement (right)

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. In detail, during daytime cool breezes from sea blows towards the soil, while during night hours breeze reverse the direction. (Fig. 2.1-30).

In a valley, air movement is more complex, as shown schematically in figure 2.1-31. 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 2.1-32.

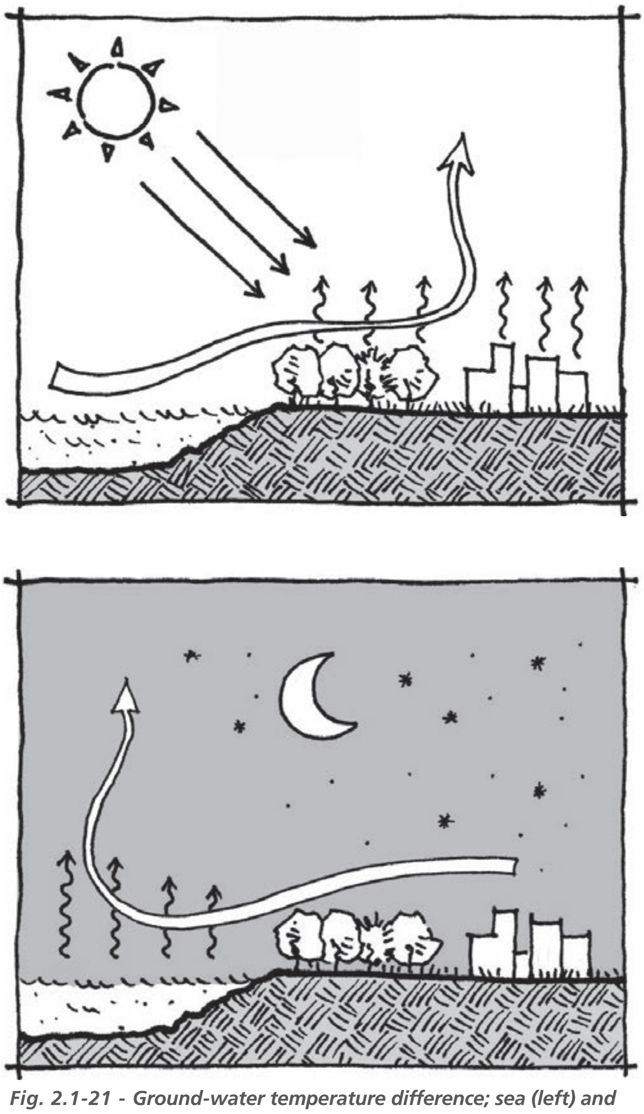


Fig. 2.1-21 - Ground-water temperature difference; sea (left) and land (right) breeze

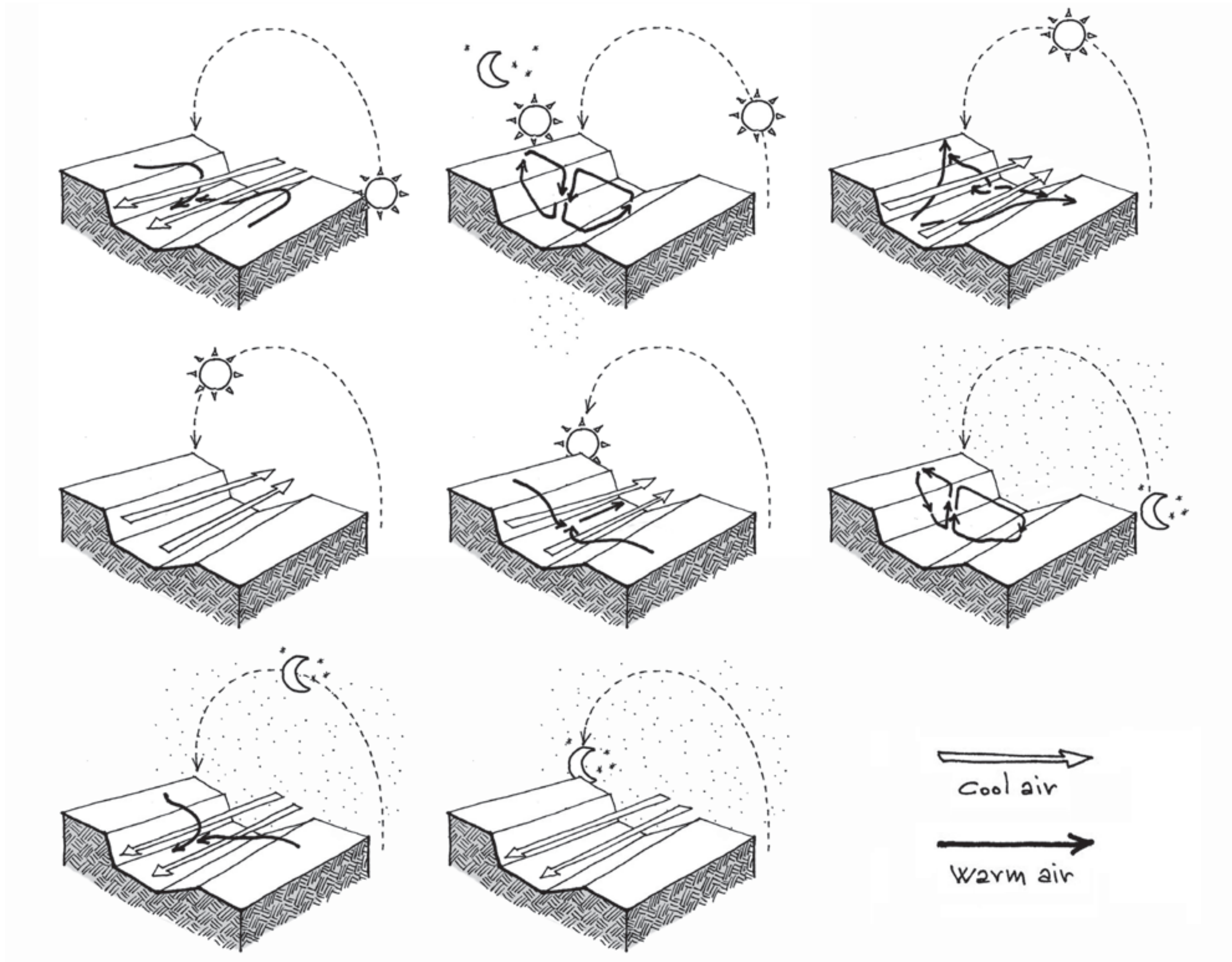


Fig. 2.1-22 - Air movement in a valley

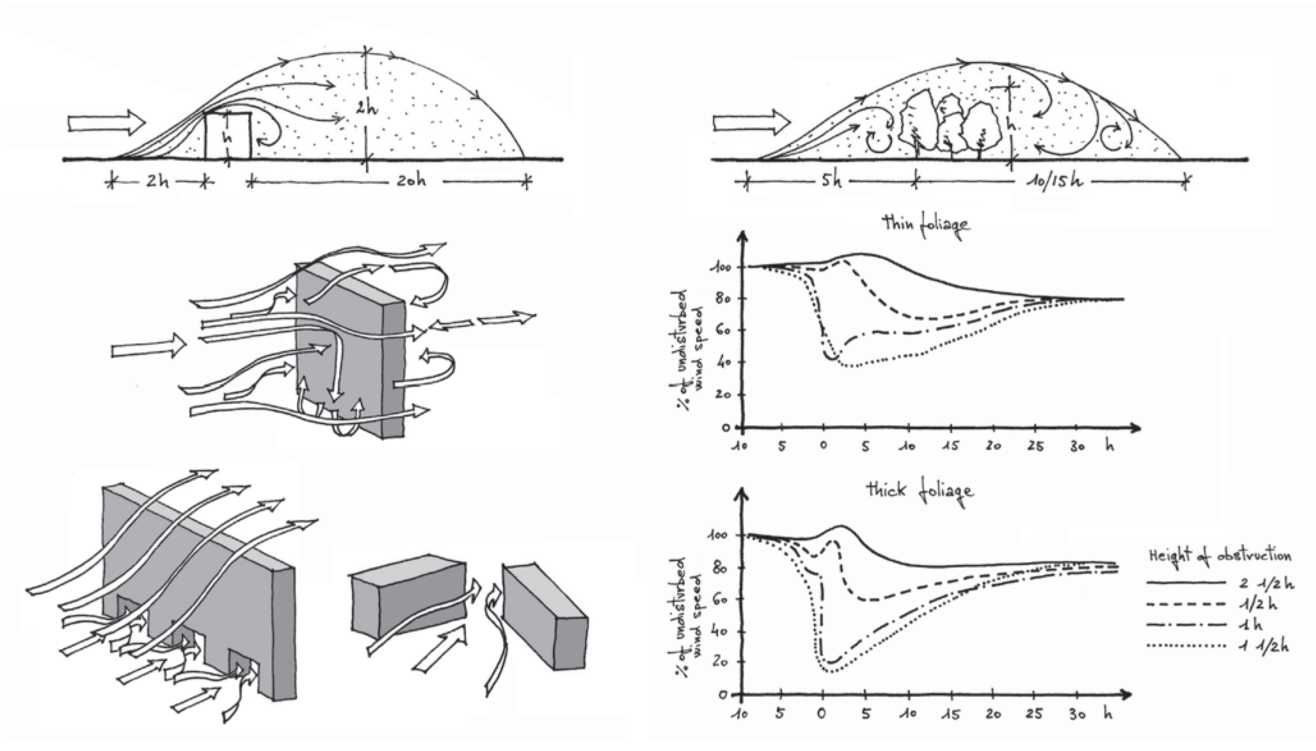


Fig. 2.1-23 - Buildings and rows of trees effects on the wind's characteristics

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).

Climate data, contained in databases, refer to specific representative locations.

For undocumented project sites, the nearest location can be used or available data can be extrapolated, for example by triangulation between three known locations.

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 steady-state or semi-stationary calculation methods.

Although the mean monthly day is frequently used, especially with regard to heating issues, there is, however, a certain limitation by not taking into account the fluctuations of the different meteorological parameters and the simultaneity at which they occur.

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 Climatic classification

The first, comprehensive, climate classification system was developed by Wladimir Köppen in 1884. This classification, with several later modifications, remains today one of the most valid classification and represents a kind of world standard. Köppen's classification is based on annual and monthly averages of temperature and precipitation and derived from 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 African 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, may be different, in some extent, from the kind of dependence shown by vegetation and must be verified before its adoption to the building energy design.

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 may react differently to the same climatic input.

For this reason, in this Handbook, the last modified Köppen's classification (Köppen-Geiger system) has been verified methodologically for its adoption to the building energy design. It has been observed that in such a large scale, like African continent, this classification with minor modifications, could be adopted fairly for climate responsive building design.

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[1] 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 adoption of Köppen-Geiger classification with minor modifications for deriving the building design strategies in different climatic zones. On this basis, each climatic zone was characterised by a set of strategies that should be adopted to minimize energy consumption and maximize thermal comfort.

Within each climatic 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 main classes of climates identified for African continent can be grouped into three different categories, each indicated with a capital letter (from A to C):

A – Hot-humid climates

B - Arid climates

C - Temperate climates

Of these three, the dominant climate type by land area is the arid B (57.2%), followed by hot-humid A (31.0%) and temperate C (11.8%).

Figure 2.2-1 shows the geographical distribution of the three main climatic classes, in turn divided into sub-climates based on the distribution of temperature and precipitation.

For further subdivision, other letters (as subscripts) were used according to the following scheme:

f = no dry season

h = annual average temperature >18 ° C

s = dry summer

k = annual average temperature <18 ° C

w = dry winter

Capital letters S and W are used to denote the two types of arid climate:

S = semi-arid or steppe

W = arid or desert

The detailed subdivision of climate is shown in the figure 2.2-2.

1 *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.*

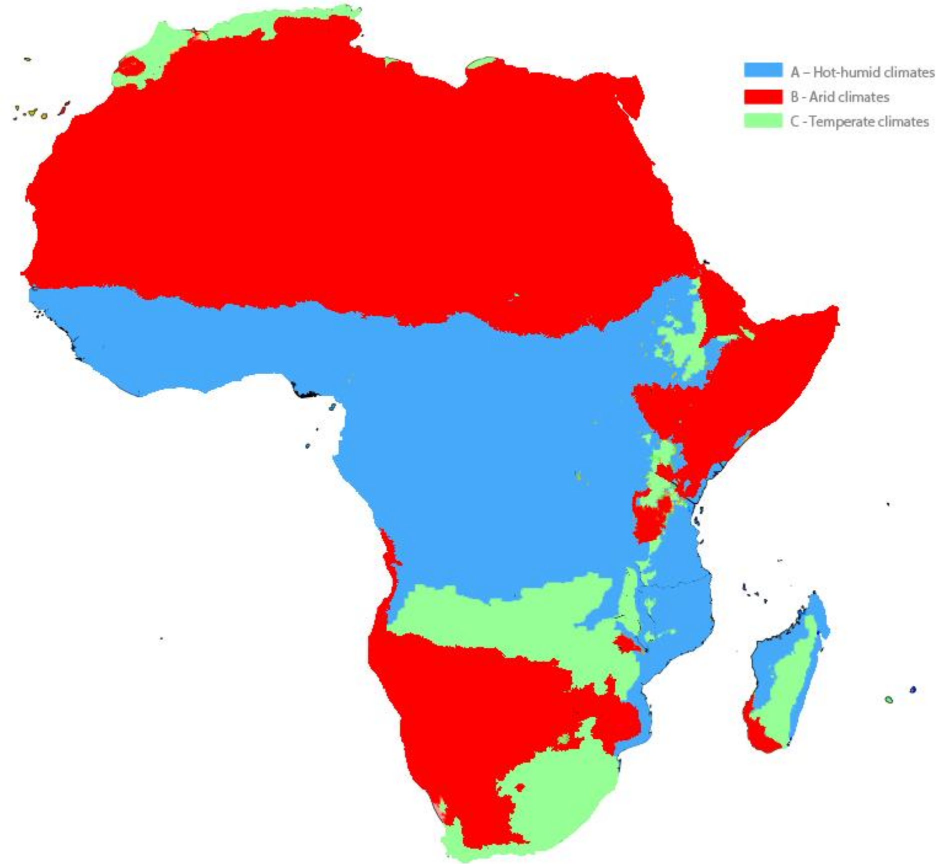


Fig. 2.2-1 – Climatic zones

Group A climates: Hot-Humid

Hot-humid climates are found in a belt near the Equator extending to about 15 °N and S. The temperature of the coldest month exceeds 18 °C. The humid climates of the intertropical zone are characterised mainly by the high temperature due to the lack of a real cold season and the annual temperature swing is always comprised within very modest limits; the daytime variation is slightly higher, and this clearly differentiates hot climates from temperate and cold ones. On the other hand, both the quantity and the precipitation regime (rain seasonal distribution) vary considerably in different places, producing different types of hot humid climates, precisely classified and differentiated on the basis of the variation in precipitation patterns. It should be noted that in the zones nearby great lakes (Victoria, Nyasa, Rukwa and Tanganyika) the temperature is slightly lower, but daily variations are comparable.

Within group A there are two types of climates:

Af = Equatorial climate

This climate is characterized by a great uniformity of the thermal regime and by abundant rainfall, well distributed over all the months of the year.

The temperature is high and almost uniform throughout the year. This is justified by the considerable sun height above the horizon and the small variations of day length that occur from one month to the another (the continuous equinox, however, only along the equator). Average monthly temperatures vary between 25-26 °C; the annual temperature range is very small (2-3 °C), and the daily one around 10-12 °C. The diurnal temperature variation remains modest due to the high value of relative humidity (55-100%) and cloud cover (60-90%). The latter also results in the modest sunshine duration, which never reaches half of the theoretically possible hours, and which indeed has lower minimums in certain coastal areas.

Some of the representative locations for this zone are: Abidjan (Côte d'Ivoire), Mombasa (Kenya), Kisangani (Democratic Republic of Congo).

Aw = Tropical climate

It differs from the equatorial one, both for the smaller quantity of annual precipitation and the existence of two clear distinct seasons: a wet and an almost dry one. The average temperatures are similar to those of Af, but the temperature swing is higher, while the relative humidity is lower. In the dry season, which is also the cold one, there

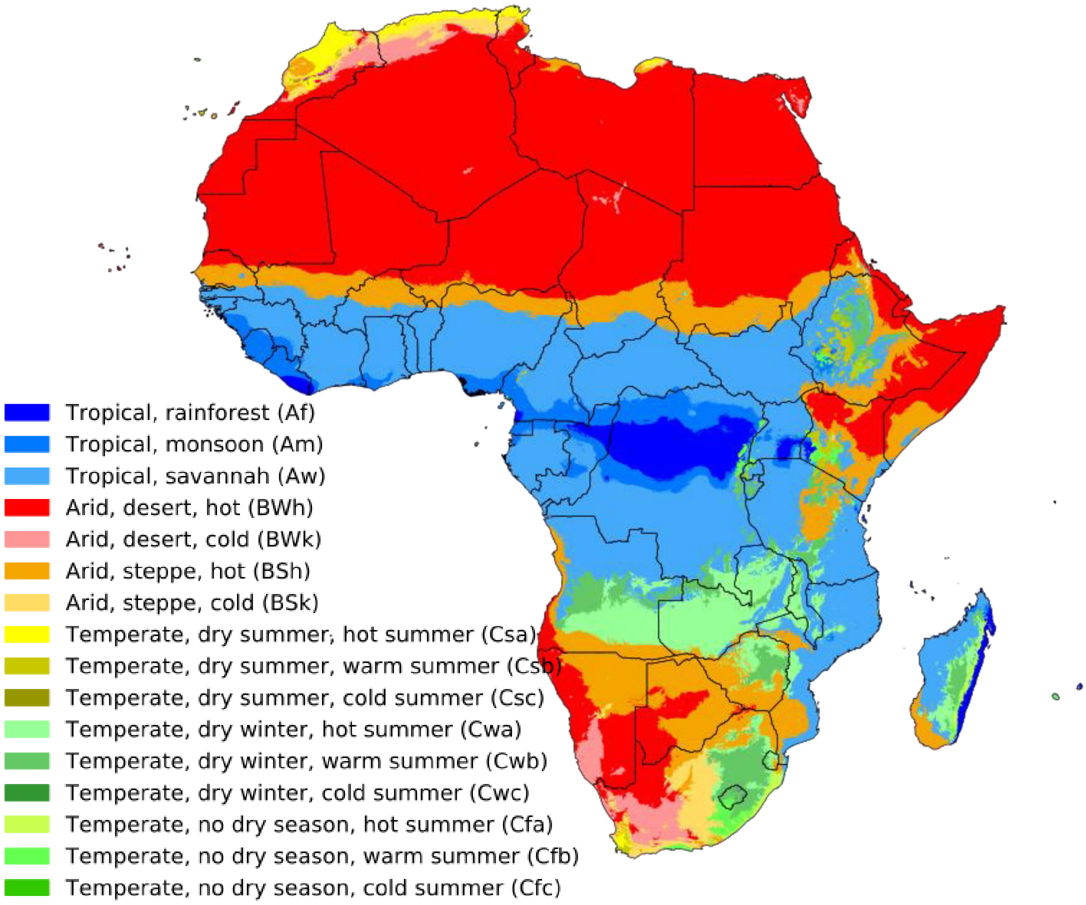


Fig. 2.2-2 – Detailed climatic zones

are long periods of clear sky interrupted by thunderstorms or days with overcast sky. The transition to the Aw climate is revealed through the plant landscape by the replacement of the rainforest, typical of the areas closest to the equator, with the savannah.

Yamoussuoukro (Ivory Coast), Abuja (Nigeria), Kinshasa (Democratic Republic of Congo), Dar es Salaam (Tanzania) can be considered some representative locations of this climate.

Comfort in zone A

Combination of high temperature and high humidity causes discomfort. Ventilation facilitating convective and evaporative cooling of the body is essential for comfort both in day and night.

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

Less critical is the period during colder months.

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

The locations nearby great lakes have a remarkably stable climate, with very slight seasonal and daily differences of temperature and humidity. Day temperatures are rather similar to 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 Victoria lake, early mornings may be uncomfortably cold during cold season and rains. Therefore, complete sun protection is not desirable in this area, whereas in other parts of the zone, sun protection 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.

Group B Climates: Arid

These climates are mainly found in the 15–30° latitude belt in both hemispheres. They exhibit low precipitation, great variability in precipitation from year to year, low relative humidity, high evaporation rates (when water is available), clear skies, and intense solar radiation. In these climates, maximum temperatures are high, higher than those of the Hot-humid climate (A) and high is the daily temperature variation. Humidity, especially in the hottest hours, is very low. Breezes are generally light with no strong predominant direction. In these climates, evaporation exceeds precipitation; two main types of climate are identified:

BW = DESERT ARID CLIMATE

BS = SEMIARID OR STEPPE CLIMATE

Within these two main groups are distinguished:

BWh = Hot arid climate

This is the climate of tropical and subtropical deserts, which extend mainly between 15° and 30° N latitude. In Africa, this occupies mainly the Northern part of the Continent (Sahara Desert in North Africa) and relatively lower part of East (Deserts of Horn of Africa) and South Africa (Namib Desert). These deserts can remain free of rainfall for many consecutive years; the total annual precipitation remains below 250 mm everywhere, but in most of the Sahara the dryness is more pronounced because the precipitations never exceed 100 mm.

The sky can remain clear for many months, so the measured daily average solar radiation is very close to the theoretical one calculated for clear sky, especially in the summer months. The sky is also clear for the high dryness of the air, as the relative humidity drops to very low values (even below 10%); which, on the other hand, makes it possible for the physical survival of man and, in many cases, by the realization - by means of suitable devices or simple technological solutions - of conditions of tolerable thermal comfort.

The annual temperature swing reaches at very high values and can be equal to daily temperature swing. The respective average values are around 18-22 °C, but the diurnal variation is still higher due to the fact that the maximum daily temperatures in the hottest months reach at very high values (the maximum recorded is 58 °C).

Another important characteristic of the desert climate is the frequency of winds, even impetuous, which are sometimes sudden and ephemeral, sometimes more persistent.

The typical characteristics of tropical deserts undergo important modifications in the deserts that extend, always in tropical latitudes, along the Western coasts of the Continent. This kind of coastal desert climate is sometimes in the literature named as BWn. These regions are under the influence of cold sea currents coming from higher latitudes (which are joined by the cold bottom water that rise along the continental slope) and therefore do not have excessively high temperatures throughout the year; on the contrary, the average values are generally 6-7 °C, lower than those of other tropical locations of the same latitude. Precipitation, despite the high relative humidity, is extremely scarce, and precisely in these coastal deserts, there are some places where the phenomenon of rain is completely unknown. The high humidity is accompanied by a high frequency of fog, but the phenomenon is limited to the strip closest to the sea.

Some of the representative locations for hot arid climate are: Lodwar (Kenya), Khartoum (Sudan), Niamey (Niger), N'Djamena (Chad).

BWk = Cold arid climate

The regions with an arid climate with cold winter are found in very limited areas of the continent at higher altitudes. The scarce amount of precipitation is the element that brings these areas closest to tropical deserts, while the thermal regime represents the most important element of differentiation. In fact, the summer is very hot (over 30 °C), while the winter is very cold, so much that average temperatures are recorded below 0 °C during coldest period. The annual temperature range is therefore very high and far exceeds the diurnal one; however, this too has not negligible values, especially in the summer months. Another characteristic of these arid climates is the considerable frequency of the wind.

Only few zones in Africa are characterized by such climate. Among them: Bamako (Mali), Ouagadougu (Burkina Faso), Kano (Nigeria). Some of them also can be found in South Africa, such as the city of Calvinia, or in the southern part of Morocco, such as in the city of Bouarfa.

BSh = Hot semi-arid climate

The regions with a semi-arid climate represent transitional bands between the real desert (BW) and humid climates; precisely, in the polar margin of the deserts they interpose themselves between these and the temperate climates, while in the equatorial margin they mark the passage towards the humid climates (Aw).

In some of these areas, such as in the Sahel - south of the Sahara, desertification processes are underway, i.e. a progressive transition to the climatic area of the BW.

Some of the representative locations for this zone are: Windhoek (Namibia) and Nyala (Southern Darfur, Sudan).

BSk = Cold semi-arid climate

As cold arid climates (BWk), cold semi-arid climates are also present in limited areas of Africa. These are located in elevated portions of the North-West and Southern parts of continent, typically bordering a hot-humid climate or a mediterranean climate. These climates usually feature warm to hot dry summers, though are typically not quite as hot as those of hot semi-arid climates. Unlike hot semi-arid climates (BWh), areas with cold semi-arid climates tend to have cold winters. These areas usually see some snowfall during the winter, though snowfall is much lower than at locations at similar latitudes with more humid climates.

These climates tend to feature major temperature swings between day and night, sometimes by as much as 20°C or more in that time frame. Cold semi-arid climates at higher latitudes tend to have dry winters and wetter summers, while at lower latitudes tend to have precipitation patterns more similar to subtropical climates, with dry summers, relatively wet winters, and even wetter springs and autumns.

The representative locations for this zone can be found in South Africa; Kimberly, Bloemfontein and Kuruman are some of them.

Comfort in zone B

In hot-arid climates, the dominant in Continent, 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 variation means that nights are relatively comfortable. Winds are generally weak, persistent; at times, strong winds are experienced locally. Severe sudden and violent windstorms accompanied by thick rising sand occur from time to time in some parts of the zone (e.g. at the southern fringe of the Sahara Desert, a special dry and hot wind, locally termed Harmattan during winter season and at the northern fringe, strong wind locally termed Hamson often occurs in the winter and spring seasons). Fresh breezes from mid to late evening are common in some places.

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

In hot semi-arid climates, the discomfort caused by the high daytime temperatures prevailing during most of the year can be critical, though steady breezes do 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 most of the areas, particularly where stagnant water abounds.

Comfort conditions at night vary considerably over the year. Many times, it is likely to be uncomfortably warm inside massive walls and poorly ventilated houses. During colder and rainy seasons, it can, however, be distinctly cool at night.

Group C Climates: Temperate

The temperate climates are found in the middle latitudes (30°-35° N, 25°-35° S) in the proximity Mediterranean Sea and Indian Ocean. These are characterised by an average temperature during the coldest months lower than 18°C, even if, generally the winter season can be considered generally as mild. The climates of the mid-latitudes have wide temperature ranges and a well-defined seasonal thermal cycle, dependent on the strong variation in the height of the sun above the horizon in the two extreme months (hot and cold). However, the precipitation regime has equal importance as the thermal one in determining the various climatic types of the temperate zone, since there are areas with maximum rainfall in summer, others in which, on the other hand, there is no rain in this season and still others where humidity and rainfall is abundant all year round. Another fundamental characteristic of temperate climates is the high variability of the weather, deriving from the fact that the middle latitudes are the normal conflict field between the cold air masses of polar origin and those of hot air coming from the tropics.

There are three main types of climate:

Cf = Humid subtropical temperate climate

This type of climate is characterized by relatively high temperatures and evenly distributed precipitation throughout the year. This climate is found on the eastern sides of the continents between 10° and 35°S latitudes.

In summer, these regions are largely under the influence of moist, maritime airflow from the western side of the ocean waters.

Temperatures are high; the warmest months generally average about 27 °C, with mean daily maximum from 30 °C to 38 °C and warm nights. Summers are usually somewhat wetter than winters. The coldest month is usually quite mild (5–12 °C), although frosts are not uncommon. Such climate is typical in some part of South Africa, Zambia and Angola. Lusaka (Zambia) can be considered a representative location.

Cw = Subtropical temperate climate with dry winter

This kind of climate is usually present in the Eastern South Africa, and is distinguished by the fact that there is no rain in the winter season and lower temperatures than Cf.

The mean daily maximum temperatures vary about from 18 °C to 28 °C along the year with minimum ranges from 3 °C to 16 °C and cold nights. As Cf climates, in Cw also, the summers are usually wetter than winters.

Some representative locations for this zone are Pretoria and Johannesburg in South Africa.

Cs = Subtropical temeperate climate with dry summer

Subtropical temperate climate is characterized by hot and dry summers and cool and wet winters and located on the Eastern parts of Mediterranean Sea between 25° and 35° N latitudes. This climate is also called Mediterranean climate, as it finds its most typical expression along the coasts of the Euro-African Mediterranean Sea.

Mediterranean climates tend to be drier than humid subtropical ones. This type of climate is characterized by relatively high temperatures and evenly distributed precipitation throughout the year. In summer, temperatures are high; the warmest months generally average about 27 °C, with mean daily maximum from 30 °C to 38 °C and warm nights. Summers are usually somewhat dry than winters, even if the humidity ratio from the sea have a constant effect along the year. Also, for such reason the coldest month is usually quite mild (5–12 °C).

Although, according to traditional Köppen-Geiger classification, such climate can be found only in the coastal regions on the North-East side of the Continent, closer to the Mediterranean Sea (e.g. Morocco, Tunis and Algeria) a similar climate can be identified in the coastal North-West side on the same sea (Egypt and Libya). In the latter, the summer temperature is slightly higher than the East side, while temperature in winter is moderate with limited rainfall that decreases according to the sea distance. A slightly higher temperature with lower precipitation, but not enough to be considered as arid, characterizes the Nile Delta. Some of the representative locations of the Mediterranean climate are Tangier (Morocco), Algiers (Algeria), Tunis (Tunisia).

Comfort in zone C

In such zones, the climate is generally pleasant. Because of the high altitude or the wind breezes due to the sea, 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. The range of summer and winter temperatures mainly depends on proximity to the sea with higher temperatures near the coast during cooler periods and higher temperatures inland during warmer periods. During nighttime, the temperature is likely to drop below the lower limit of the comfort zone. The low night temperatures represent a major source of discomfort especially in higher altitudes.

In the winter, the coastal areas tend to be fog free. In general, during the cold seasons, heating is required and during hot seasons the higher temperatures (>30°C) create discomfort.

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 or special envelope components (e. g. solar walls), while solar active refers to a building where solar energy is harnessed by means of plant systems added to the architectural envelope. Historically, these components consisted mainly of solar collectors, but in recent years photovoltaics have also been included, given the widespread use and effectiveness of this technology.

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, hot water production and, with regard to photovoltaics, electrical uses.

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 solar and bioclimatic architecture.

Generally, 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 insulation and colour, opening size and type of glazing.

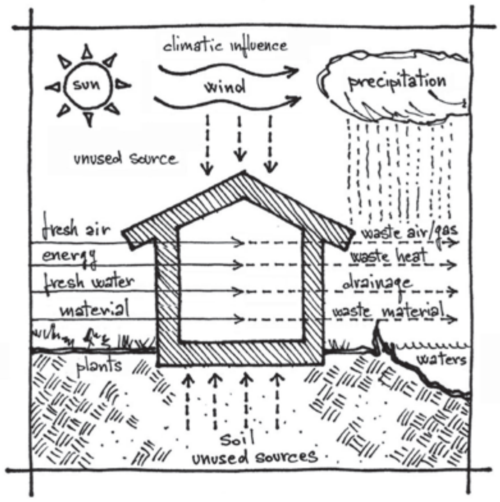


Fig. 3.1-1 – Conventional building design

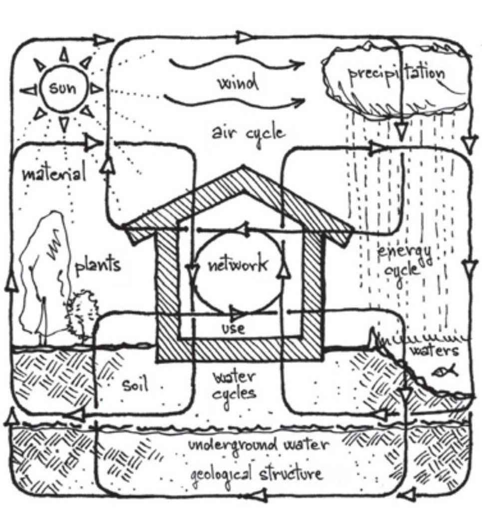


Fig. 3.1-2 – Bioclimatic building design

3.2 Bioclimatic charts

Passive strategies for building design derive from climatic conditions, since it is the gap between the comfort level in these conditions and the desired level, that creates the need to take appropriate measures to reduce the gap as much as possible, without the use of any artificial heating or cooling systems.

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

Olgyay’s bioclimatic chart (Fig. 3.2-1) is a simple tool for analysing the climate of a particular site. It indicates the zones of human comfort based on ambient temperature and humidity, wind speed and solar radiation.

On the chart, dry bulb temperature is used as the ordinate, and relative humidity as the abscissa. In the middle of the diagram a curvilinear perimeter delimits the so-called comfort zone, in which the combination of temperature and relative humidity pairs corresponds to diverse comfort conditions. The left and right portions of the area, lighter grey, delimited by dotted lines, represent environmental conditions producing acceptable comfort conditions, while the central, darker, the ones for which the desirable comfort conditions are achieved.

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 comfort.

For example, at dry bulb temperature of 25 °C, with 50% relative humidity, 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. These measures can be provided even by local climatic factors and verification can be done directly on the diagram.

For example, at dry bulb temperature 15 °C and 50% relative humidity the need is 500 W/m^2 solar radiation (this means that comfort can be achieved provided there is solar irradiance of at least 500 W/m^2).

If the point is above the perimeter of the comfort zone, air movement needs to be increased. For example, at dry bulb temperature 30 °C and relative humidity 70%, the need is 0.4 m/s wind to reach the comfort level.

In all cases falling outside the comfort zone and not able to benefit from the corrective measures provided by sun and wind, it is necessary to intervene with HVAC systems.

Thus, the bioclimatic chart can give preliminary information about the requirements for comfort in a given place and at a particular time. Design decisions can be taken accordingly.

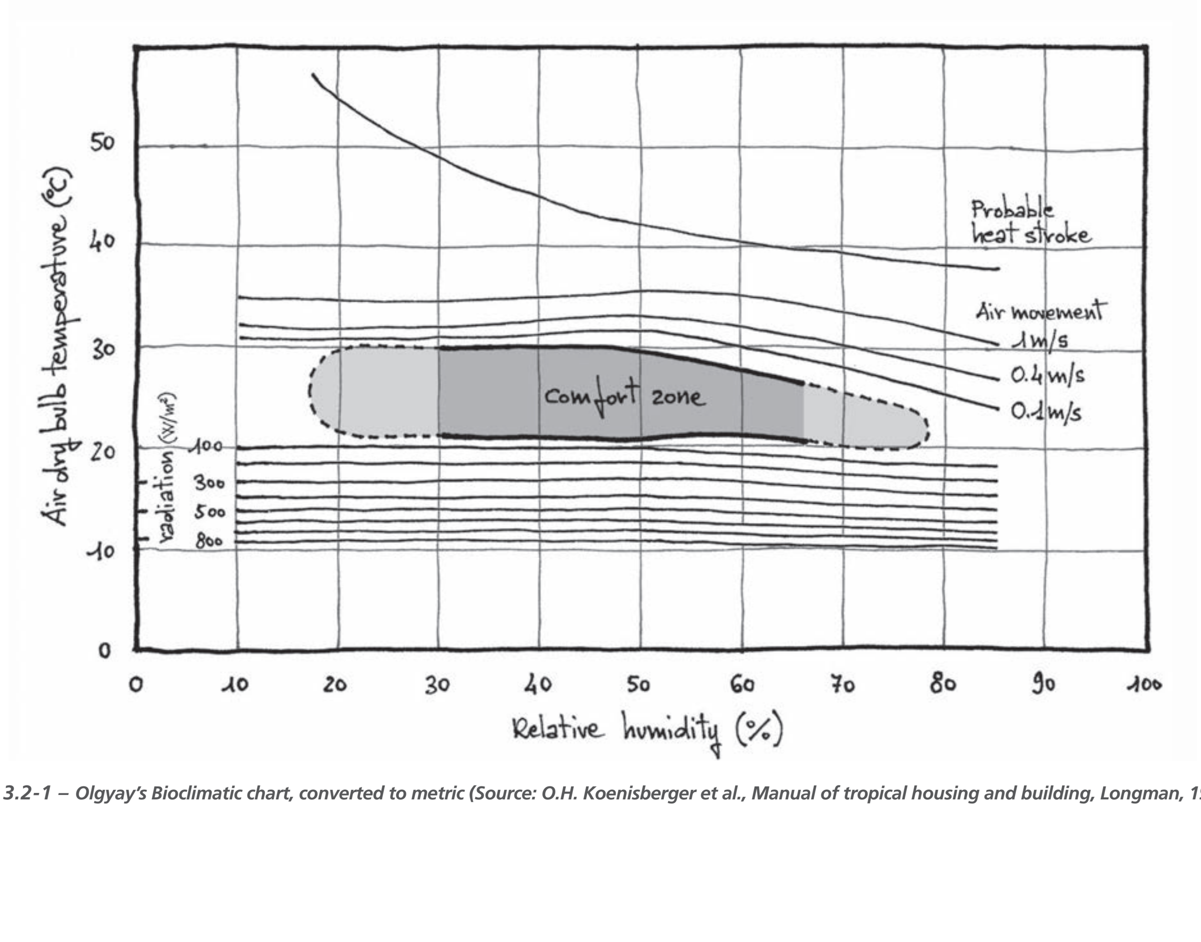


Fig. 3.2-1 – Olgyay’s Bioclimatic chart, converted to metric (Source: O.H. Koenisberger et al., Manual of tropical housing and building, Longman, 1973)

3.2.1 Givoni charts

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 outdoor temperature and humidity values, 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[1].

Givoni's chart identifies suitable climatisation techniques on the basis of the outdoor climatic conditions.

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[2].

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.

Non-passive strategies, such as air-conditioning, humidification and artificial heating, are not considered 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.

1 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.

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

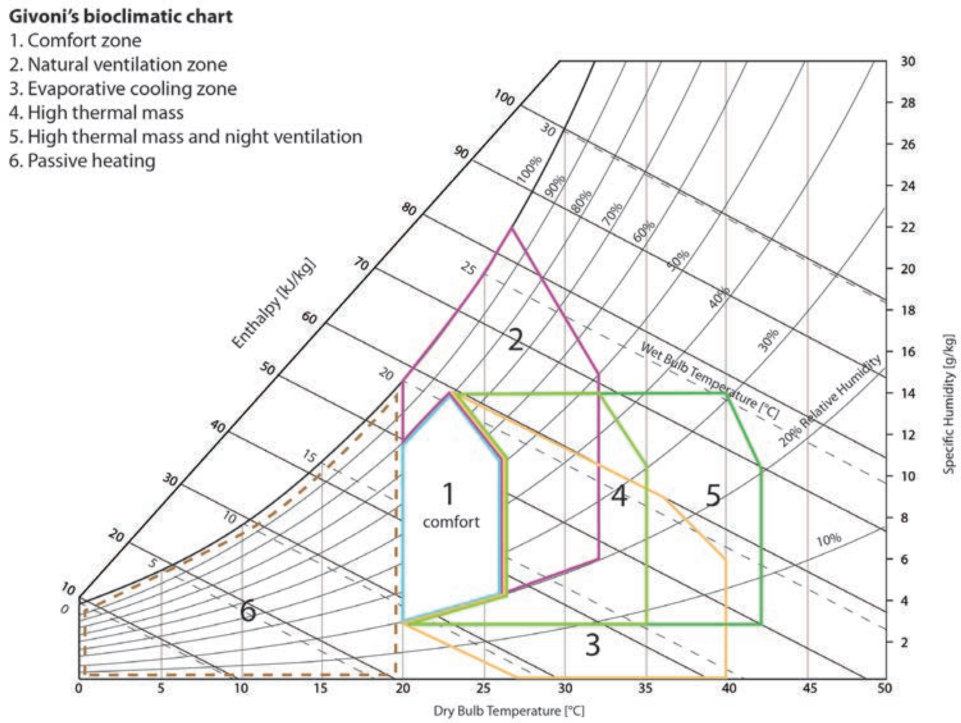


Fig. 3.2-2 – Givoni Bioclimatic chart

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.

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 night-time 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 night-time ventilation, exploiting the cooler air to cool the indoor space.

In temperate climatic conditions, on the other hand, natural ventilation can be continuous, provided that it is limited during the hottest periods of the day.

Evaporative cooling

Water evaporation can reduce air temperature and at the same time increase the relative humidity of a living space. In many cases, this combined effect can restore the comfort conditions (Fig. 3.2-5).

It has to be noted that 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 air humidity 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.

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 evening 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 of the ground can also be exploited.

High thermal mass and night ventilation

Thermal mass can be used in conjunction with night ventilation 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 night-time 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. To prevent gains from turning into loads in warmer seasons, it is always advisable that windows are also equipped with solar protection and control devices.

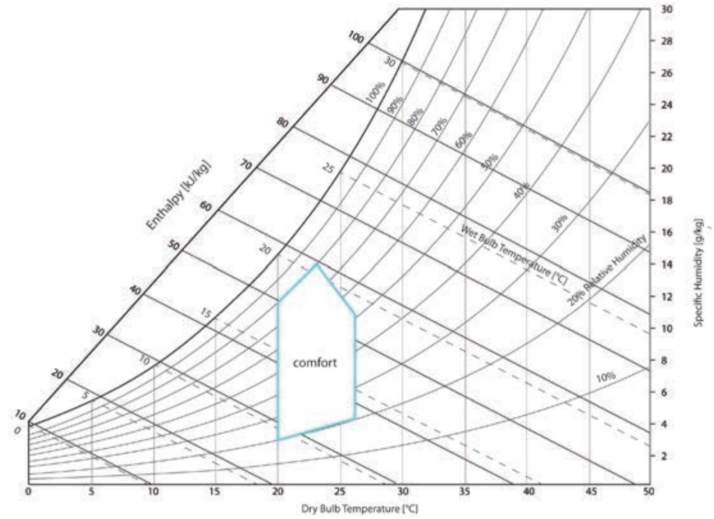


Fig. 3.2-3 – Comfort zone

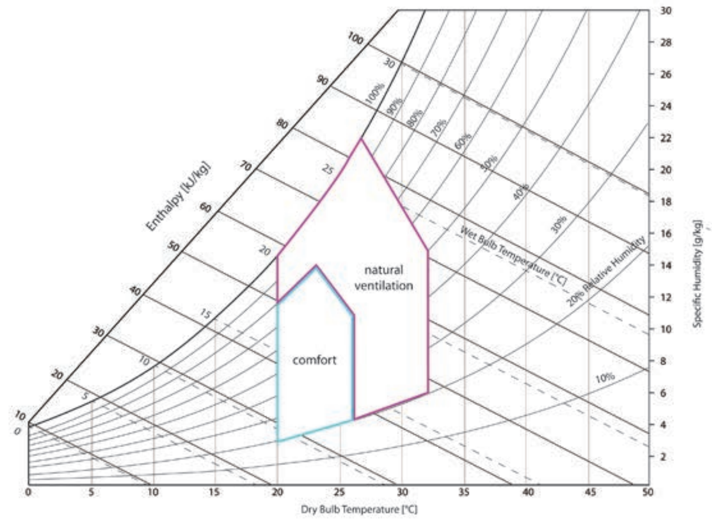


Fig. 3.2-4 – Natural Ventilation Zone

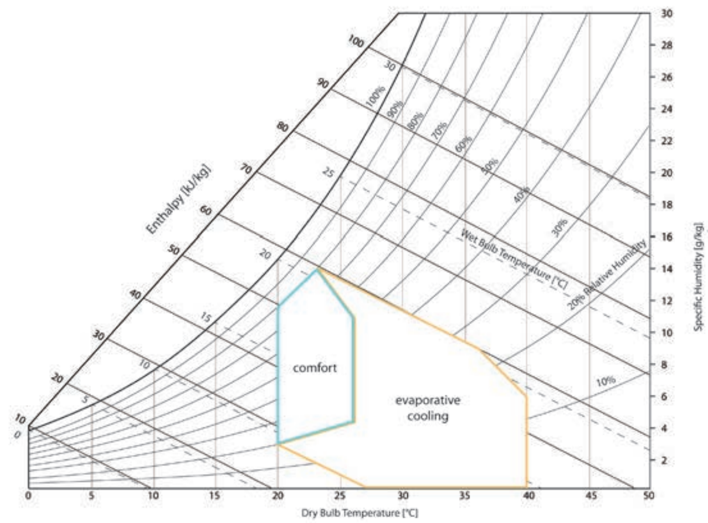


Fig. 3.2-5 – Evaporative cooling zone

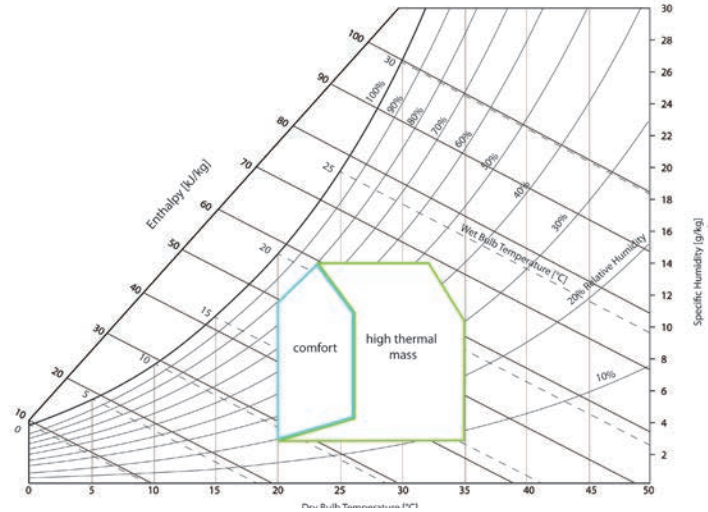


Fig. 3.2-6 – High thermal mass zone for cooling

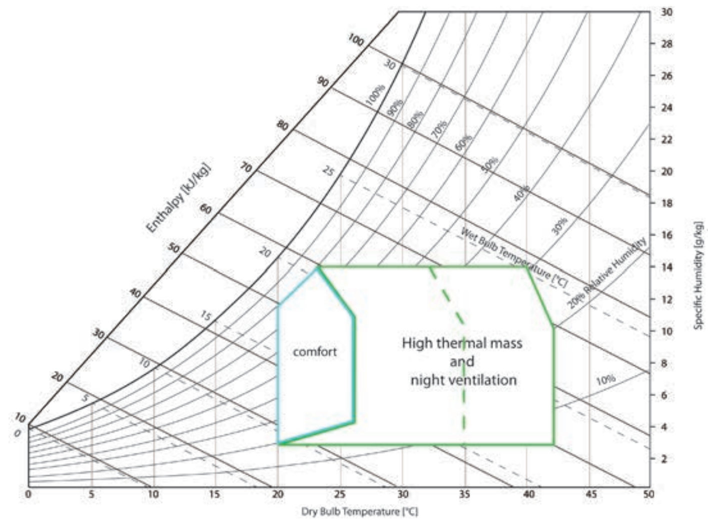


Fig. 3.2-7 – High thermal mass and night ventilation zone for cooling

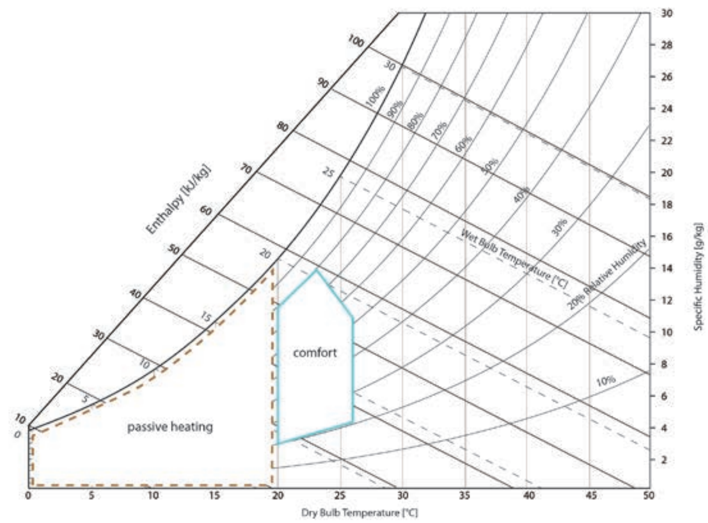


Fig. 3.2-8 – Passive heating zone

3.2.2 Combined strategies

As shown, Givoni bioclimatic diagram diagram can provide useful and specific guidelines on how to design buildings making the most of natural resources and passive solutions. Other observations can be drawn directly from the plotted information reported on the chart about the local climate. For example, for temperatures above 20-22 °C, it is always advisable to use solar shading systems in order to prevent indoor overheating.

Rather than prevailing strategies, it is generally convenient to apply combined strategies, as suggested by the intersections between the various zones. For example 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 natural ventilation, high thermal mass and evaporative cooling can be exploited. In region C, the three strategies can be adopted separately or together.

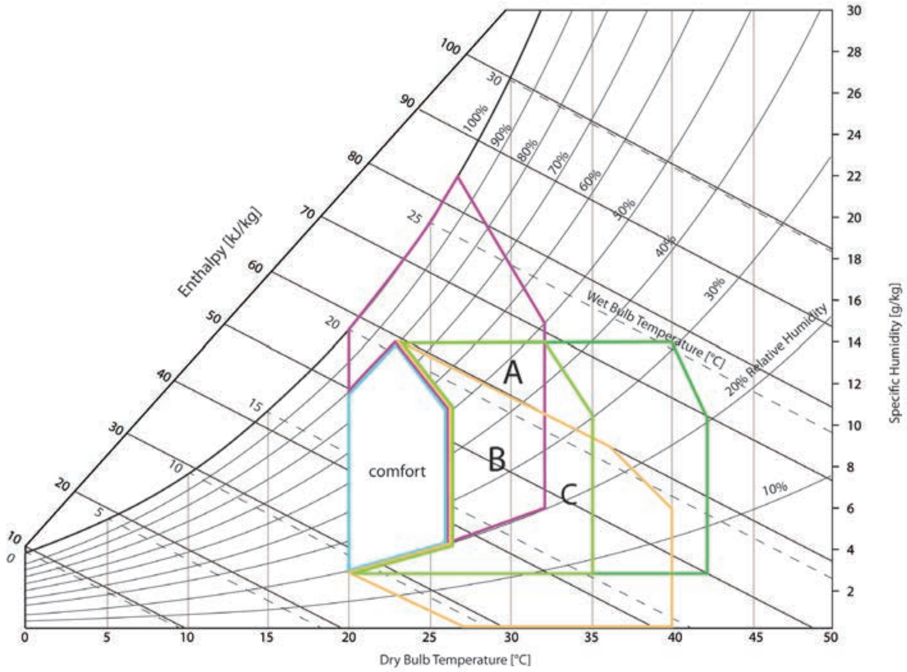


Fig. 3.2-9 – Intersection between natural ventilation, high thermal mass (and night ventilation) and evaporative cooling

3.2.3 Application of Givoni bioclimatic chart to African climates

In the following examples some applications of the Givoni diagram in specific locations with different climates are shown.In addition to the climatic zones described above, the diagrams display the points corresponding to the pairs of relative humidity and temperature's hourly values for the whole year at that location.

By looking at where most of the points fall, one can identify the most appropriate passive strategies to implement in that context.

Af, Equatorial climate (Mombasa, Kenya)

According to the Givoni bioclimatic chart (Fig. 3.2-10), in equatorial climate (Af) like Mombasa, solar shading and-natural ventilation are the most effective passive design strategies for improving thermal comfort.

Aw, Tropical climate (Kinhasa, Democratic Republic of the Congo)

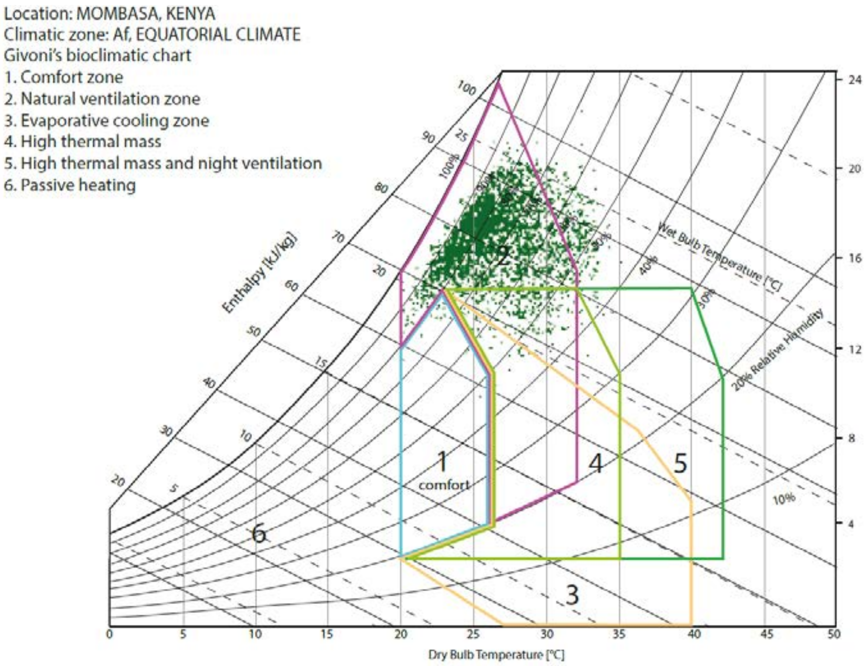


Fig. 3.2-10 – Givoni bioclimatic chart for Mombasa

In a tropical climate like Kinhasa (Fig. 3.2-11), solar shading and high thermal mass with natural ventilation (night ventilation) are the most effective passive design strategies for improving thermal comfort.

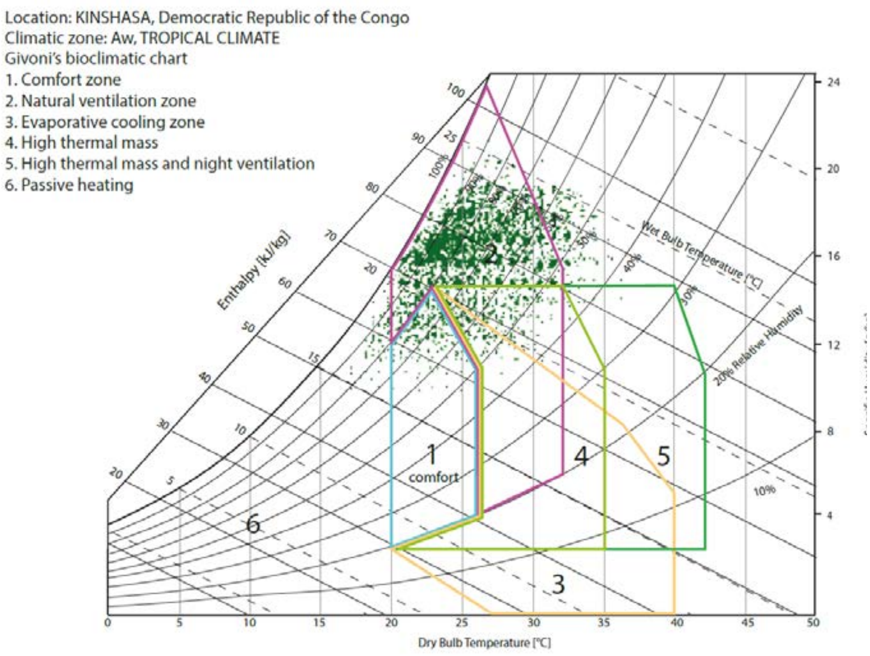


Fig. 3.2-11 – Givoni bioclimatic chart for Kinhasa

BWh, Hot arid climate (Niamey, Niger)

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

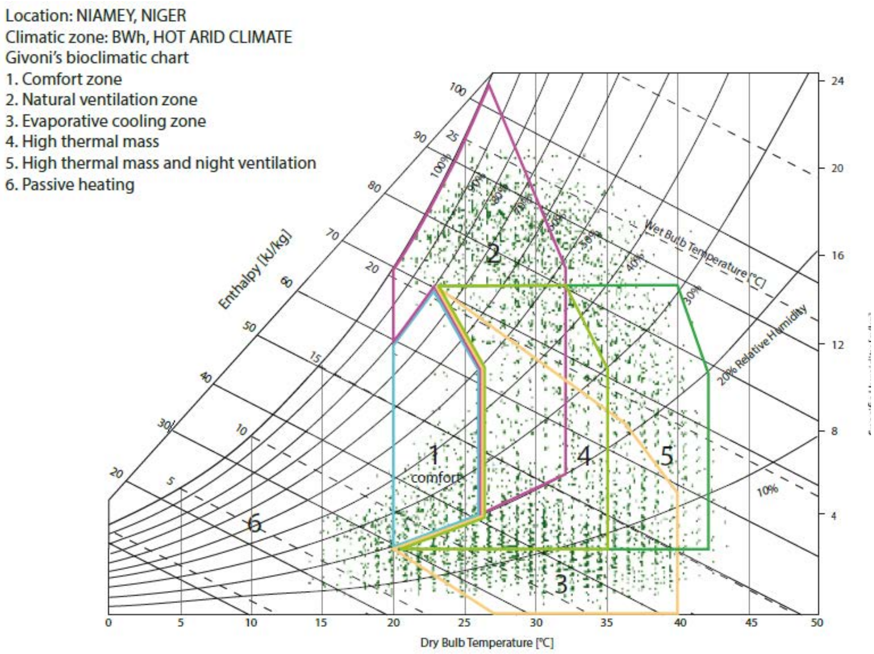


Fig. 3.2-12 – Givoni bioclimatic chart for Niamey

BWk, Cold arid climate (Calvinia, South Africa)

In a cold arid climate like Calvinia (Fig. 3.2-13), passive heating, evaporative cooling and solar shading are the most effective passive design strategies for improving thermal comfort.

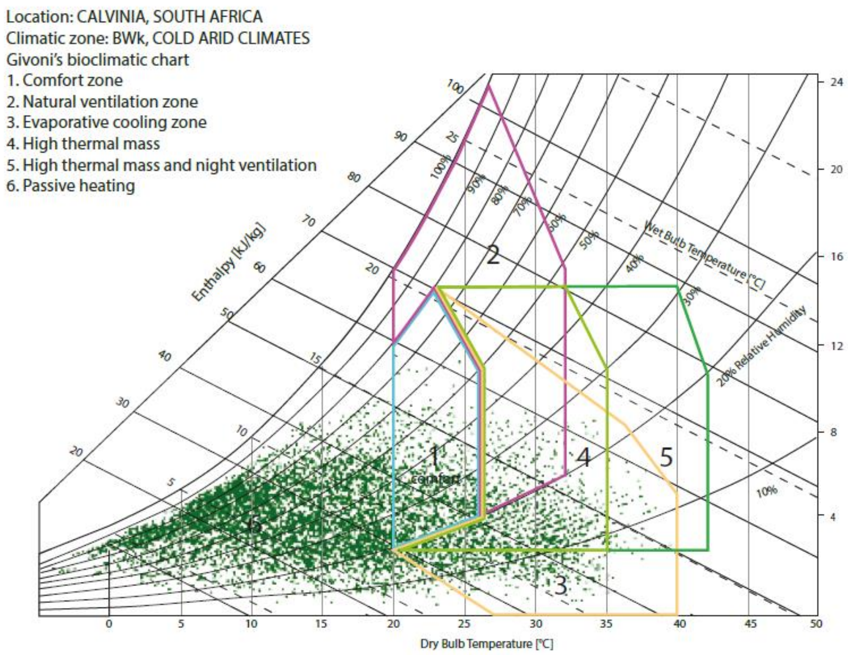


Fig. 3.2-13 – Givoni bioclimatic chart for Calvinia

BSh, Hot semi-arid climate (Nyala, Sudan)

In a kot semi-arid climate like Nyala (Fig. 3.2-14), solar shading, natural ventilation and evaporative cooling are the most effective passive design strategies for improving thermal comfort.

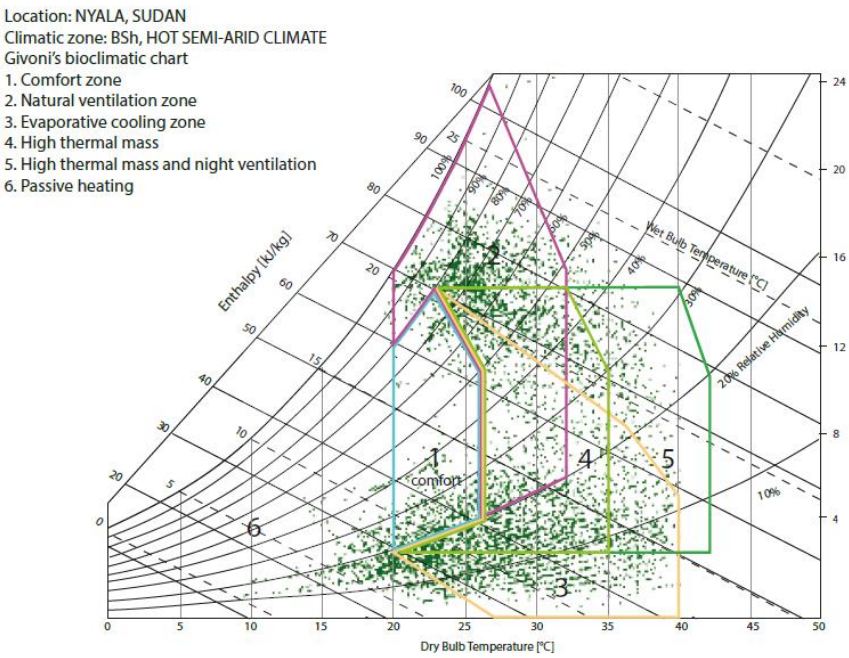


Fig. 3.2-14 – Givoni bioclimatic chart for Nyala

BSk, Cold semi-arid climate (Kimberley, South Africa)

In a cold semi-arid climate like Kimberley (Fig. 3.2-15), passive heating, solar shading and evaporative cooling are the most effective passive design strategies for improving thermal comfort.

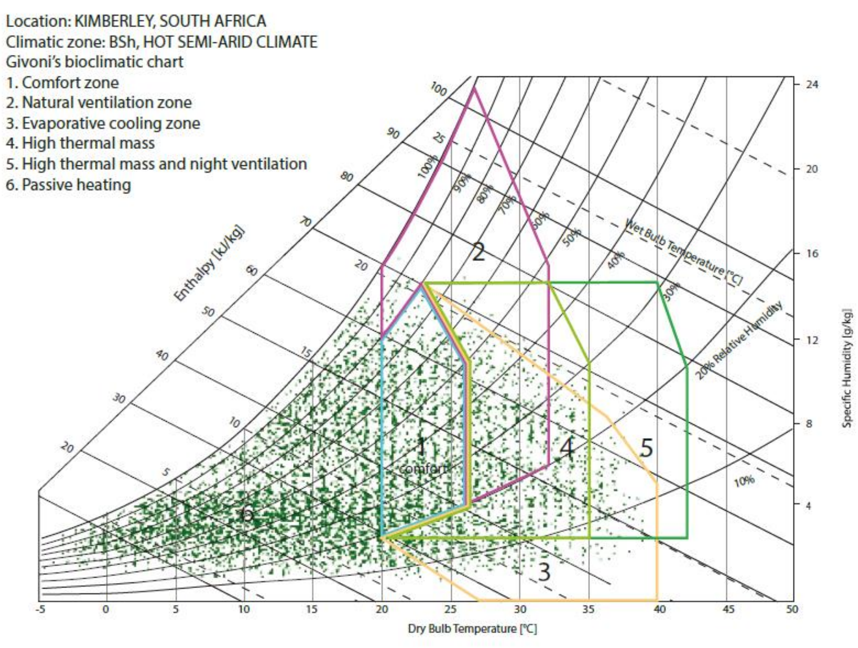


Fig. 3.2-15 – Givoni bioclimatic chart for Kimberley

Cf, Humid subtropical temperate climate (Lusaka, Zambia)

In a humid subtropical temperate climate like Lusaka (Fig. 3.2-16), solar shading and passive heating are the most effective passive design strategies for improving thermal comfort.

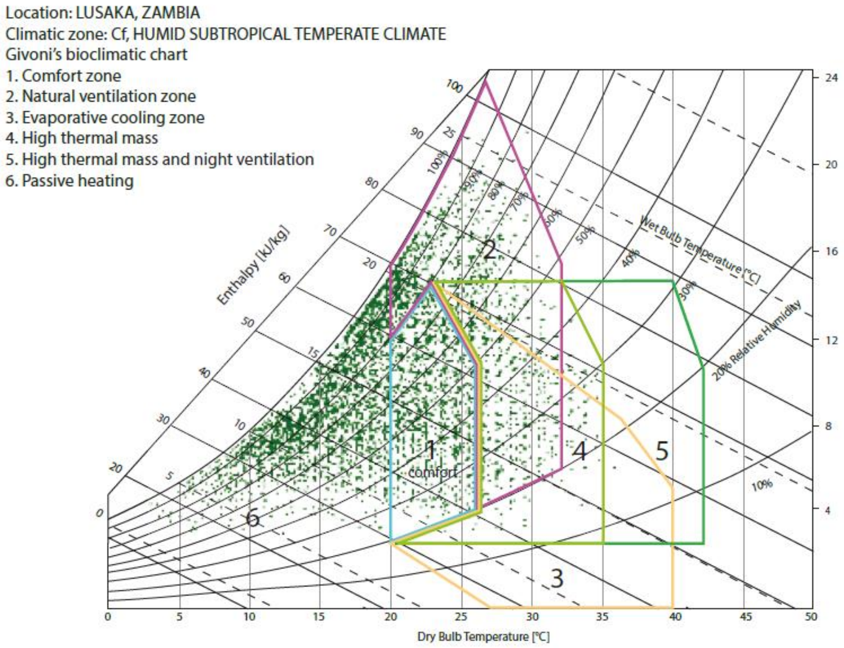


Fig. 3.2-16 – Givoni bioclimatic chart for Lusaka

Cw, Subtropical temperate climate with dry winter (Pretoria, South Africa)

In a subtropical temperate climate with dry winter like Pretoria (Fig. 3.2-17), solar shading, evaporative cooling and passive heating are the most effective passive design strategies for improving thermal comfort.

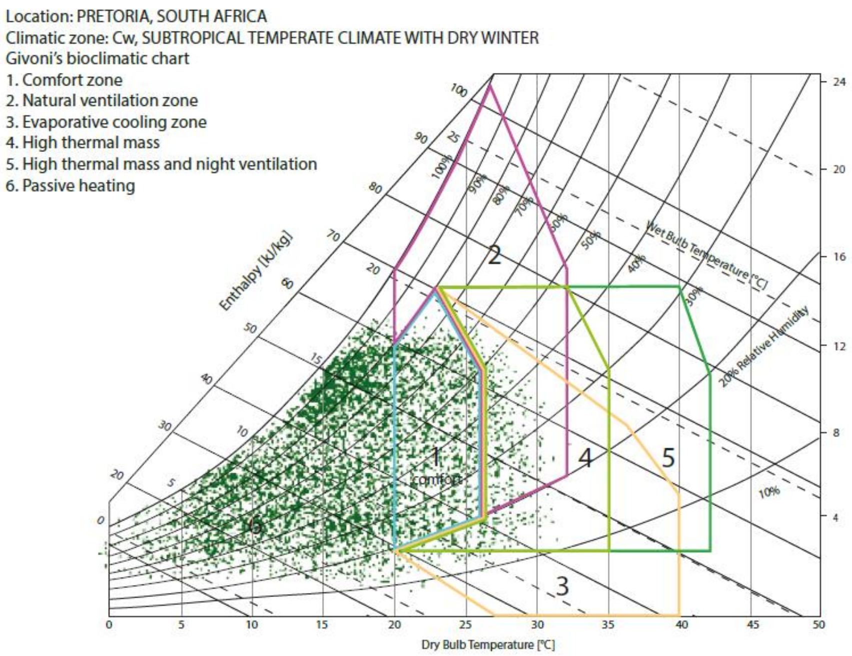


Fig. 3.2-17 – Givoni bioclimatic chart for Pretoria

33 Cs, Subtropical temperate climate with dry summer (Algiers, Algeria)

In a subtropical temperate climate with dry summer like Algiers (Fig. 3.2-18), solar shading, high thermal mass and passive heating are the most effective passive design strategies for improving thermal comfort.

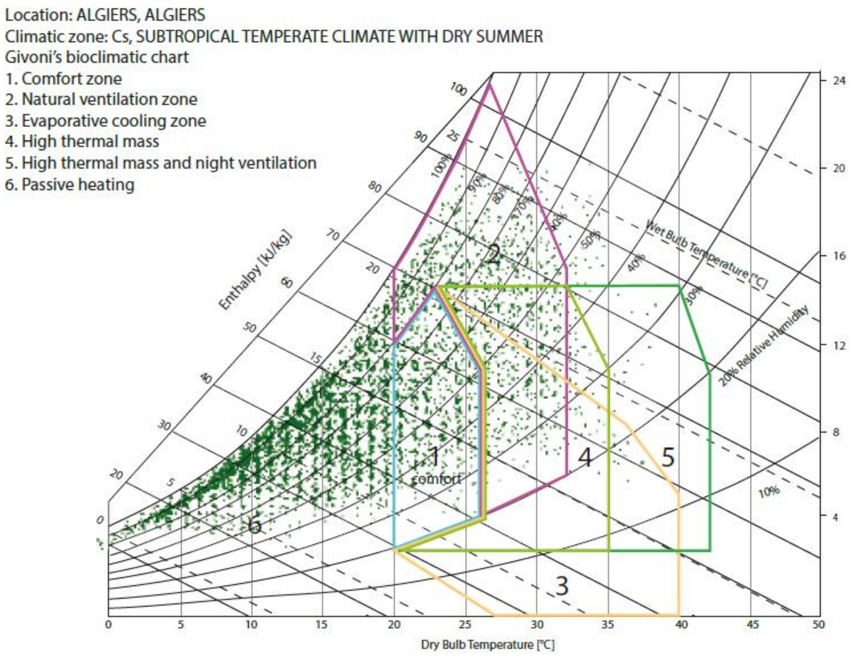


Fig. 3.2-18 – Givoni bioclimatic chart for Algiers

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, wind 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, technologies and related costs.

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 (see paragraph 2.1.3.3), which can be mitigated by reducing the total paved area allowed on site, 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. In warmer climates, basic concerns are the provision of shading and air movement, whereas in colder or temperate climates, differentiated conditions between summer and winter should be favoured. 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 climate A) 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 climate B) 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 temperate areas (such as climate C) are generally laid out to make use of solar radiation during the coldest period and for protection from cold winds (Fig.3.2-2a).

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

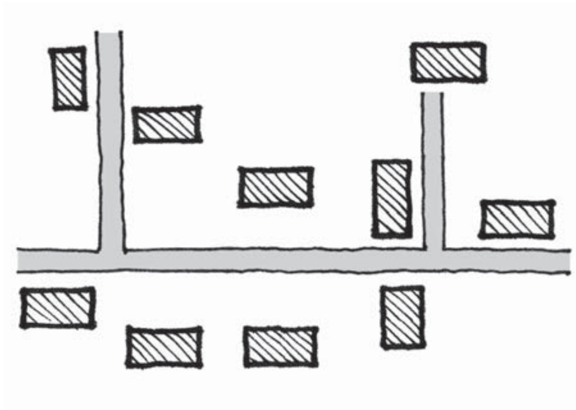


Fig. 3.3-1 – Typical settlement for hot-humid regions

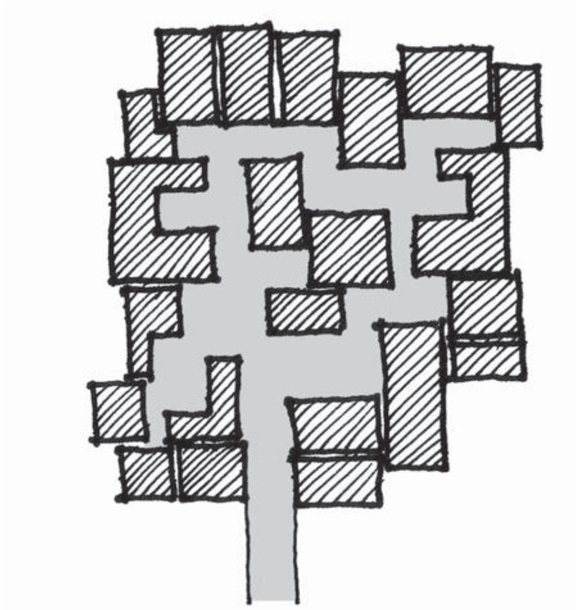


Fig. 3.3-2 – Typical settlement for hot-arid regions

3.3.2 Recommended urban patterns

Urban planning is not only the arrangement of buildings and infrastructures, but a more complete and articulated spatial organisation. The design of the space between things is as important as the things themselves; this consideration refers not only to the theme of urban design but also to that of landscape, of which the city is a part[1].

Regarding the African context, for example, 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.

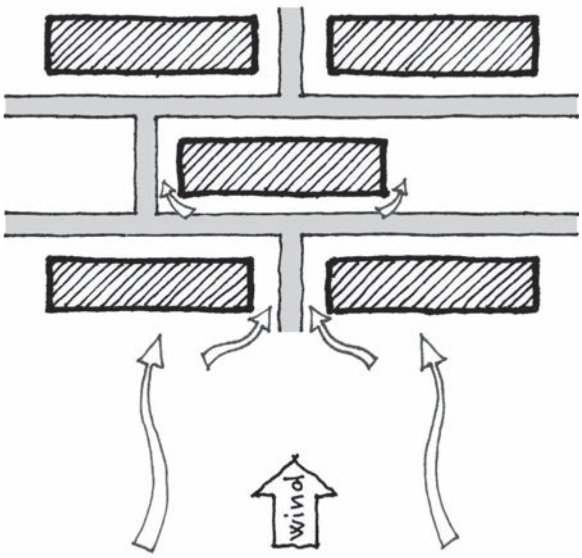


Fig. 3.3-2a – Typical settlement in temperate regions

1 V. Gregotti, Opening speech, Open City Summer School, Politecnico di Milano, September, 2014

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.

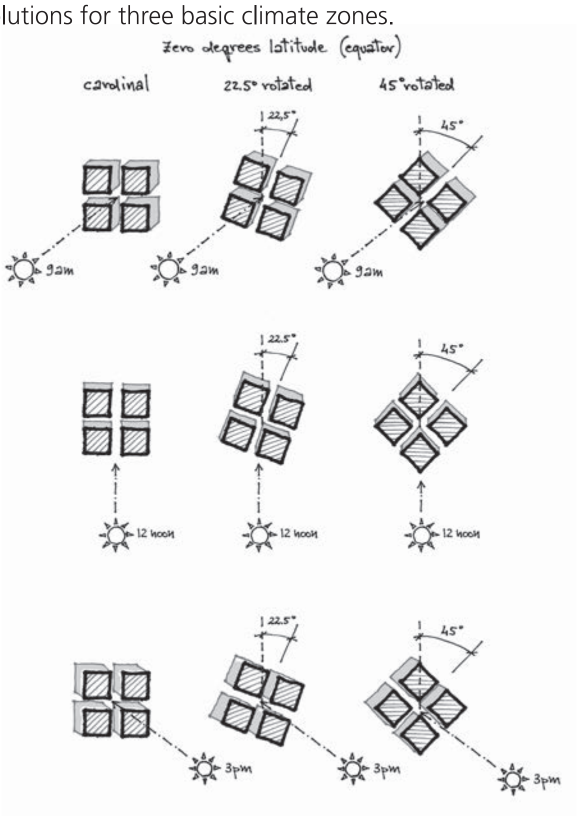


Fig. 3.3-3 – Urban layout and shading

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[2] (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.

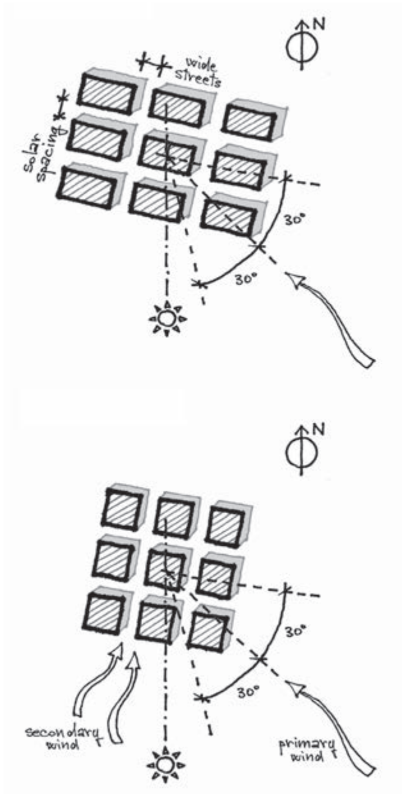


Fig. 3.3-4 – Urban layout and wind access

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).

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

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 facades 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 facades facing east and west, so maximising the shading of the street. In an urban layout with narrow streets this

2 V. Olgyay, Design with climate, Princeton University Press, 1963

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 Africa, 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.

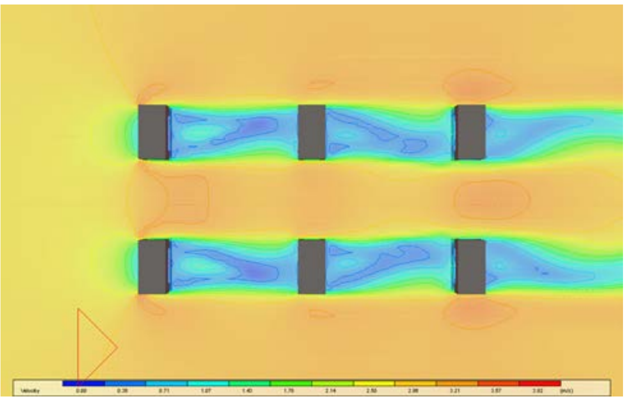


Figure 3.3-5 – CFD simulation of the airflow pattern in row arrangement with a ratio distance/height = 7

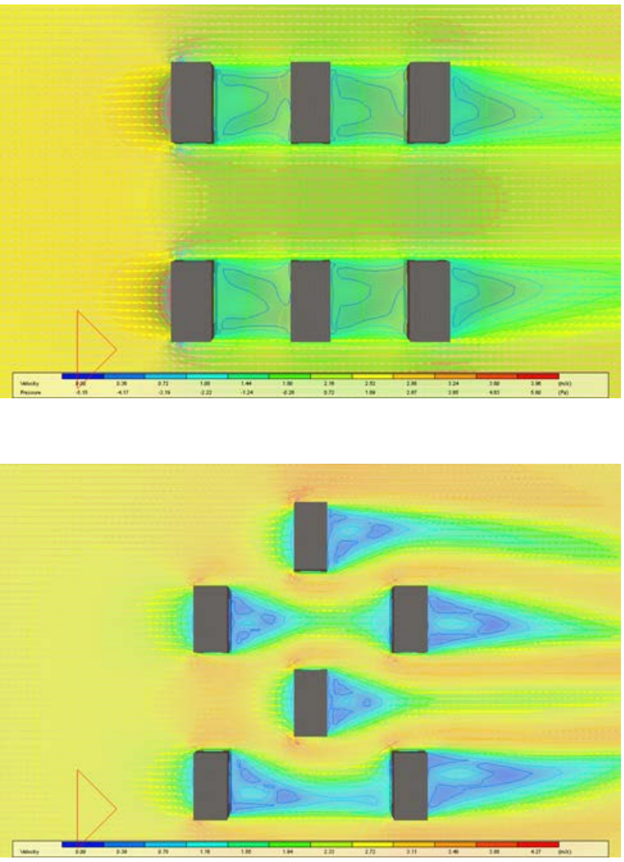


Figure 3.3-6 – CFD simulation of the airflow pattern in row arrangement with a ratio distance/height = 3. Air flow patterns in row arrangement (above) and staggered (below)

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.

Table 3.3-1 summarises the recommendations for three climates. Hot-arid, hot-humid and temperate climates are at the vertexes of a triangle encompassing the complex variety of climates in African countries.

Other climates 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.

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.

		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.
Temperate	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.

Table 3.3-1 – street orientation and layout by climatic priority

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

A sustainable building is a building that fits harmoniously into its geographical, environmental and climatic context. 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 features of the envelope, in its opaque and transparent components, which filters the environmental conditions from outside. Thermal mass and insulation of walls and roofs, together with type of glass and sizing of openings, have a huge influence on the energy performance of the building.

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 envelope 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 shape coefficient, i.e. 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 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

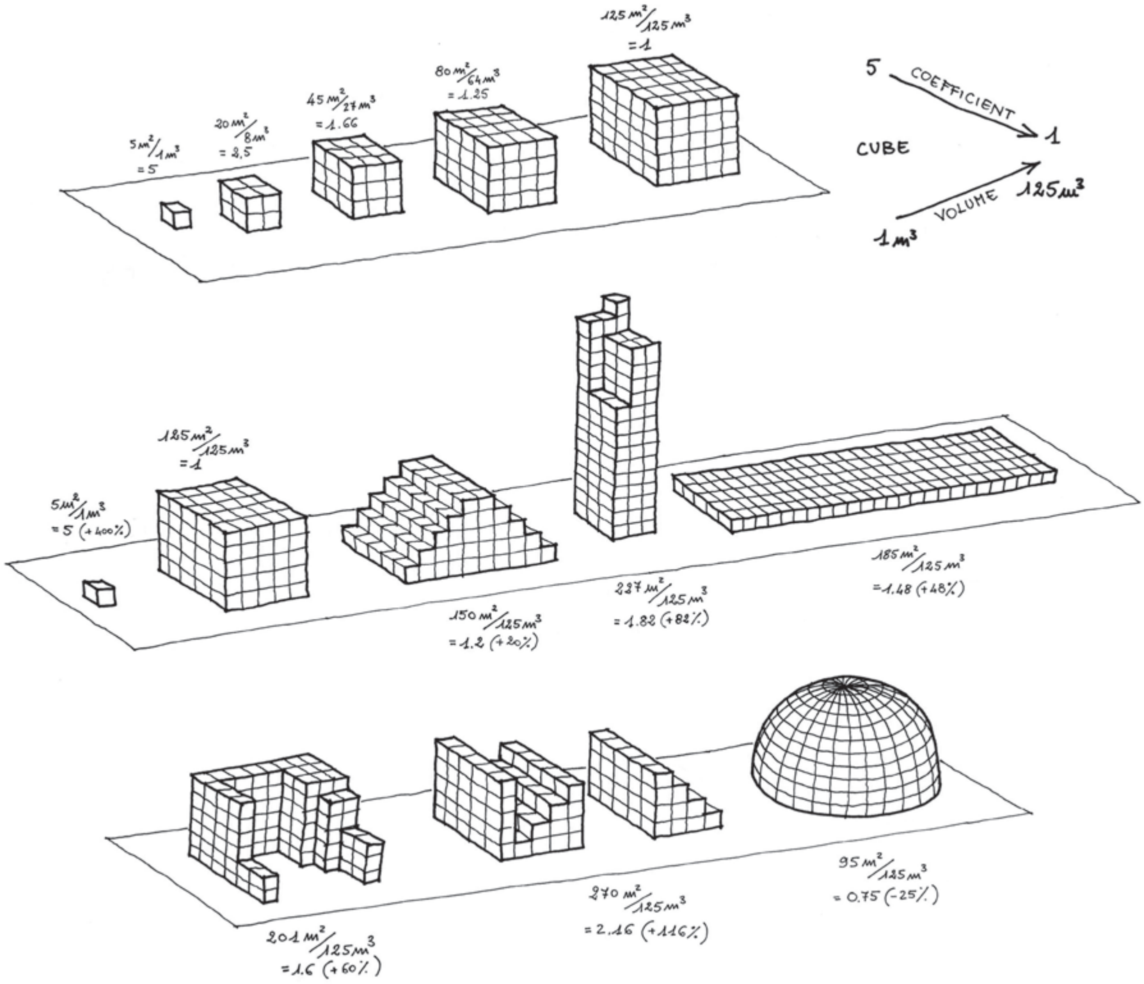


Fig. 3.4-1 – Top: variation of surface to volume ratio (shape coefficient) for increasing volume of a cube. Bottom: evolution of the shape coefficient for different combinations of a 125 m3 volume

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.

In temperate climates, where winter needs are present in addition to summer needs, the optimal shape can be compact or partially open, depending on the prevailing conditions. It is also advisable to take advantage of differences in height and overhangs in order to favour sunshine in the cold season and shade in the hot one.

Of course, all these considerations must be put in relation to the specific architectural, internal distribution, intended use and urban plot requirements,

The height of buildings also influences energy performance and needs to be carefully considered. 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). In hot climates, since solar gains from the roof are a critical issue, medium rise (4-5 floors) buildings should be preferred. This preference is also valid in temperate and cold climates, because of the lower heat transfer surface. 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 facades, is another deciding factor from the conceptual point of view, especially in hot climates.

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).

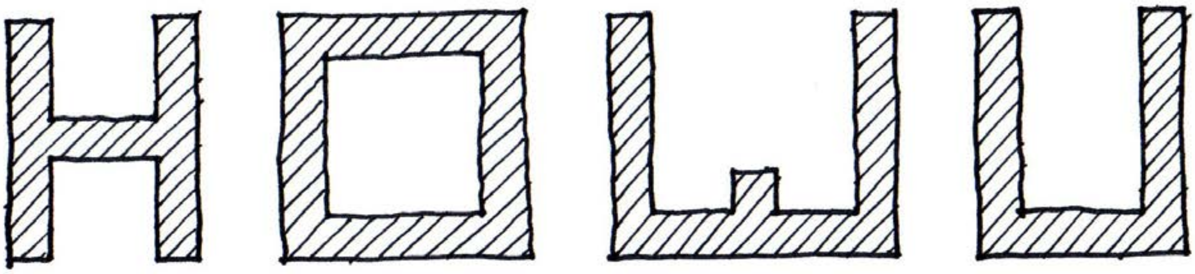


Fig. 3.4-2 – Examples of building plans with good access to natural light and with good potential for natural ventilation

Lastly, in temperate climates the depth should be governed by the possibility of exploiting seasonal natural ventilation and daylighting.

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.

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 many African 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 for the dissipation of 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.

It should be noted that the courtyard offers a good architectural solution even in temperate climates, where it provides the above performance during the warm season,

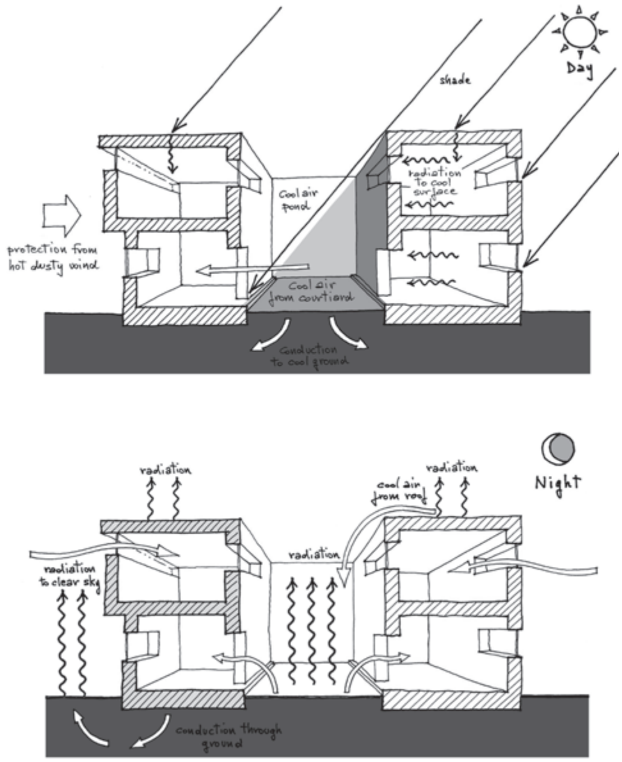


Fig. 3.4-3 – Courtyard

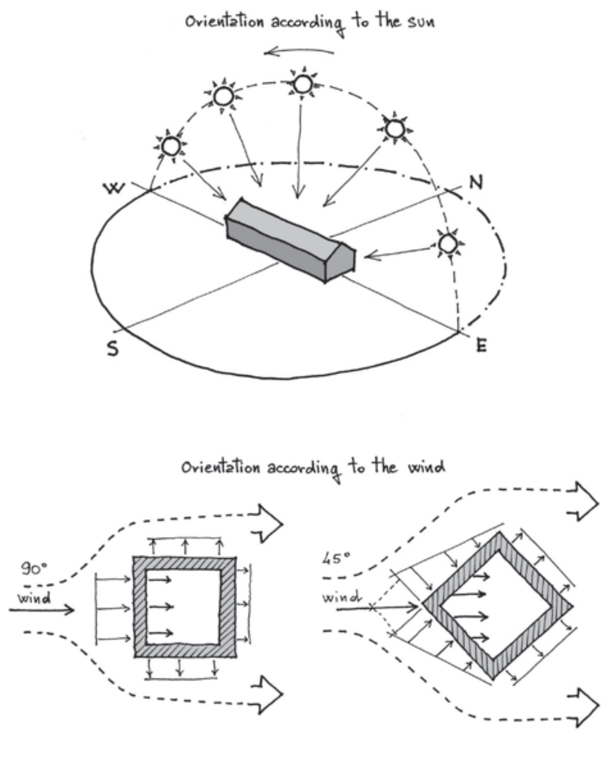


Fig. 3.4-4 – Orientation according to sun and wind

while during the winter it protects against wind and bad weather.

3.4.2 Building Orientation

Building orientation is very critical, because it significantly impacts on the interaction between envelope surfaces and climatic factors, in particular sun and wind.

In general, it is advisable to configure the building so that it can benefit from solar radiation in the coldest periods while shielding it in the hottest, and vice versa to take advantage of ventilation in summer but minimise it in winter.

The first basic rule is: minimise as far as possible facades facing east and west to avoid overheating and glare in the morning and evening hours (when the sun's path is low on the horizon) and take into account local prevailing winds, because of their connection with natural ventilation (Fig. 3.4-4).

On the African continent, the optimal orientation varies according to the local climate and latitude.

Within the tropical belt the solar path is such that a significant amount of solar energy can fall on east and west-facing facades, 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 facades (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.

Particularly,westerly orientation of the largest facades 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.

Beyond the tropics, the solar paths always pass southward (northern hemisphere) or northward (southern hemisphere), higher in summer and lower in winter. Also in these cases it is relatively easy to protect the building from overheating when necessary, by means of small overhangs or shielding systems.

In hot and particularly 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 temperate climate, where also heating is needed, a compromise has to be found in the size of the area of east and west-facing facades, 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 has to be considered both in temeprate climates, where heating is required during the cold season, and in hot-arid climates, 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 hot-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, in addition, in temperate climates it can also cause significant winter losses. 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. In hot climates, 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. In winter conditions, on the other hand, the convective effect can be prevalent regardless of colour, causing considerable heat loss.

The optimum insulation of walls and roofs depends on a variety of factors: the outside temperature, the thermal resistance and inertia of the building materials,the air velocity, the intensity of the incident radiation, the coefficient of absorption of solar radiation and the emissivity in the far infrared.

Regarding roofs, 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. In hot climates thermal transmittance U value of 0.8 W/m^2K for the combination roof-ceiling is a reasonable first guess while in temperate climates it can drop to 0.3, depending on the winter rigours. As far as walls are concerned, once again the assessment must be made according to the specific climatic conditions and the ratio of warm to cold seasons.

3.4.3.2 Thermal mass

Thermal mass of buildings, and in particular of building envelope components, is a generally useful factor in containing thermal loads and fluctuations. Massive stratifications, in fact, shift the transmission of heat over time and absorbs a certain amount of it.

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 temperate climates, 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 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.

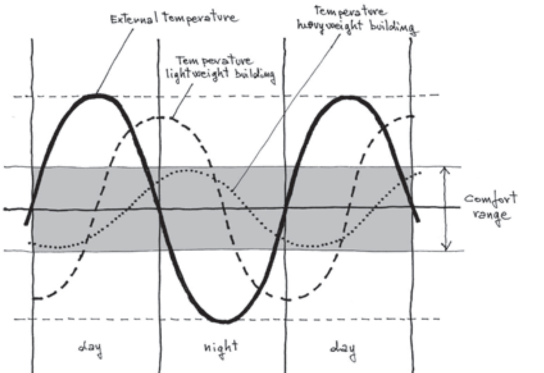


Fig. 3.4-5 – Effect of thermal mass on the behaviour of a building without air conditioning. The higher the mass, the smaller the fluctuation and the longer the time within the comfort range

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 strongly influence 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 and, since it faces the sky, it is also subject to significant re-irradiation losses during cold periods (night,

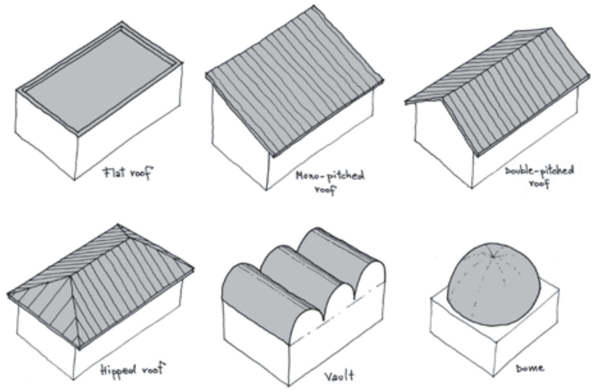


Fig. 3.4-6 – Basic roof types

winter) In addition to this, there is also heat transmission depending on the temperature difference between inside and outside and on the transmittance of roof slab or pitch.

In hot climates, 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. The thermal performance of the roof is critical for thermal comfort

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[1].

In general, in order to keep roofs cool, they should be exposed towards the prevailing breeze and any obstructions that would prevent the airflow along the roof surfaces should be avoided.

In temperate climates the same considerations apply in the hot season, while in colder periods heat loss must also be taken into account, which cools the internal surface of the room under the roof, causes discomfort and requires heating. In this case, thermal insulation should be included in the roof layering.Ultimately, thermal performance depends to a great extent on the shape of the roof, its construction and the materials used. Moreover, 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).

Domed and vaulted roof

Domed roofs have been traditionally used 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.

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.

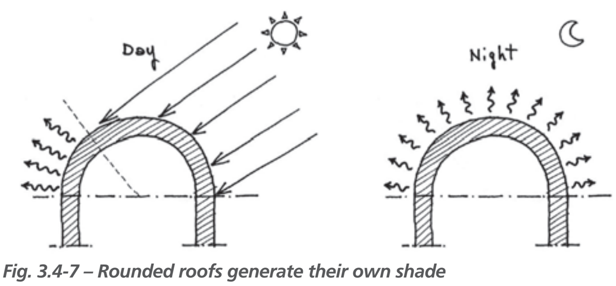


Fig. 3.4-7 – Rounded roofs generate their own shade

1 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.

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

In hot-humid climates, where it is the most common type, 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[2]. 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[2]. 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.

In temperate climates, where this is also a quite common type, the same considerations as above apply once again: roof construction and materials must be selected to prevent overheating in summer and losses in winter.

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 facade. Warm air rising up a facade should be able to escape through suitable vents.

Finally, it should also be noted that the sloping shape allows rapid drainage of rainwater, preventing infiltration and moisture in this and following roof types.

Double leaf roof

The most effective roof type for all African 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 especially in hot climates, as shown in Table 3.4-1, where the temperature difference between indoor air and the underside of the ceiling is given

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

for various combinations, in the absence of ventilation.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.

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

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

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

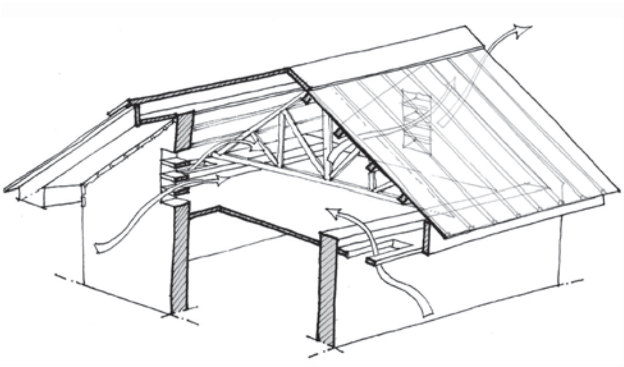


Fig. 3.4-8 – Attic ventilation

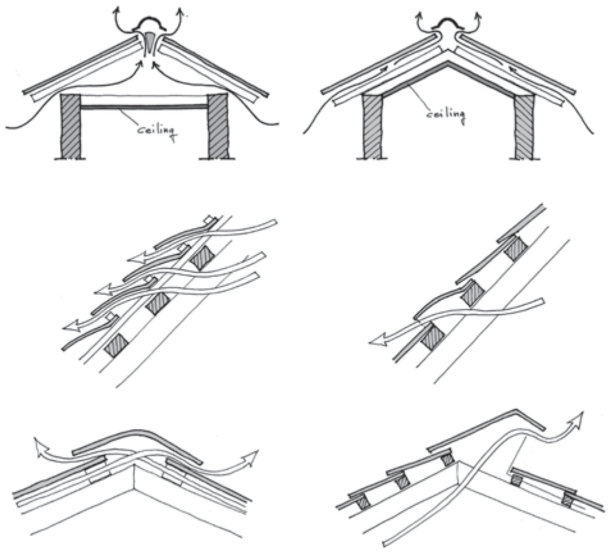


Fig. 3.4-10 – Ventilation of the gap between the two roof leafs

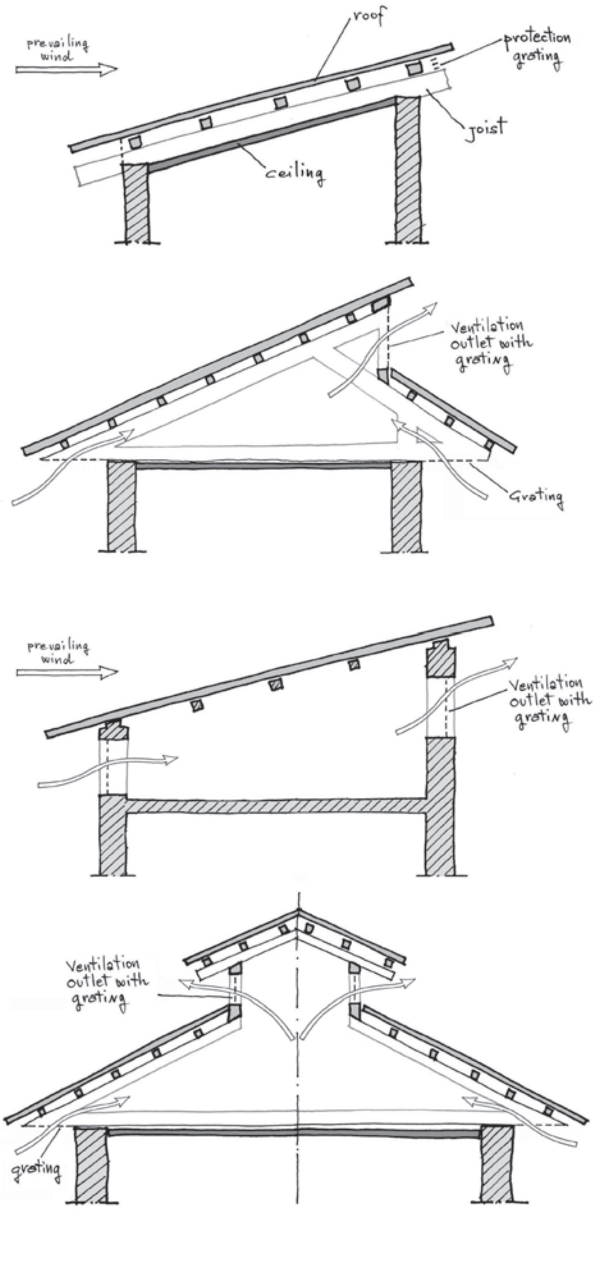


Fig. 3.4-9 – Ventilation of the space between roof and ceiling

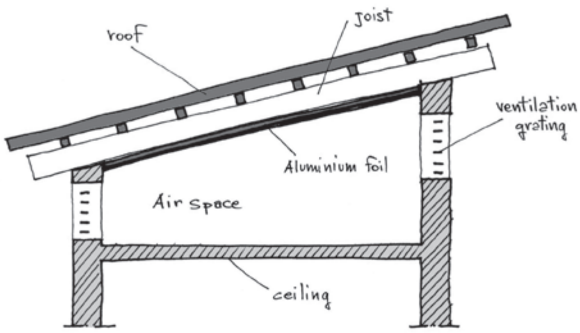


Fig. 3.4-11 – Aluminium layer between the roof and the ceiling

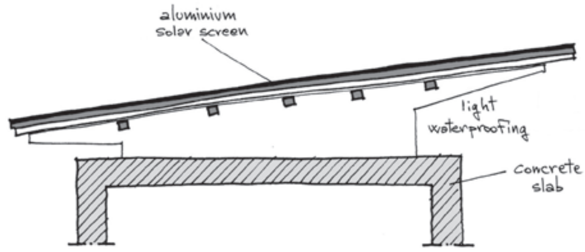


Fig. 3.4-12 – Aluminium sun screen above a flat roof

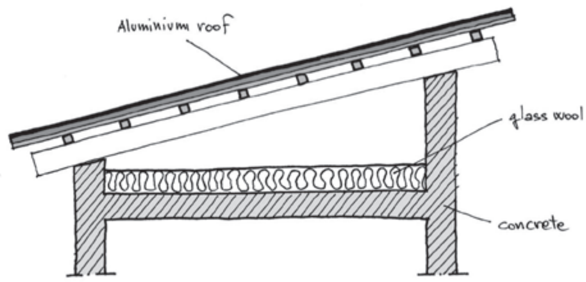


Fig. 3.4-13 – Aluminium roof; concrete ceiling and insulation

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 a sloped 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.

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.

In temperate climates, winter performance can be improved by inserting insulation in the cavity and limiting or avoiding inner ventilation.

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.

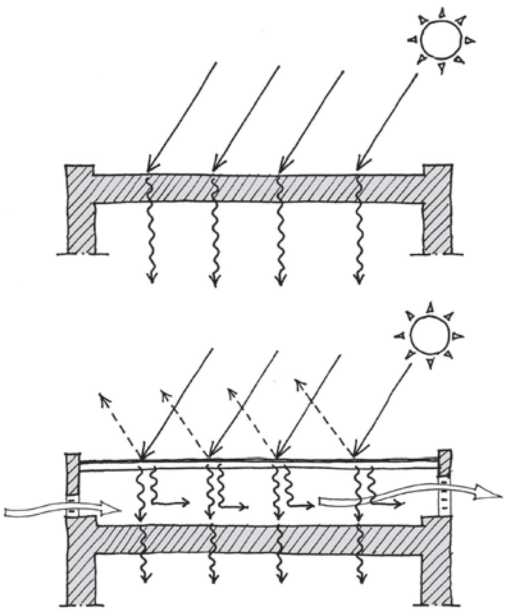


Fig. 3.4-14 – Top: flat roof; bottom: ventilated double roof with heavy ceiling

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.

Of course, even for this type of roof the suitability of interposing thermal insulation must be evaluated according to the local climatic conditions.

General rules for roof design by climatic area

More than other building components, the roof should be, as far as possible, climate responsive: mainly reflective and ventilated in hot climates and insulated in temperate ones.

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 temperate climates roof ventilation may not be necessary, but insulation is necessary and some thermal mass is helpful.

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. A poorly insulated wall can also dissipate heat at low outdoor temperatures.

The thickness and material of a wall can be varied to control heat gain and loss. The resistance to heat flow through the walls may be increased in the following ways:

- increase the thickness of the wall;
- adopt cavity wall construction;
- use suitable heat insulating material;
- use radiant barriers;
- apply light coloured on the walls most exposed to the sun.

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

In general, a certain level of wall insulation is always preferable, as it dampens thermal losses and loads. In many cases the decision depends on economic factors and the cost/benefit ratio must always be assessed.

Thermal insulation can be achieved by applying panels of low-conductivity materials or by using appropriate building materials, such as hollow bricks or light concrete.

In temperate climates, where heating needs also occur, insulation helps to reduce them. However, the thermal transmittance must be carefully assessed to avoid over-insulation and related summer over-heating.

In hot climates, thermal insulation may not be strictly necessary, but it is generally useful, especially for east and west-facing walls.

A very common construction solution is represented by multi-layered walls, with stratifications of solid (bricks, stone, concrete, etc.) and insulating materials. Depending on the positioning of the insulation in the layering, some variants are possible (as reported in figure 3.4-14a), but a careful assessment of the related thermal performance is needed.

Insulation on the external side is a very popular solution in Europe and provides benefits on both resistance and thermal inertia. It is recommended in temperate climates, but must be thoroughly evaluated in hot climates. In the latter, indeed, 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.

However, 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.

An intermediate solution is represented by the positioning of the insulation between two solid layers, so that the inertial performance includes both the outside and the inside of the wall.

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 little thickness is used without plastering.

Solar protection of walls

Where high temperatures require it, shading of walls is a strategic issue.

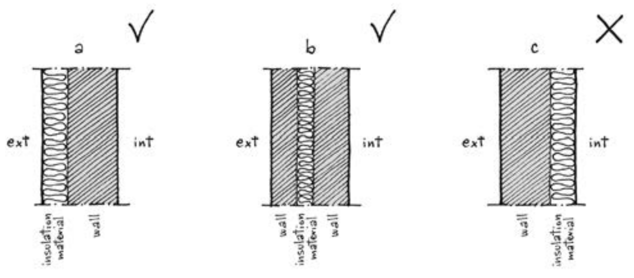


Fig. 3.4-14a – Different position of the insulation layer in the envelope

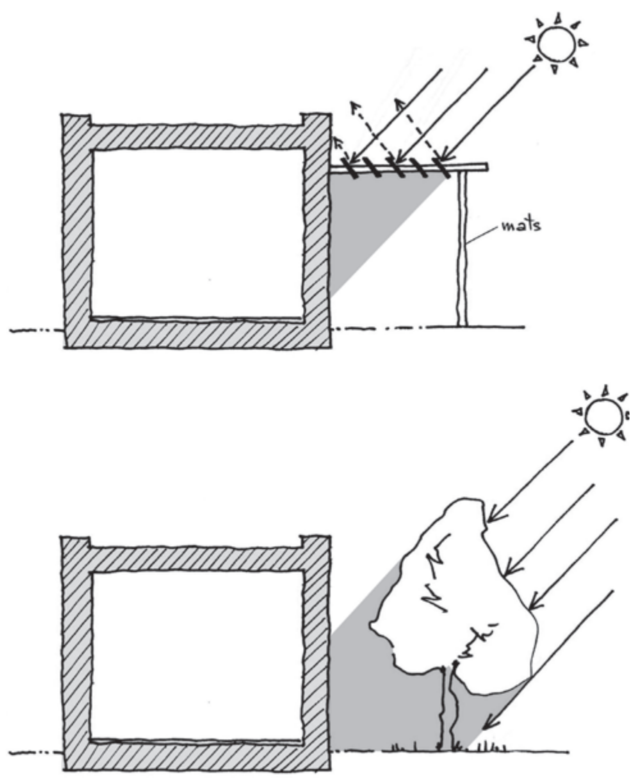


Fig. 3.4-15 – Walls solar protection

In particular, east and west-facing walls are subject to the highest radiation loads, which can be transmitted indoors and cause overheating.

In low-rise buildings the problem can be easily solved by pergolas or other means, as shown in figure 3.4-15.

For larger buildings, the correct orientation becomes particularly important, but the effects of orography and surrounding buildings can also be considered.

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.

The outer skin can be made of different materials, as long as they are weather resistant. In general, ceramic, metal or brick panels fixed to a framework are used.

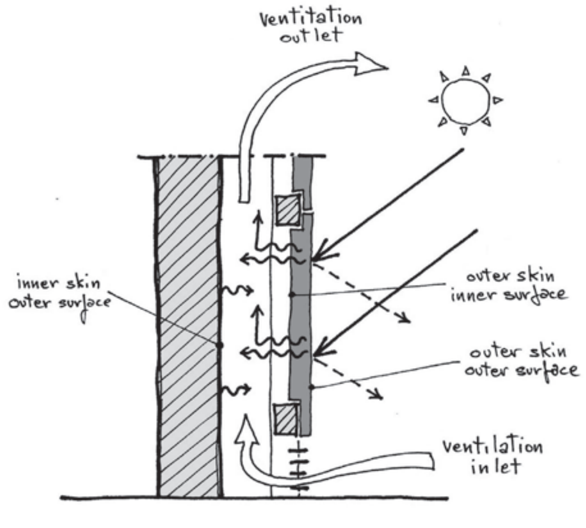


Fig. 3.4-16 – Diagrammatic section of double-skin wall

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.

Cavity wall

A simpler version of the ventilated wall is the cavity wall (Fig. 3.4-16a), in which two solid layers (e.g. of brick) separate an air gap. Its 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.

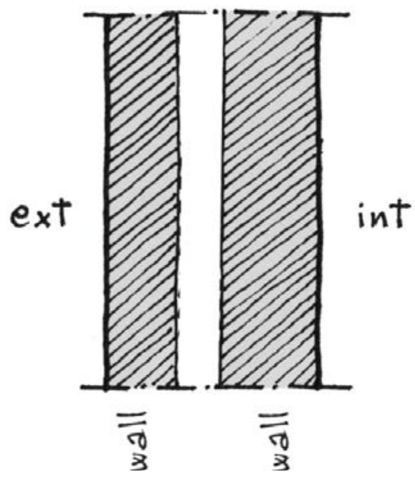


Fig. 3.4-16a – Diagrammatic section of the cavity wall

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

General rules for wall design by climatic zone

In climate sensitive buildings, walls should preferably be built with techniques and materials taken from or inspired by local tradition. This is because over the centuries, builders have selected the most suitable technologies for the specific geographical and climatic context. Of course, the tradition can be updated, adding or improving features.

In general, all types of clay, stone and brick are traditionally used in all African areas. Concrete blocks have more recently replaced these materials. In this respect, note that where the storage of coldness is required, solid blocks are more effective than hollow blocks.

Borrowing from modern fashions and trends in international architecture, facades built with dry technology and lightweight materials have been introduced also in Africa since the 1950s. These solutions, however, can hardly be defined as climate responsive, as they are very sensitive to temperature variations and in any case require close synergy with HVAC systems.

In hot-arid climates, walls of daytime living areas should be made of heat-storing materials; walls of rooms for night-time 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, 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.

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.

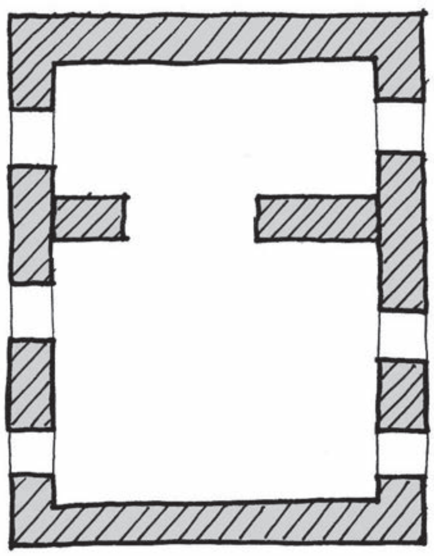


Fig. 3.4-17 – Increasing the surface area of internal partitions in a large room

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.

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 temperatre climates, the walls must function as a filter from outside conditions, in both cold and warm seasons. In this respect, a proper balance between thermal inertia and insulation is generally effective.

Moreover, solar radiation can be used in such a way as to improve comfort and reduce, or even eliminate, any need for winter heating.

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).

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 is the sunspace.The sunspace is very critical in terms of comfort

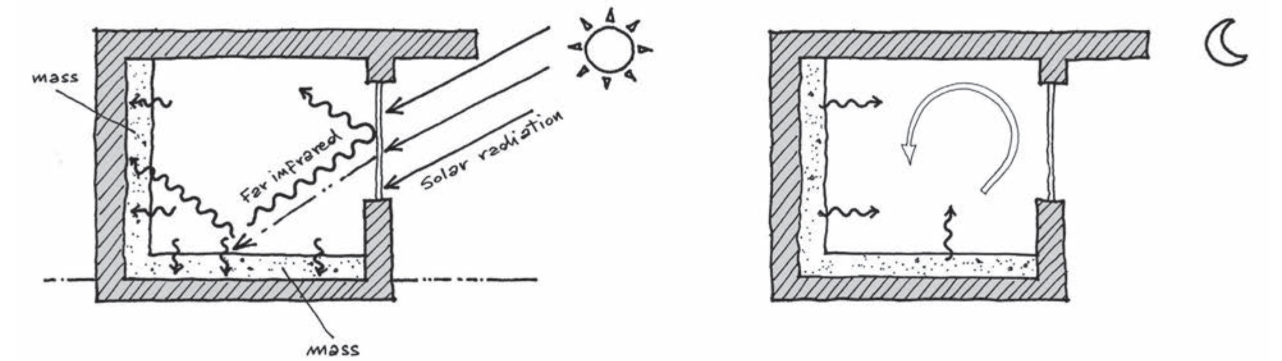


Fig. 3.4-18 – Solar energy during the day is trapped and stored in the mass due to the greenhouse effect; the energy stored in the mass is released during the night

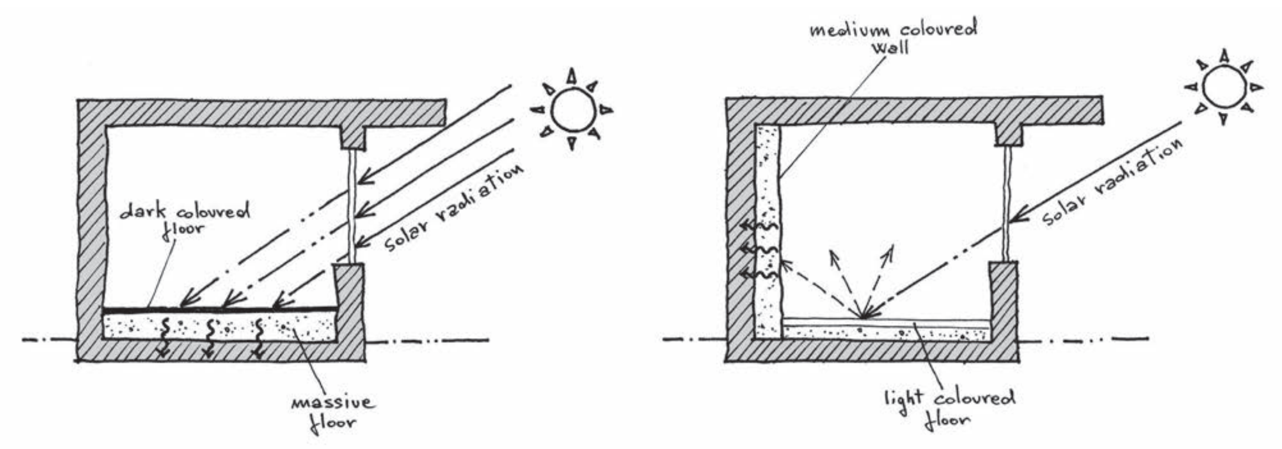


Fig. 3.4-19 – Floors should be dark-coloured if massive; light-weight floors should be light coloured, to reflect the solar radiation onto massive surfaces.

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 sunshaded and fully opened in warm periods.

3.4.5 Openings

Openings and glazed surfaces must be treated very carefully, as they are responsible for significant energy exchange between inside and outside. In addition to solar radiation, glass transmits heat up to 20 times more than a wall. This results in losses and loads that weigh heavily on the performance of the whole building.

Glazing will be dealt with in more detail in the 4th

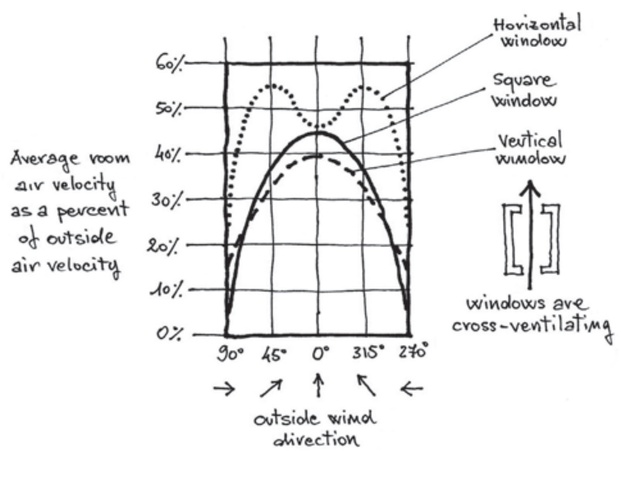


Fig. 3.4-20 – Impact of window shape on air velocity (Source: Chandra, Subrato, Philip W. Fairey, and Michael M. Houston. 1986. Cooling with ventilation, Solar Energy Research Institute).

chapter, while here simple guidance on size and shape of the openings is given.

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

Sunscreens are an effective mean of reducing undesirable solar light. In particular, movable louvers are an effective shading system because they can regulate the inflow of solar energy and light according to specific needs.

In hot climates, 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.

In temperate climates, openings should be sized according to the orientation, to optimise the balance between solar heat gains and heat losses. As a general rule, a 20% proportion of transparent surface area in facades is recommended, but it is always better to adopt more accurate sizing, depending on the particular context.

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 many African 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.

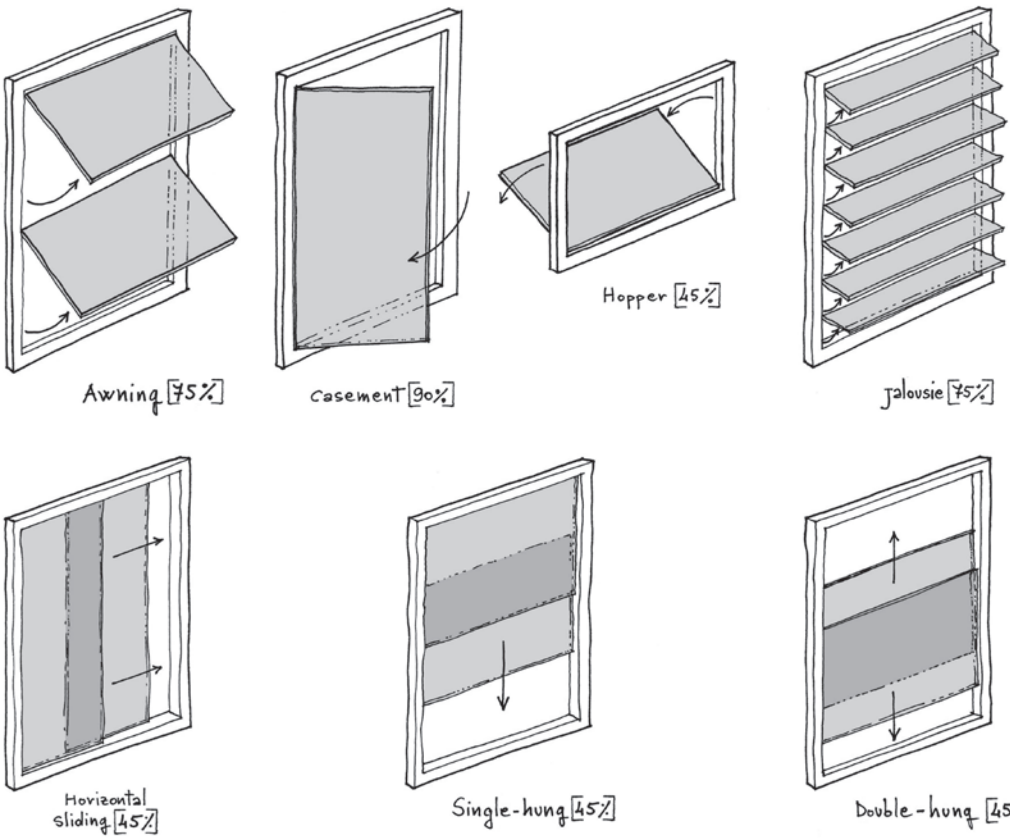


Fig. 3.4-21 – Different window types; in brackets the effective open area (permeability) as percentage of the opening area

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. More in detail,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 temperate climates, ventilation must be regulated according to external conditions: exploited in mid-season and on summer nights, while limited in cold periods.

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); the change in direction causes a densification of the fluid streamlines, resulting in an increase in velocity and a decrease in pressure.

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 airplane, 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;

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).

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, enabling natural ventilation.

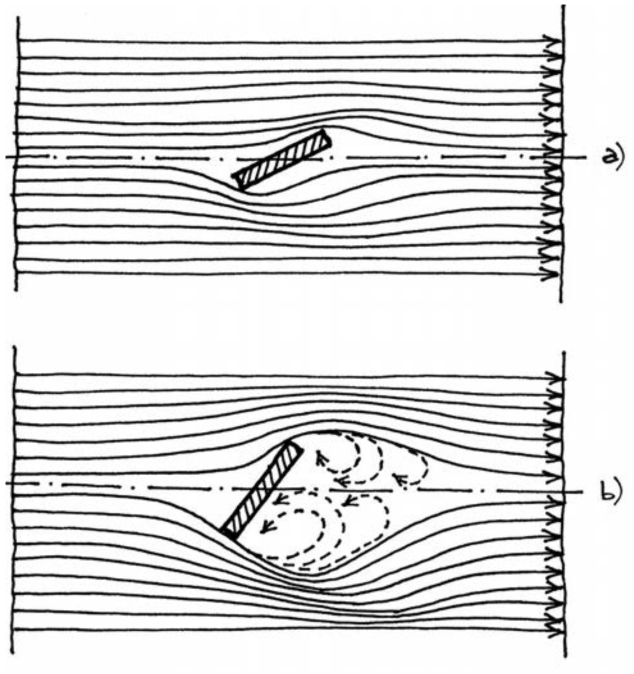


Fig. 3.5-1 – Laminar and turbulent flow

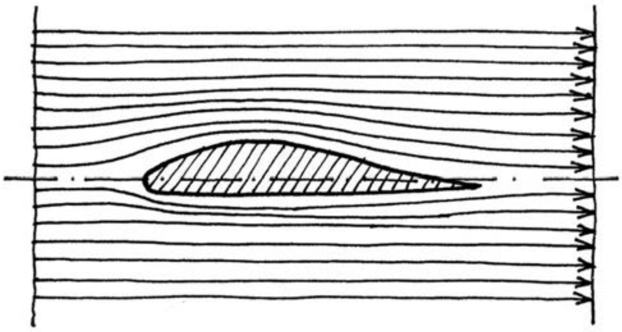


Fig. 3.5-2 – Bernoulli effect

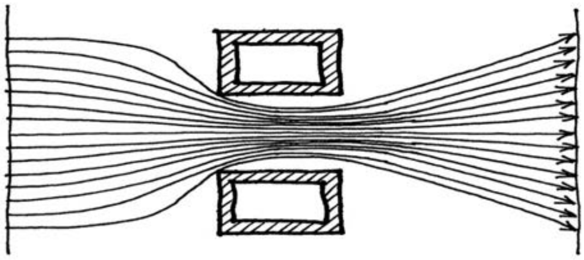


Fig. 3.5-3 – Venturi effect

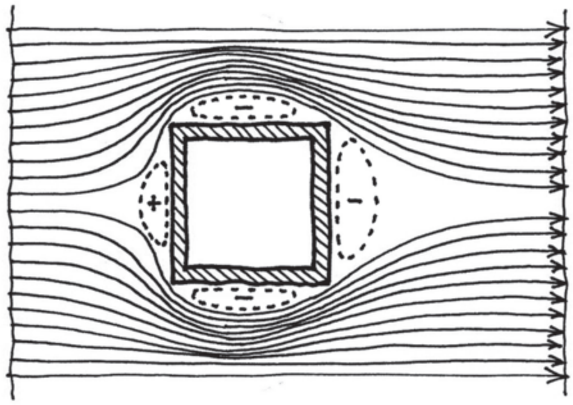


Fig. 3.5-4 – Pressure distribution around a building

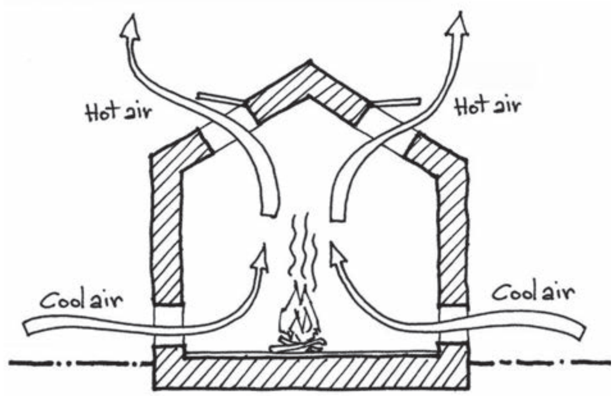


Fig. 3.5-5 – Stack effect

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;
- • In a building on stilts leeward pressure is reduced and in correspondence to the stilts wind speed significantly increases, figure 3.5-7;
- • 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;
- • 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;
- • 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;
- • 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[1]).

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).

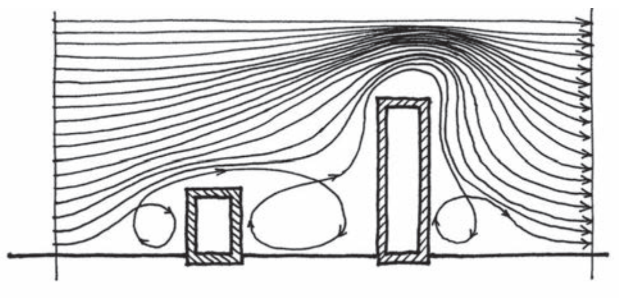


Fig. 3.5-6 – Low-rise building to windward of a high-rise one

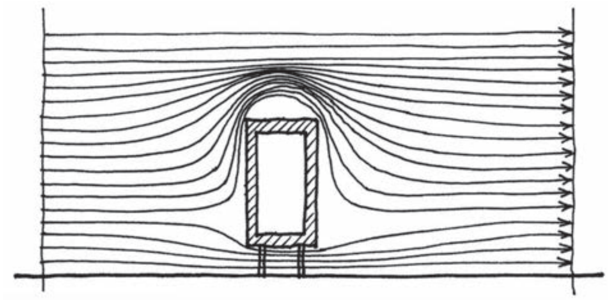


Fig. 3.5-7 – Building on stilts

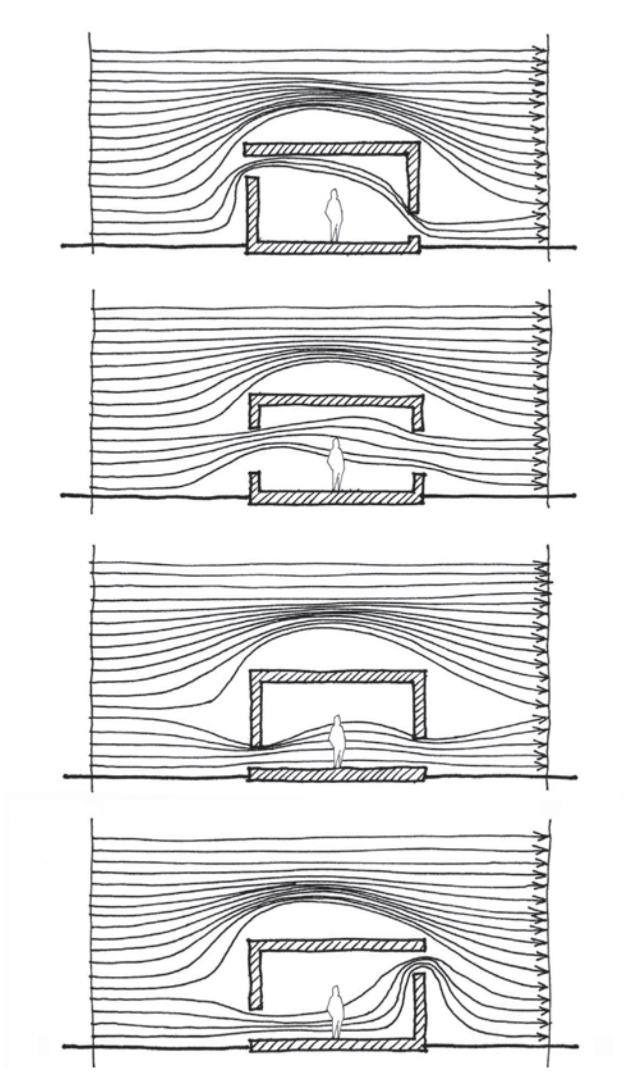


Fig. 3.5-9 – Air flow pattern, according to the relative position of the openings

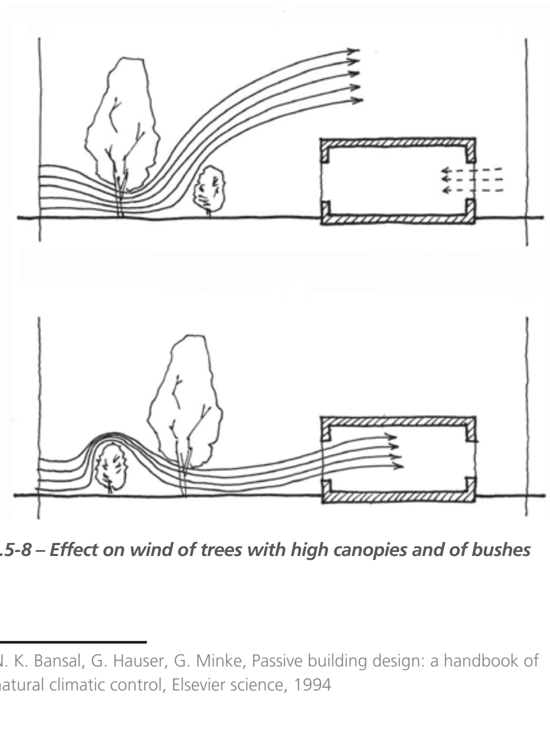


Fig. 3.5-8 – Effect on wind of trees with high canopies and of bushes

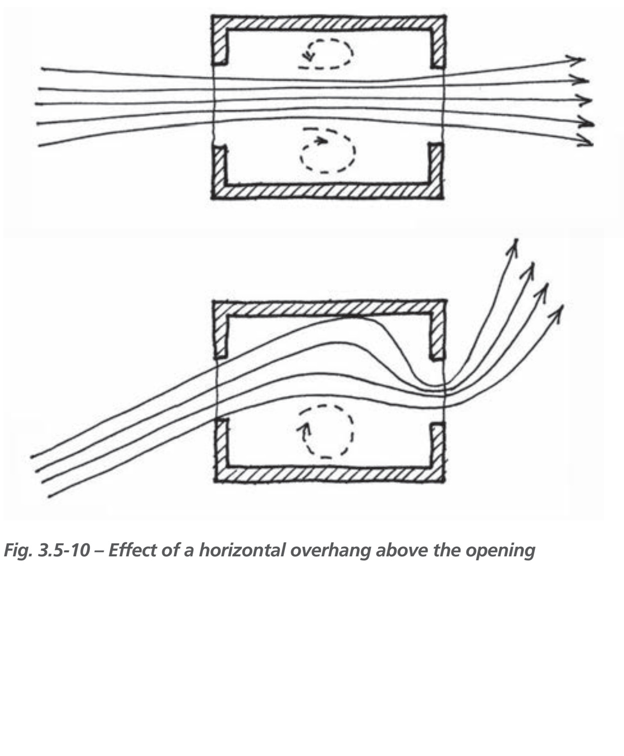


Fig. 3.5-10 – Effect of a horizontal overhang above the opening

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

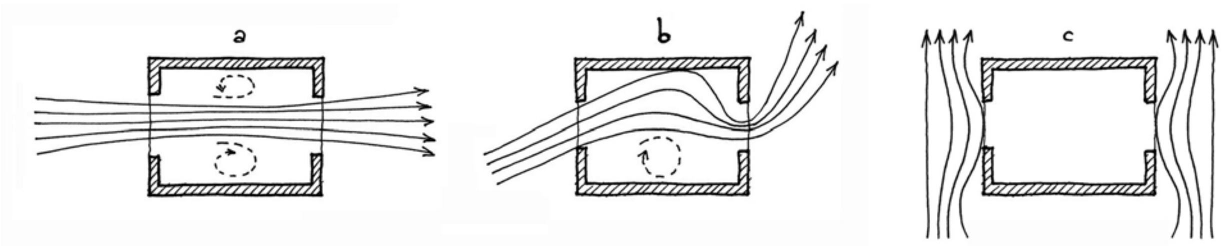


Fig. 3.5-11 – Effect of alignment of openings on cross ventilation

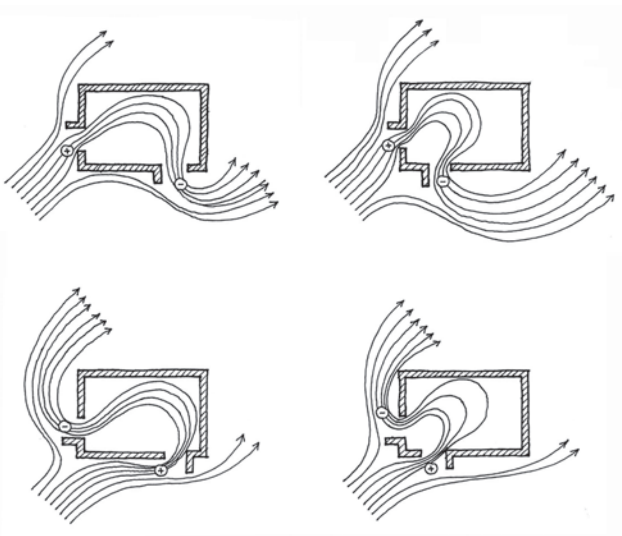


Fig. 3.5-12 – Improving ventilation with openings on adjacent walls, and wing walls

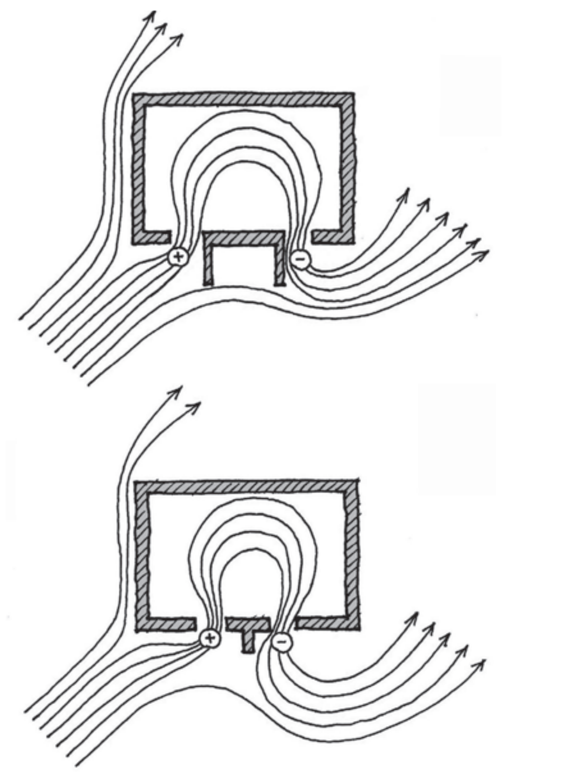


Fig. 3.5-13 – Ventilation, with wing walls, in rooms with only one wall facing outside and two openings

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[2]:

$$V=KAv \qquad (3.5\text{-}1)$$

where:

V = air flow rate [m^3/s];

K = coefficient of effectiveness, between 0 and 1;

A = net free area of inlet openings[m^2];

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 inlet opening and it increases with the relative size of the larger opening.

For opposite openings of equal area, K = 0.6 for angles of wind incidence on the window between 0° and 30°and K = 0.3 for wind at 45° or more.

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 between 30° and 45°, after which it gradually decreases

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.

When opposite openings are of different area, 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.

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

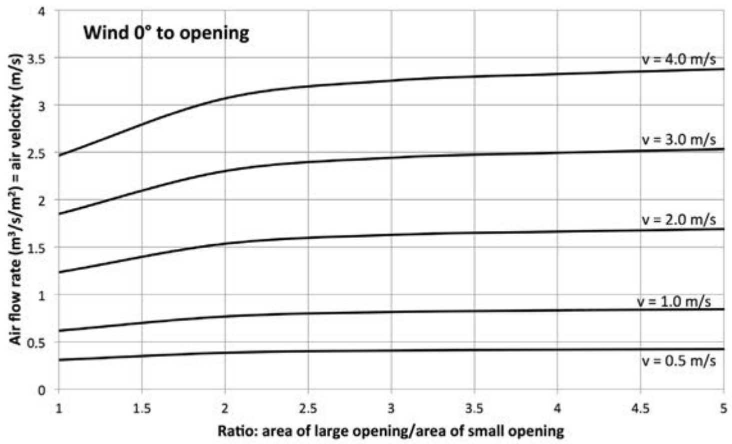


Fig. 3.5-14 – Air flow rate per square meter through the smaller opening (or air velocity in m/s) with different wind speed – Wind incident at 0° (Adapted from: N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994)

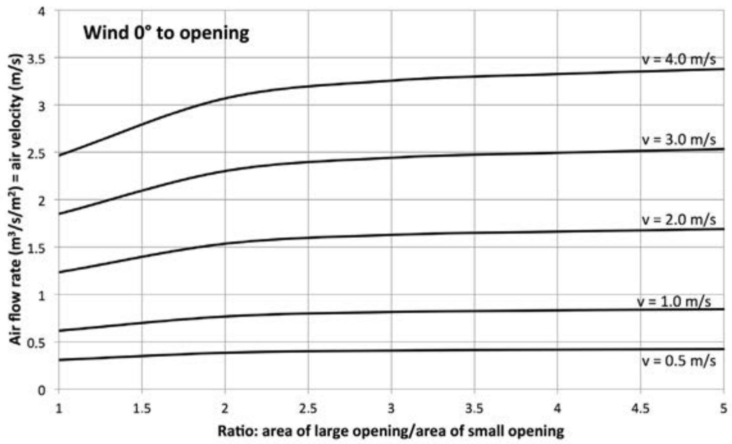


Fig. 3.5-15 – Air flow rate per square meter through the smaller opening (or air velocity in m/s) with different wind speed – Wind incident at 45° (Adapted from: N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994)

3.5.2.2 Indoor air velocity

Indoor air velocity has a significant effect on comfort conditions, so it must be kept within certain limits, usually less than 1 m/s (see Appendix 2 - Principles of thermal and visual comfort).

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.

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.

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.

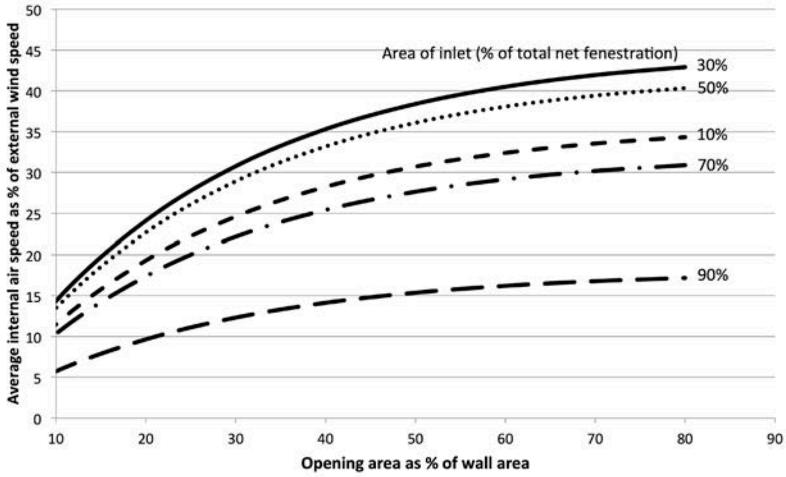
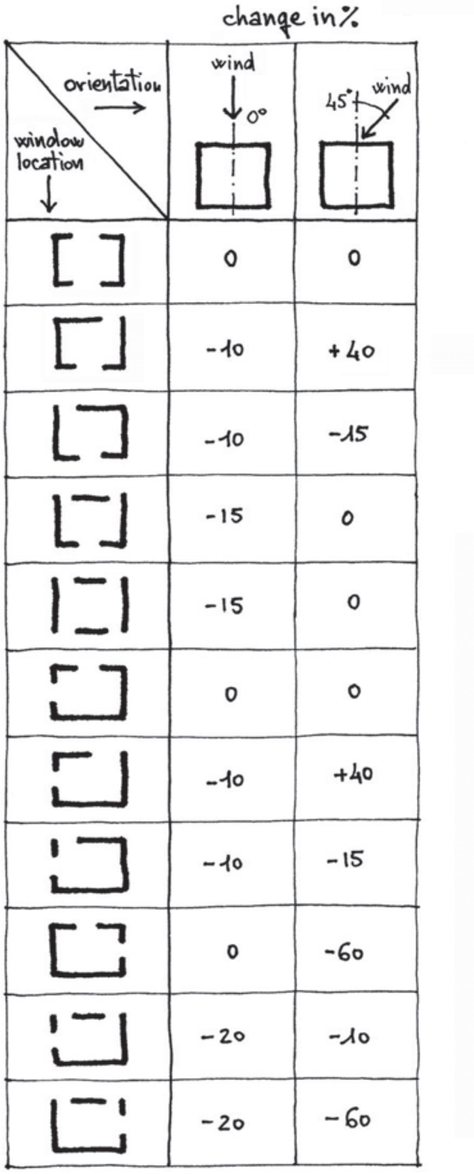


Fig. 3.5-16 – Average internal air speed for different areas of the openings for cross ventilation (Adapted from: N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994)



window location	wind 0°	wind 45°
	0	0
	-10	+40
	-10	-15
	-15	0
	-15	0
	0	0
	-10	+40
	-10	-15
	0	-60
	-20	-10
	-20	-60

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)

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.

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.

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

Table 3.5-2 – Effect of louvers on indoor air motion (Source: N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994)

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

Table 3.5-3 – Effect of verandas on indoor air motion (Source: N. K. Bansal, G. Hauser, G. Minke, Passive building design: a handbook of natural climatic control, Elsevier science, 1994)

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[3]:

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

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.

3 ASHRAE Handbook of Fundamentals, 1993

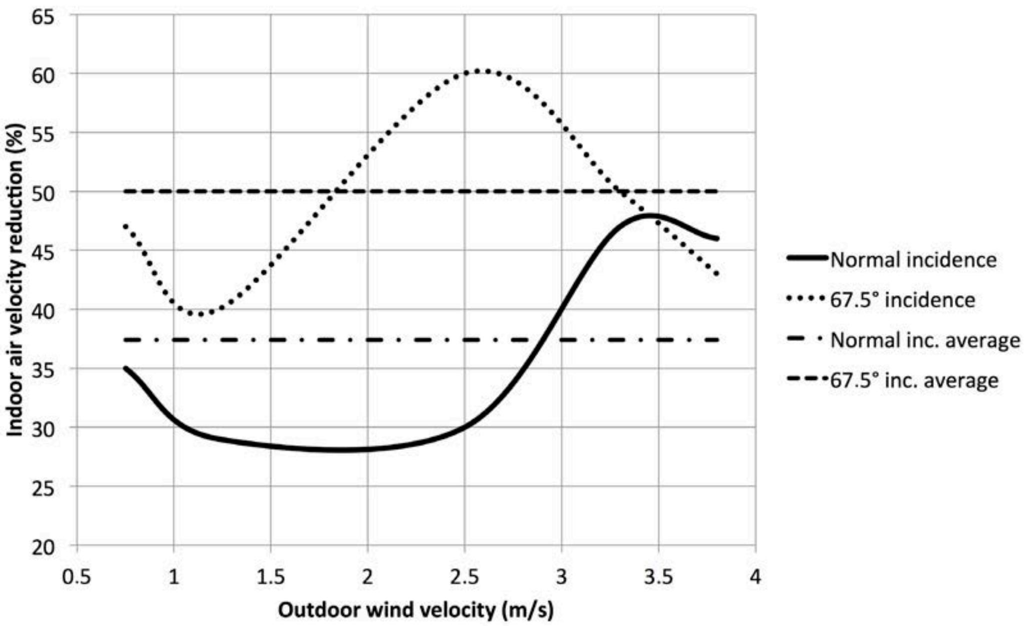


Fig. 3.5-17 – Flyscreen. Reduction of wind velocities with the incident angle (Adapted from: O.H. Koenisberger, T.G. Ingersoll, A. Mayhew, S.V. Szoklay, Manual of tropical housing and building, Longman, 1975)

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).

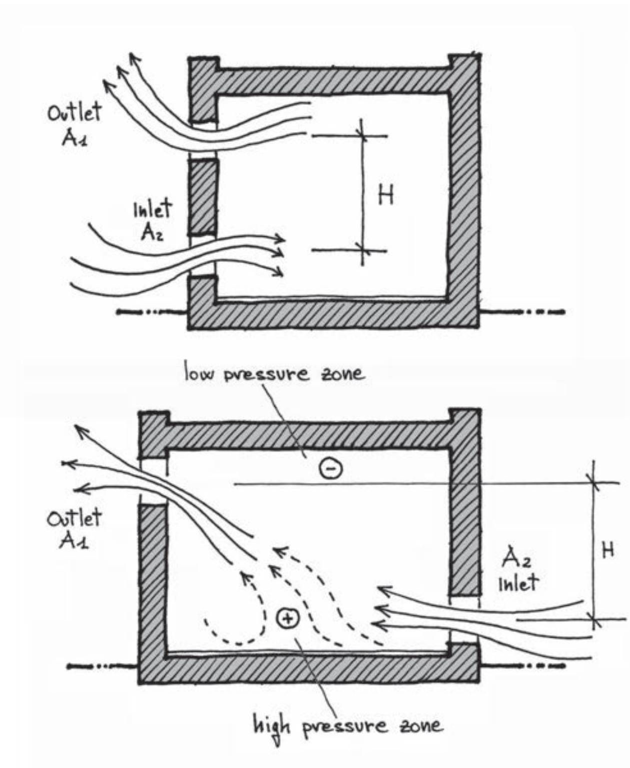


Fig. 3.5-18 – Airflow due to the height difference between the openings and the temperature difference between inside and outside, in the absence of wind

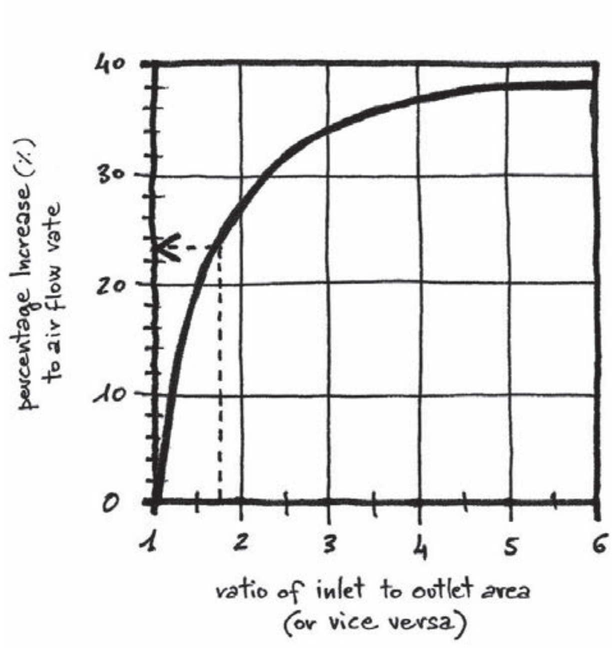


Fig. 3.5-19 – Increase in stack flow rate due to differential opening sizes

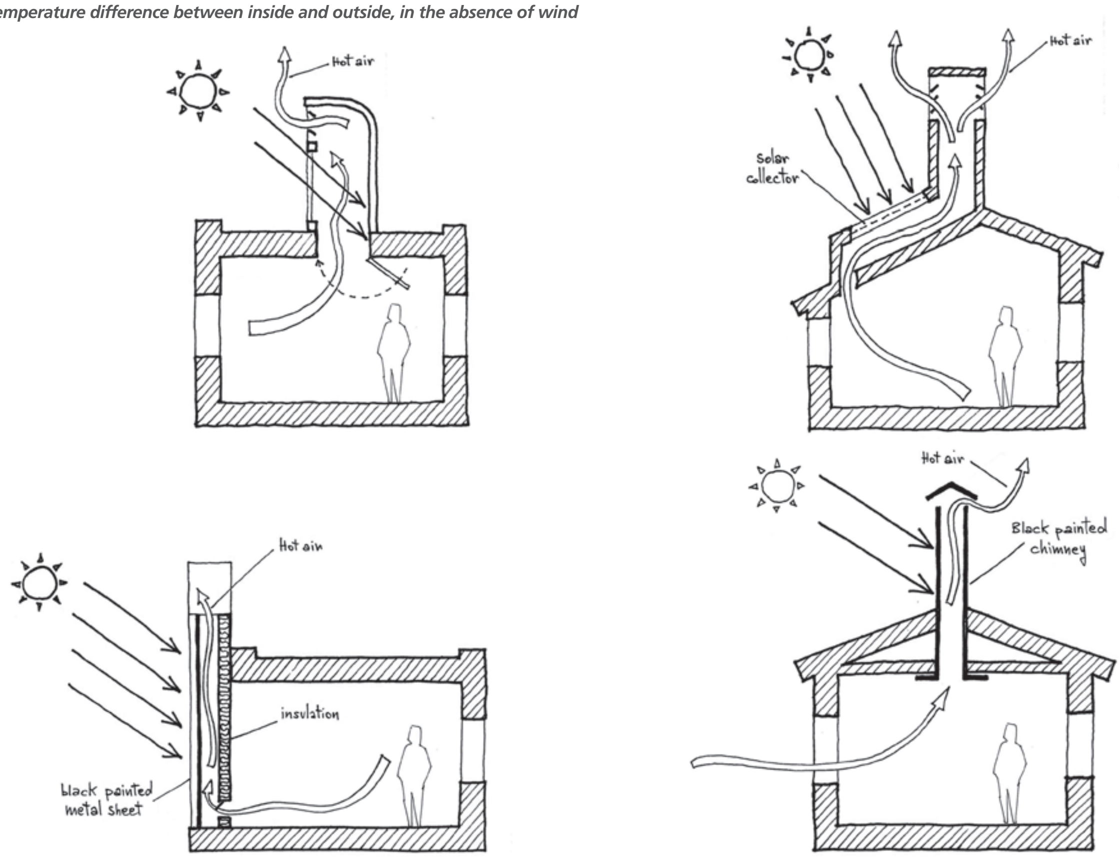


Fig. 3.5-20 – Different types of solar chimney

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[4]:

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

where:

V = resultant air flow rate [m³/s];

V_w = air flow due to wind [m³/s];

V_s = air flow due to stack effect [m³/s].

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 pre-requisite for using a wind catcher is that the site should experience winds with a fairly good consistent speed, with values above 2 m/s.

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.

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 (wider angles are less effective).

For wind catcher designs with openings in multiple directions, the opening in each direction should be sized to meet by himself the airflow rate required, as the wind only blows from one direction. 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

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

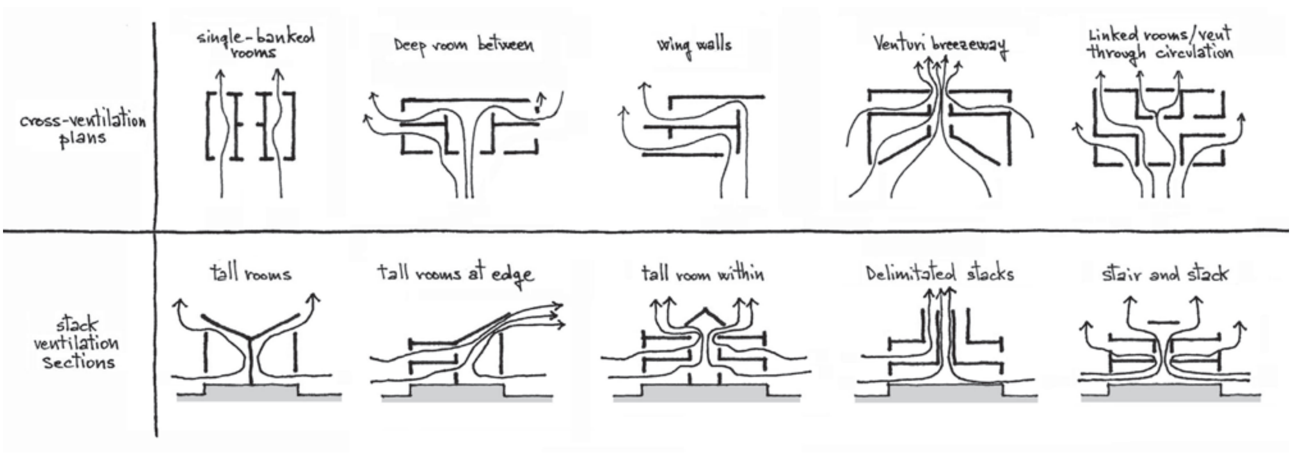


Fig. 3.5-21 – Room organisation strategies facilitating both cross and stack ventilation (Source: G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001)

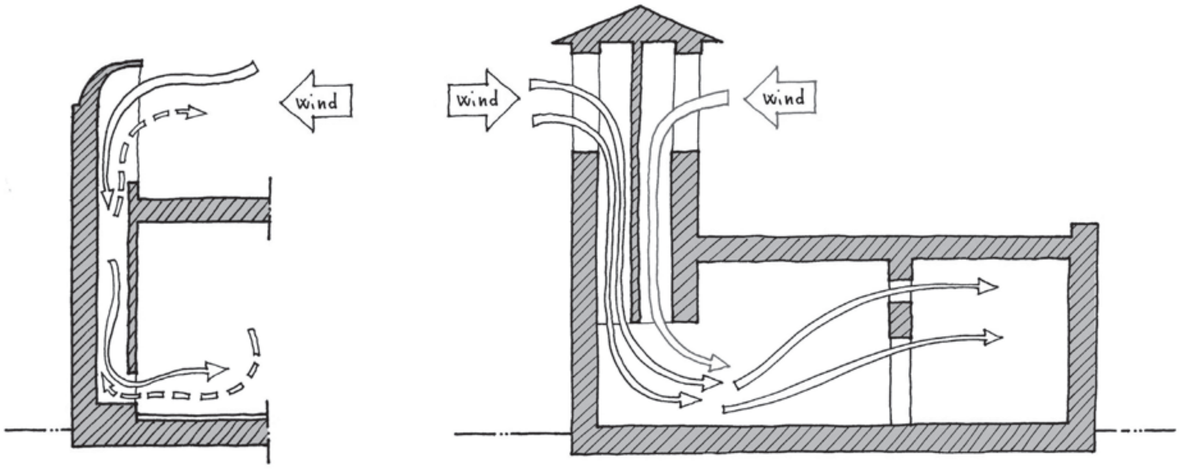


Fig. 3.5-22 – Unidirectional (left) and multidirectional (right) wind catcher

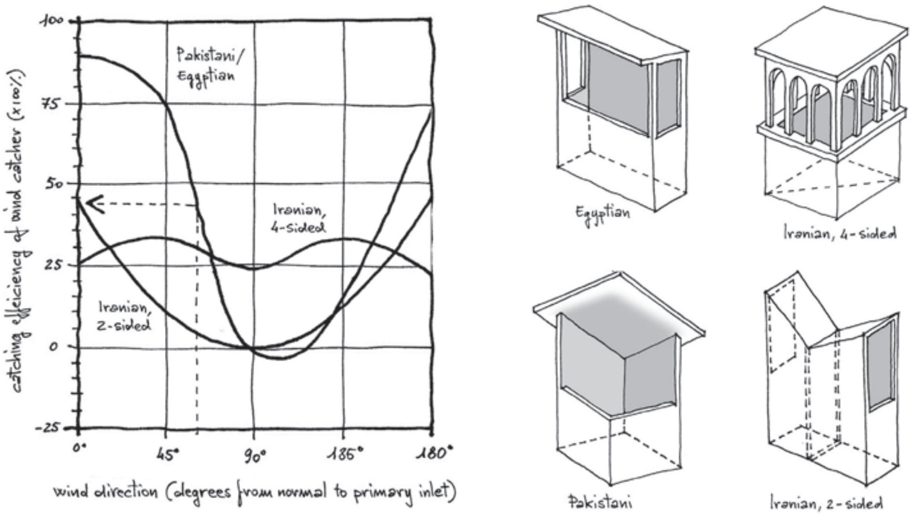


Fig. 3.5-23 – Catching efficiency for different wind catcher design (source: G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001)

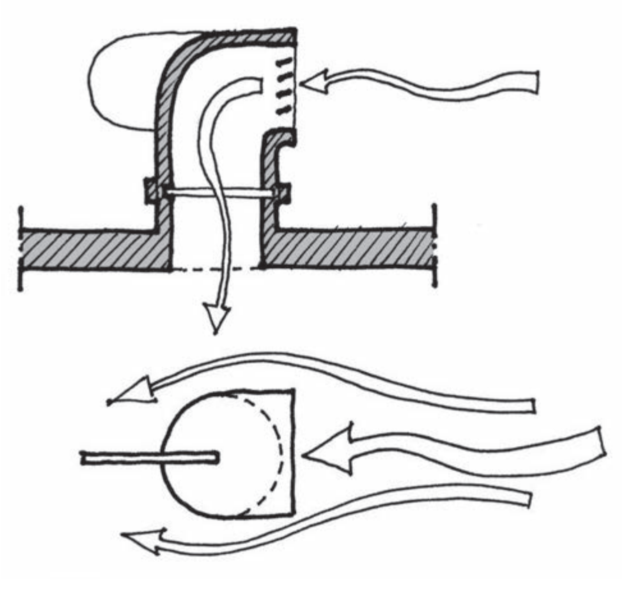


Fig. 3.5-24 – Spinning wind catcher

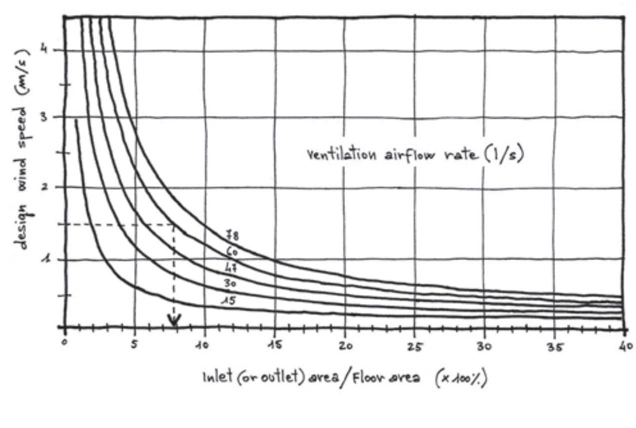


Fig. 3.5-25 – Sizing wind catchers for cooling (Source: G.Z. Brown, M. DeKay, Sun, Wind & Light, Wiley, 2001)

about twice as large as the inlets.

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.

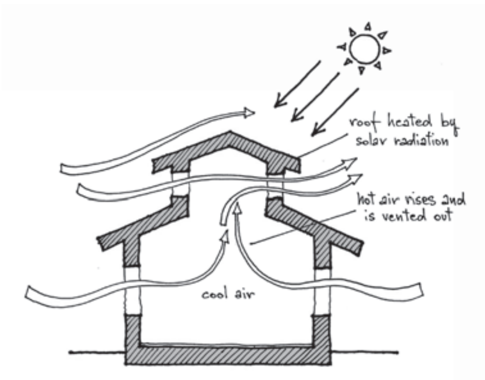


Fig. 3.5-26 – Induced ventilation: stack effect

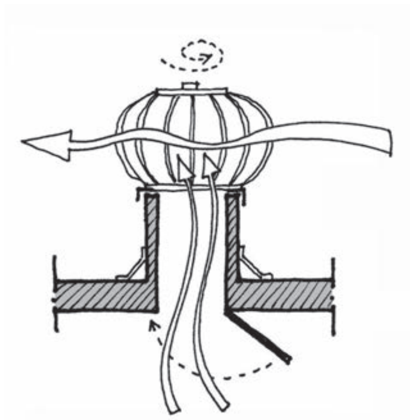


Fig. 3.5-28 – Induced ventilation: rooftop air ventilator

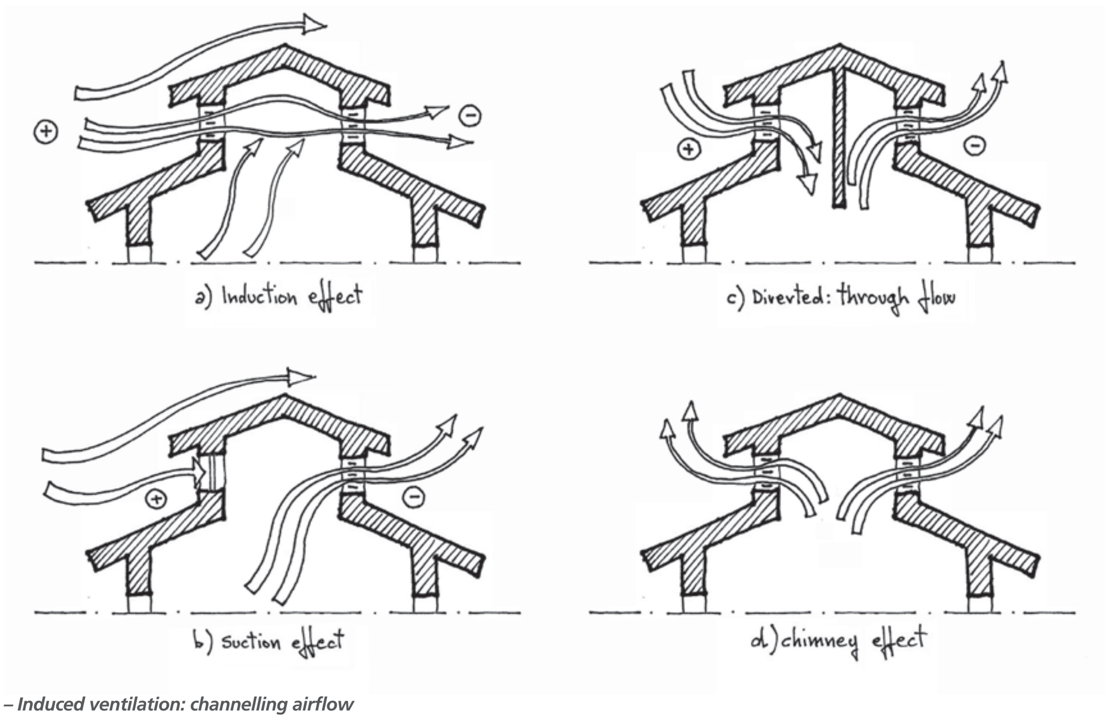


Fig. 3.5-27 – Induced ventilation: channelling airflow

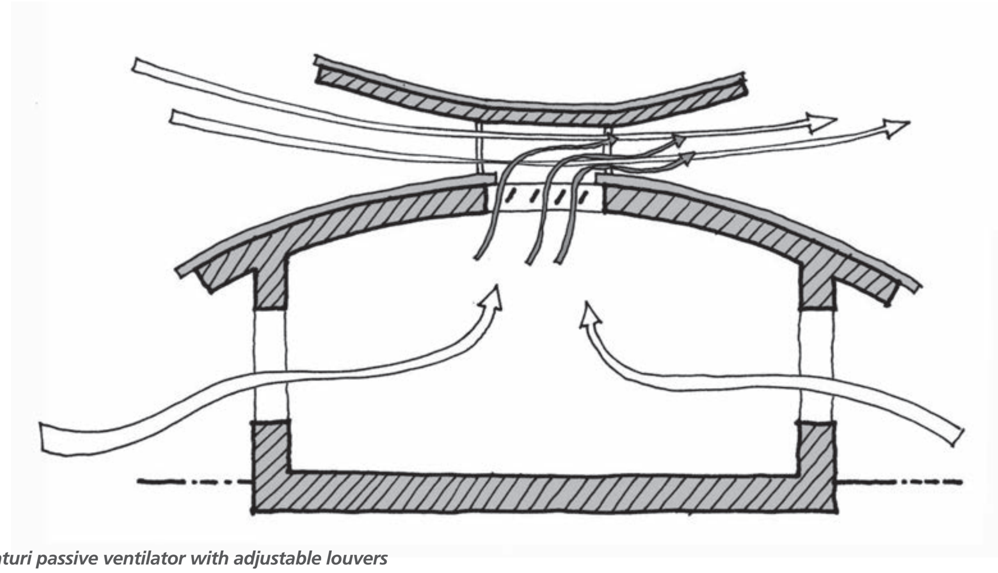


Fig. 3.5-29 – Venturi passive ventilator with adjustable louvers

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 temperate 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[5].

  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.

5 Of course, when planning the building it must be taken into account that for sills less than 1.1 m high, appropriate safety railings must be applied.

- 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.

For a more detailed discussion of the principles of lighting engineering, please refer to Appendix 2 – Principle of thermal and visual comfort, while in this section some practical design rules and tools are explained.

Sky luminance and thus passive design strategies are different depending on the specific climate.

Indoor daylighting usually depends on three components: direct sunlight, light from the sky and light reflected from external surfaces. Moreover, once the light enters the building, it is partly reflected by internal surfaces.

Direct sunlight is associated with a number of undesirable effects, such as glare, discolouration of objects and overheating. For these reasons it is rarely considered as a source of interior lighting.

The main source of daylight in the built environment is usually the sky, whose contribution is calculated through the luminance parameter.

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. Finally, in less extreme climates and especially in temperate ones, there is a more or less marked alternation between clear and overcast days, but daylighting assessments are generally made with reference to the latter, as a precautionary measure.

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 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 and 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 illuminance 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 temperate 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 protected, for example by means of shading devices, overhanging roofs, or large verandas (Fig. 3.6-2).

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 building or 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 checking later 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.

Ultimately, window design must ensure that an appropriate daylight factor is provided inside, in relation to the geometry and positioning of the openings, the type of glass used and the surrounding shading obstructions.

In a good design practice, moreover, this requirement

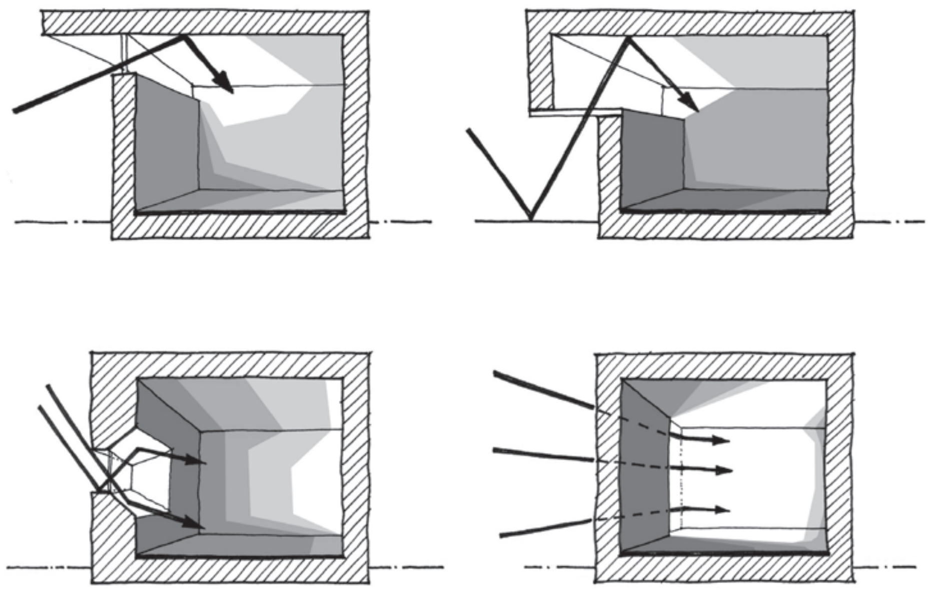


Fig. 3.6-1 – Opening types allowing the reduction of glare in a hot-arid climate

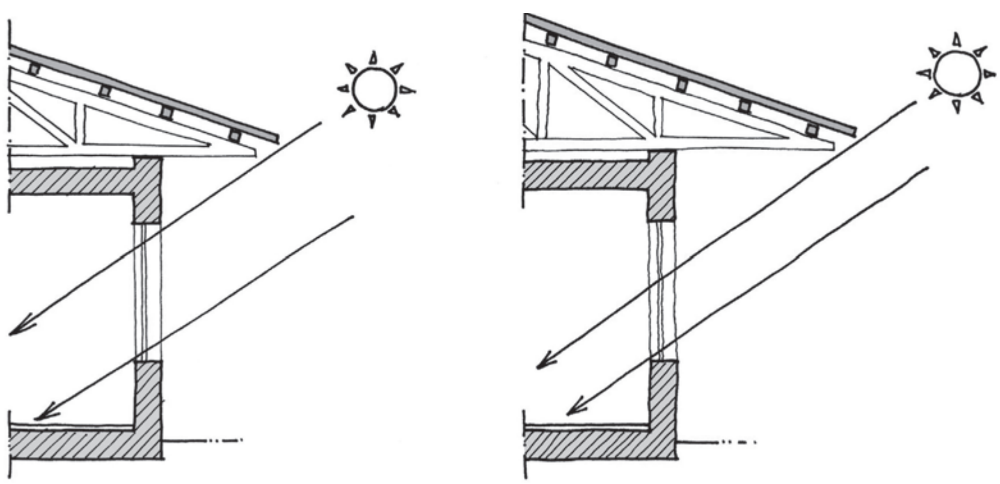


Fig. 3.6-2 – In a hot-humid climate overhanging roofs help to reduce the glare from the sky

must be harmonised with the aesthetic, architectural and visual aspects, according to an integrated and reasoned logic. This does not seem a superfluous remark, given the heavy effects that the indiscriminate use of glass in architecture over the last century has had on energy consumption and (un-)sustainability of buildings.

3.6.1.2 Checklist

A high quality integrated design is always based on specific assessments and specialised calculations, which cannot disregard the particular context, climate, building and intended use.

However, at a preliminary stage, general rules can be applied, as outlined in the following checklist.

1. Minimize the glass surfaces in the east, and especially in the west facades.

2. Keep WWR factor preferably around 0.2, and no more than 0.3-0.4, especially in particularly hot contexts.

3. Keep in mind that the most effective contribution of daylight is provided by wide windows placed close to the ceiling.

4. Choose a type of glass appropriate for the local climate, balancing the ratio of light and heat transmission.

5. Consider the application of shading elements, louvres and light shelves, preferring if possible adjustable devices that can be adapted to different conditions.

6. Provide light-coloured interior walls and finishing.

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, 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 (in order of effectiveness: only internal, only external or a combination, figure 3.6-3), 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.

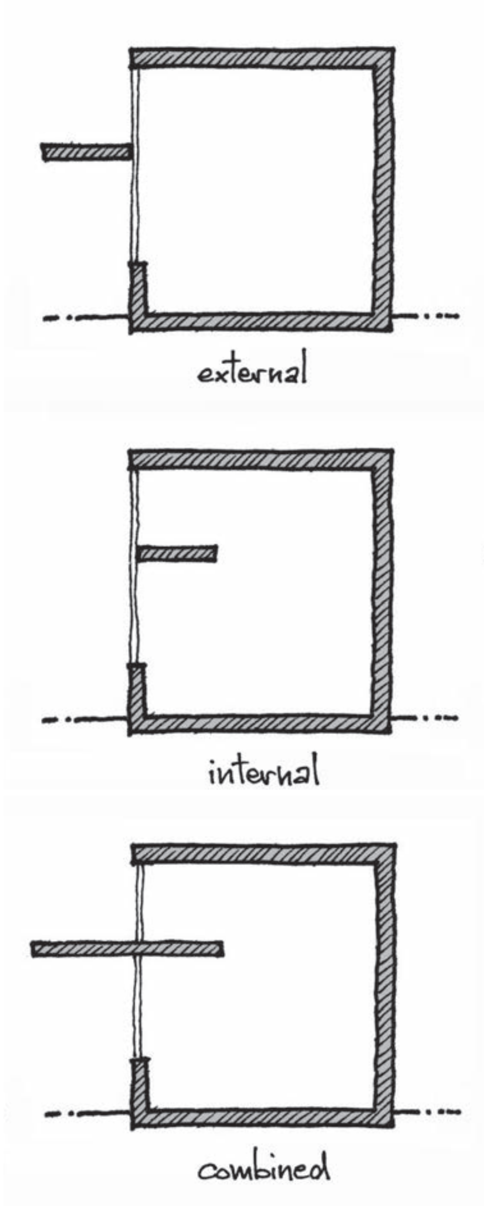


Fig. 3.6-3 – Possible positions of a light shelf

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 facades, and it varies with the orientation. In facades 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 and hence latitude, the depth of the internal light shelf may be roughly equal to the height of the ribbon window above (Fig. 3.6-4). 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. 3.6-5); 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 the direct radiation is able to penetrate the space between the light shelf and the ceiling, and then it becomes necessary to provide some additional means of shading.

At low latitudes, if the south (north) facing light shelf is tilted upwards (Fig. 3.6-6), the contribution of natural light increases, but the exterior part must be extended to provide satisfactory lower window shading. The optimum tilt angle, at latitudes near the equator depends on the ratio of X/H, according to figure 3.6-7.

The use of a light shelf - if the glass ribbon above it is appropriately sized and the depth of the internal shelf is such as to prevent direct radiation into the space - allows natural lighting to be ensured even when, to avoid glare,

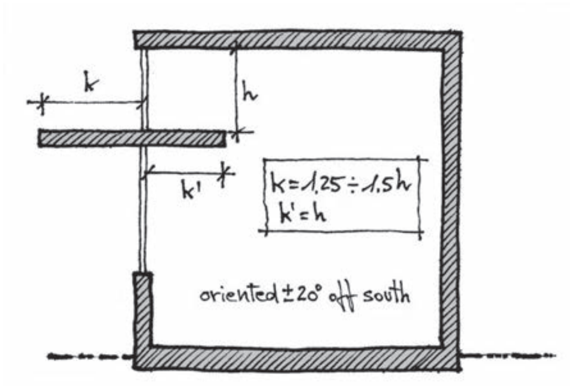


Fig. 3.6-4 – Sizing the light shelf

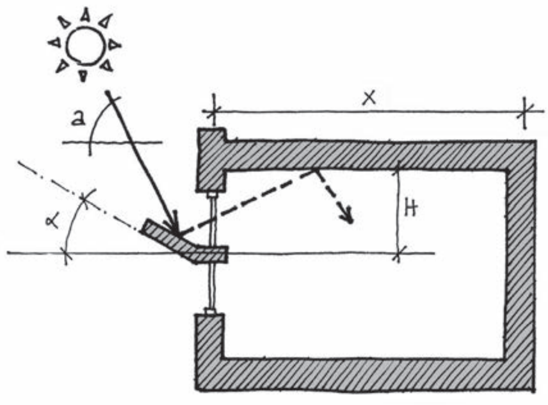


Fig. 3.6-9 – Tilted light shelf

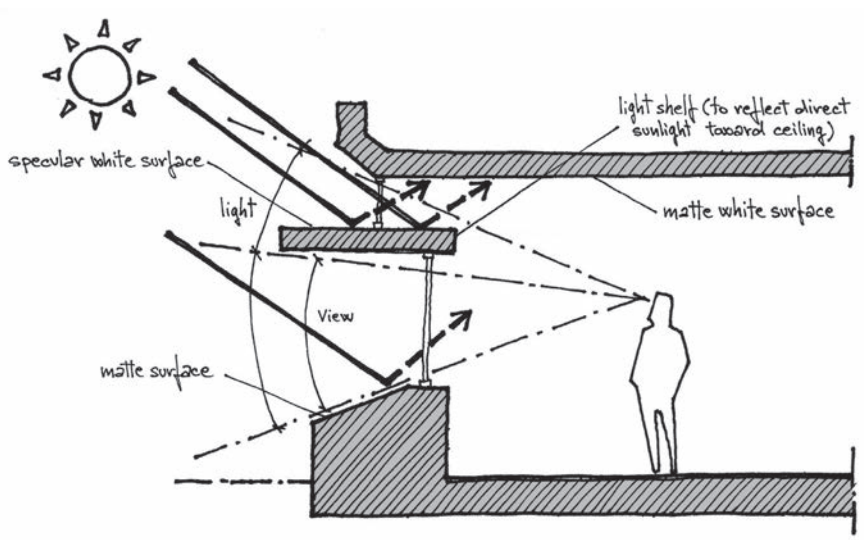


Fig. 3.6-5 – Light shelf with recessed window

the glass area below is protected with a sunscreen. For south-east or south-west (north-west or north-east) facing facades, the resulting depth of the inner shelf may be excessive; in this case a series of smaller shelves, properly spaced, can be used, (Fig. 3.6-8).

An alternative solution consists of a venetian blind with reflective, fixed or mobile, blades on the inside (Fig. 3.6-9) 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. 3.6-10). 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, in order to maximise daylight penetration.

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.

3.6.2.2 Venetian blinds with reflective blades

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. 3.6-11), and can be placed outside, inside or in the cavity of double glass. The

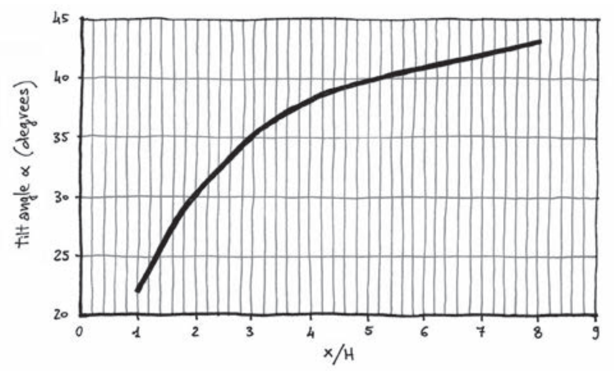


Fig. 3.6-7 – Light shelf optimum tilt angle vs, X/H

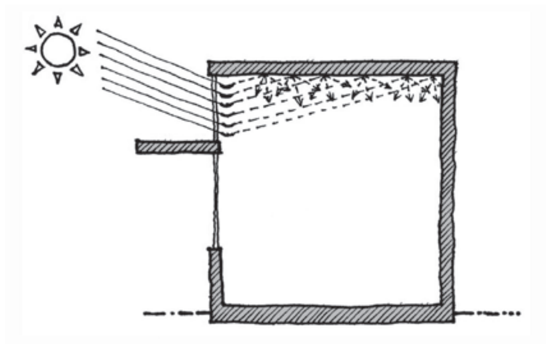


Fig. 3.6-9 – Reflecting blades instead of internal light shelf

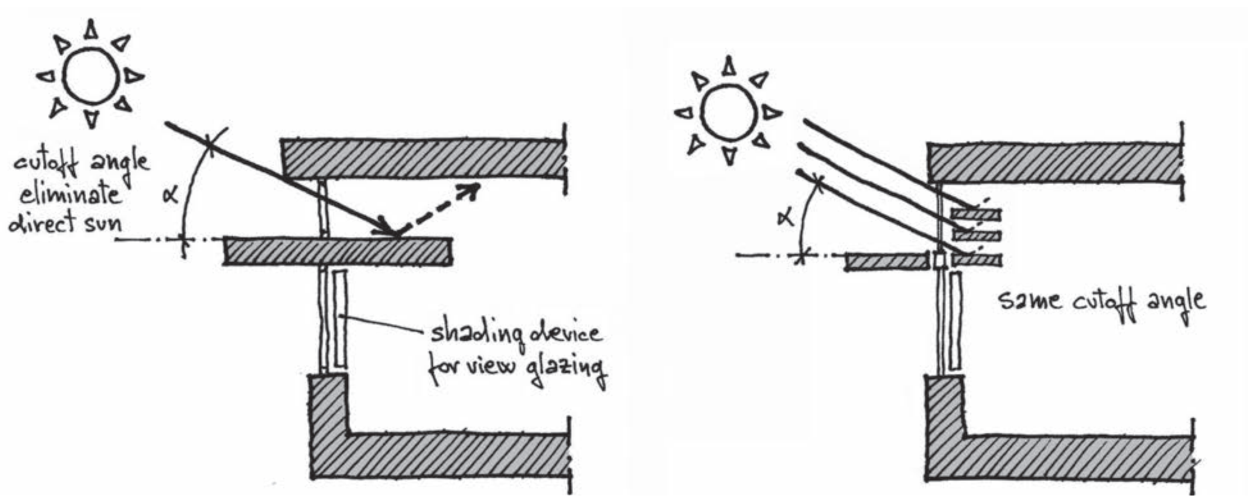


Fig. 3.6-8 – Reducing the depth of the light shelf

latter is not recommended since they become very hot and re-radiate towards the inner pane, which warms upunless low emissivity coatings are used.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, permit a reasonable level of inside illumination, and some view outside, even if they are completely shut (Fig. 3.6-12).

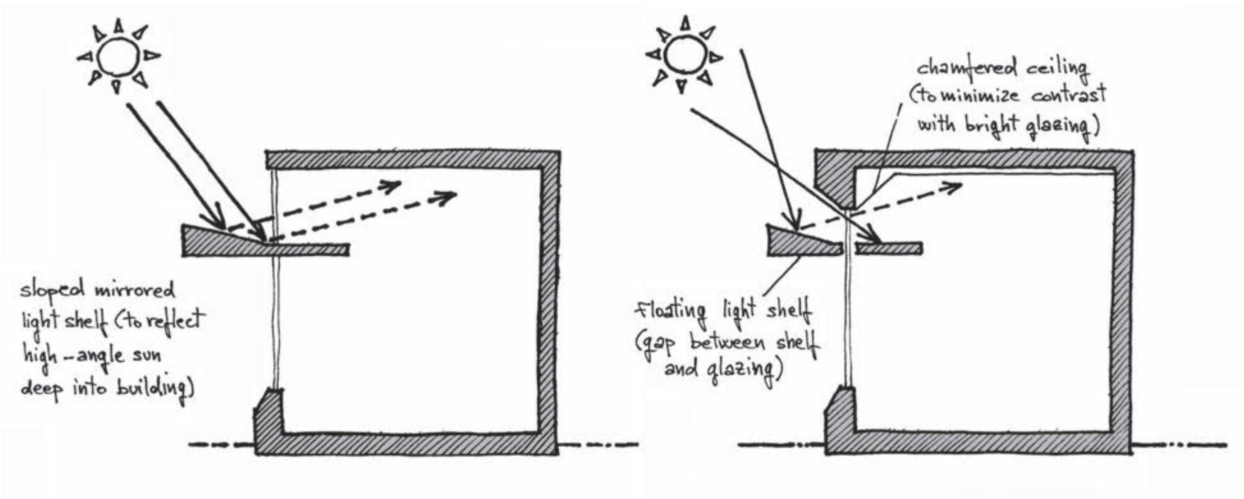


Fig. 3.6-10 – Light shelf with profiled surface

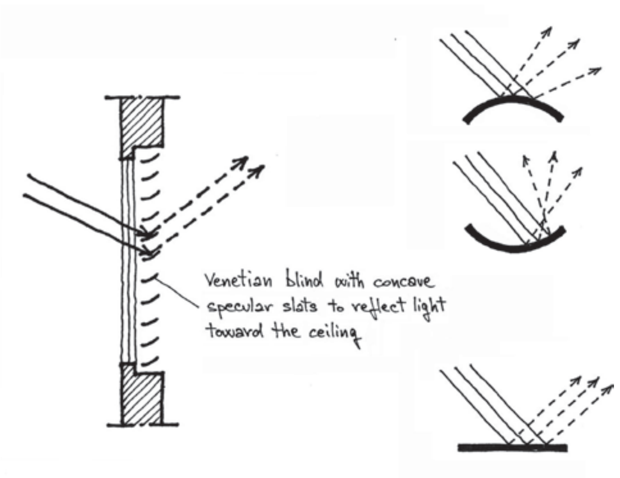


Fig. 3.6-11 – Venetians with reflective blades to redirect the light

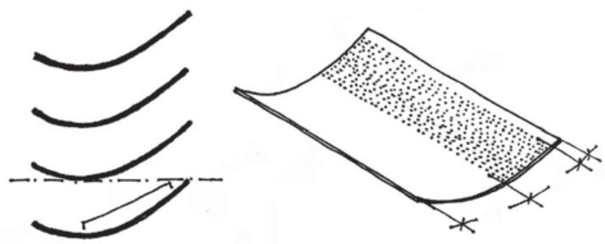


Fig. 3.6-12 – Adjustable reflective perforated slats

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. In this sense, the application of shading systems and their correct positioning and sizing are crucial to avoid overheating of buildings in hot climates and seasons.

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 surrounding 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).

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;

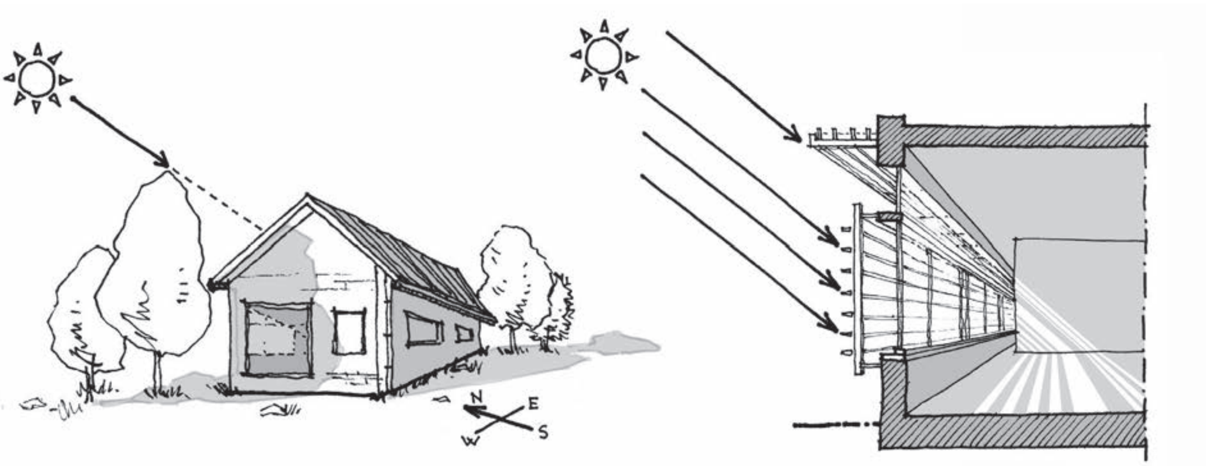


Fig. 3.7-1 – Shadows cast by the context and by elements of the building

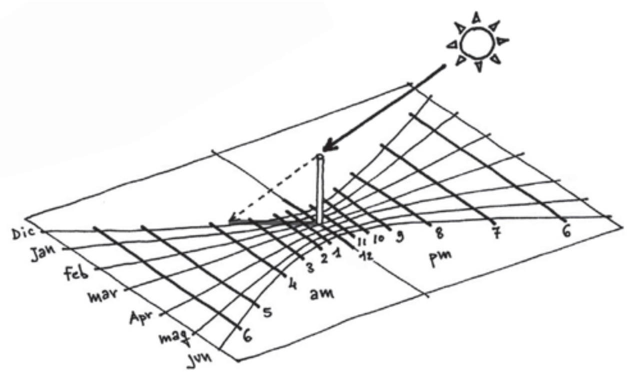


Fig. 3.7-2 – Peg's shadow cast on a sundial

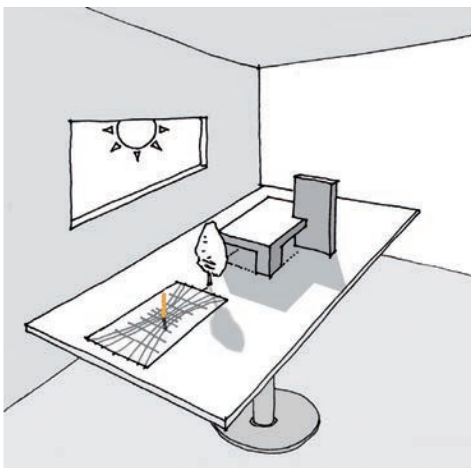


Fig. 3.7-3 – Example of application of sundial method

• 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.

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.

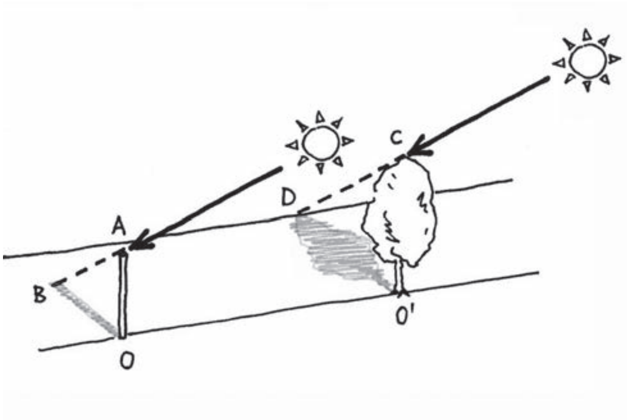


Fig. 3.7-4 – Evaluation of shadows cast by objects using the sundial

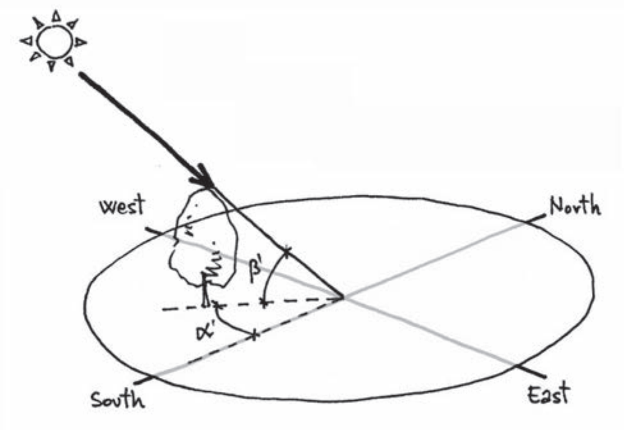


Fig. 3.7-5 – Angular coordinates of a shading obstruction

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).

Sundials for latitudes between 5N and 11S are provided in Appendix 3.

3.7.2 Shading masks

Solar path diagrams (see paragraph 2.1.1.2) 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.

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).

This method makes it possible to work on even a large context, while a similar tool has been developed to carry out analyses at a more detailed scale on buildings' facades, enabling us to study the effects of sunshades, overhangs and fins: the solar shading protractor (Fig. 3.7-7)

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.

• 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

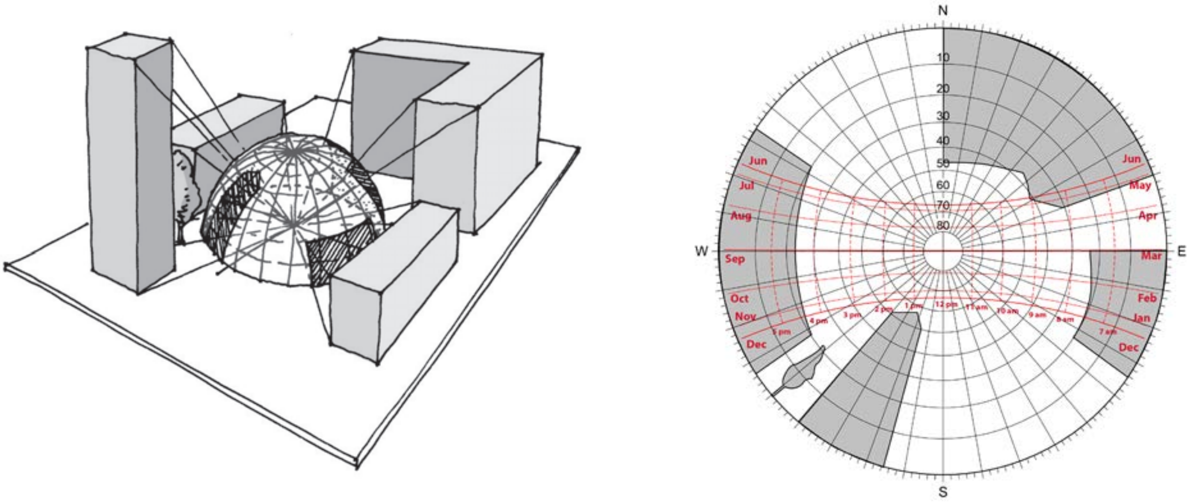


Fig. 3.7-6 – Shading obstructions profiles on the polar diagram

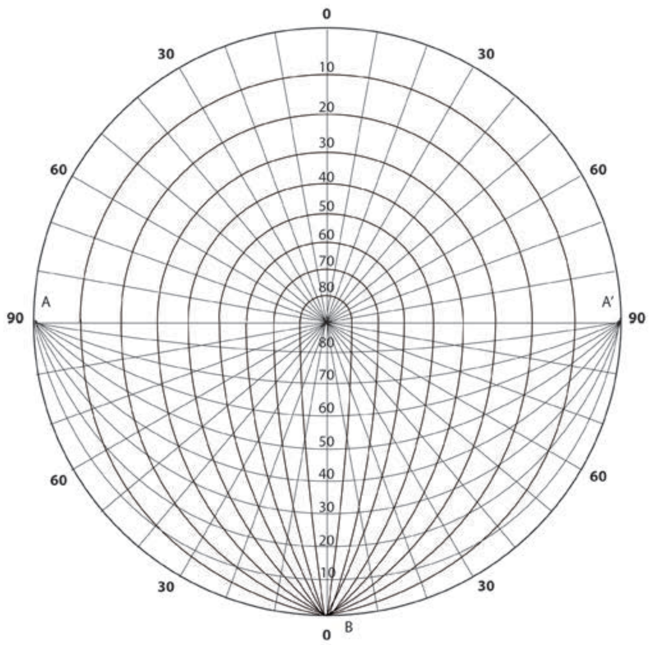


Fig. 3.7-7 – Solar shading protractor

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.

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.

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 facade 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 facades 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 facade. 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.

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).

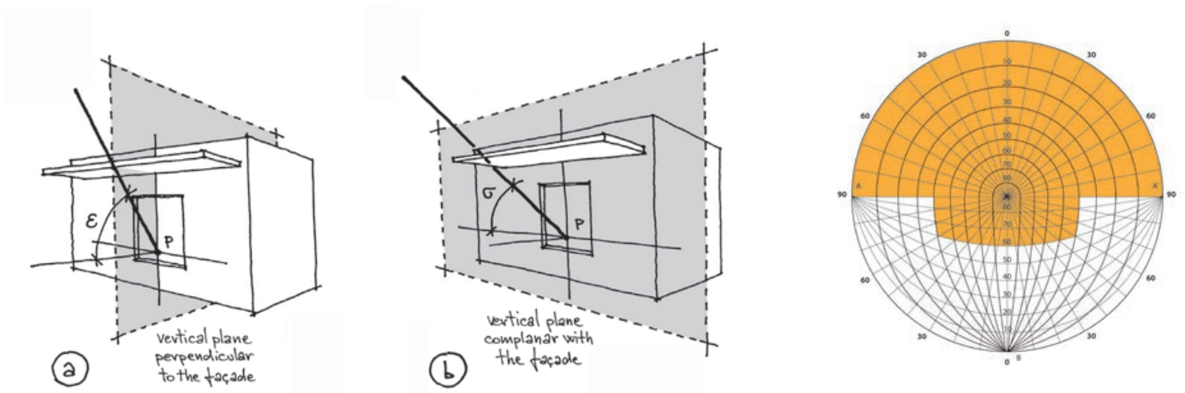


Fig. 3.7-8 – Construction of the shading mask for a horizontal overhang

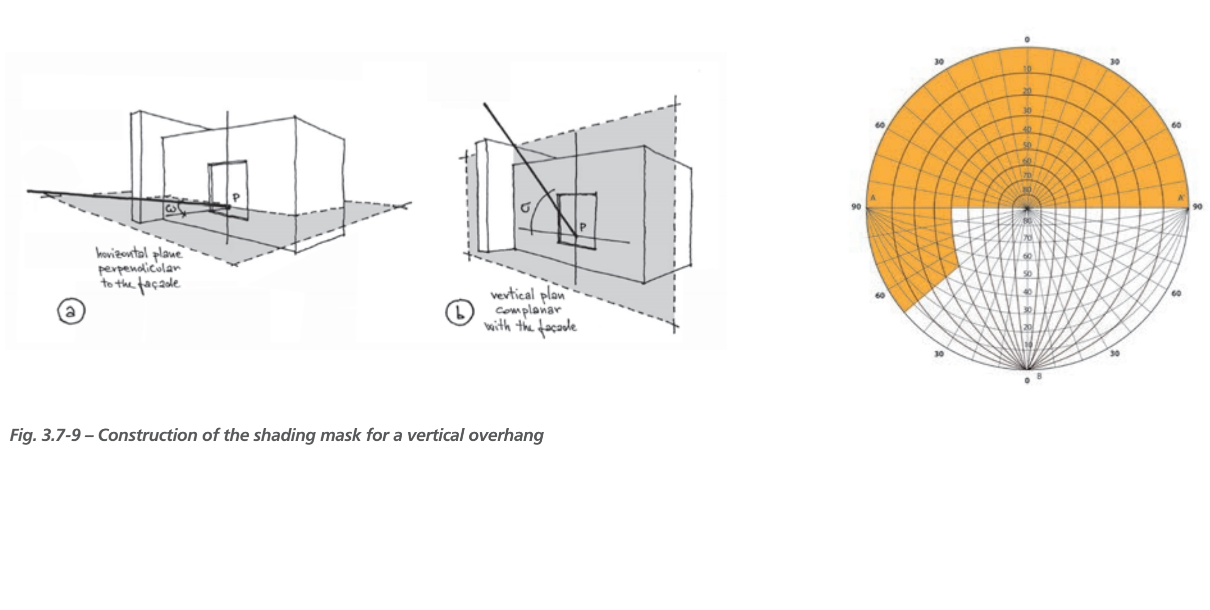


Fig. 3.7-9 – Construction of the shading mask for a vertical overhang

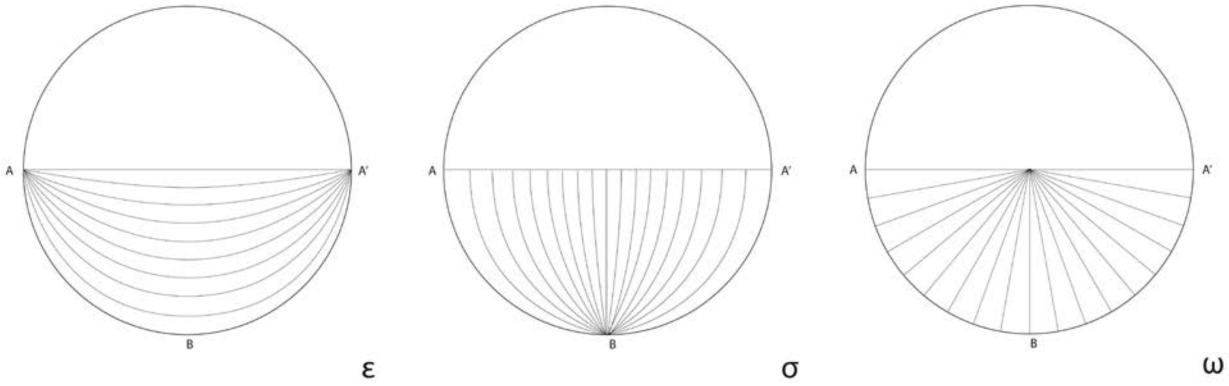


Fig. 3.7-10 – Construction lines of ε, σ and ω

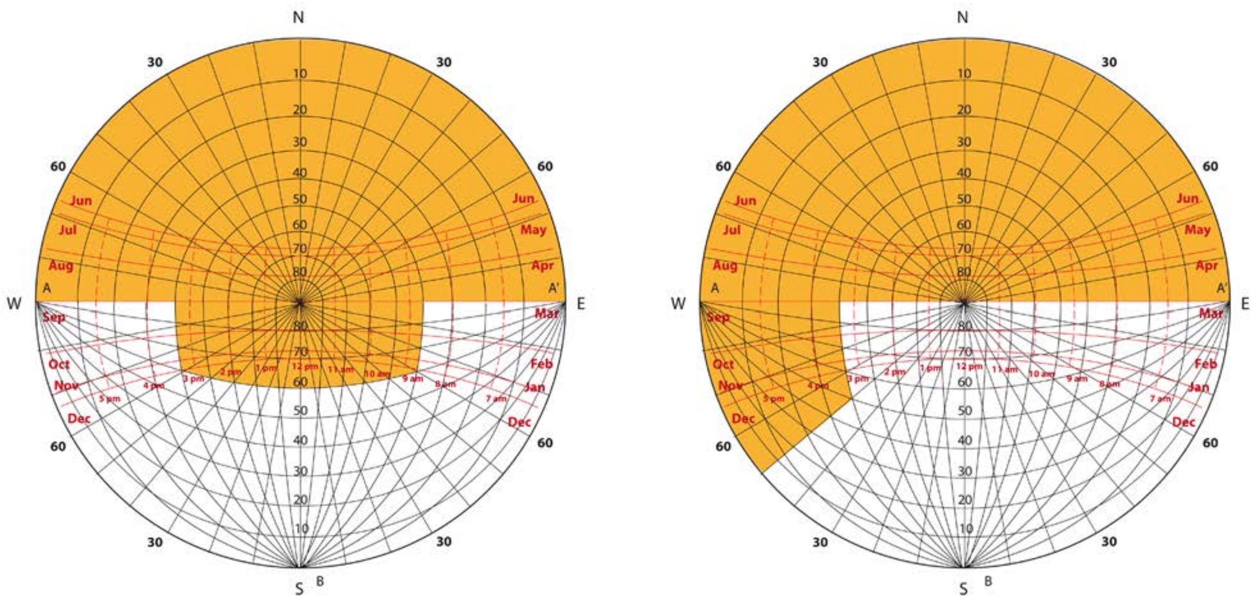


Fig. 3.7-11 – Overlaying the shading masks on the polar diagram

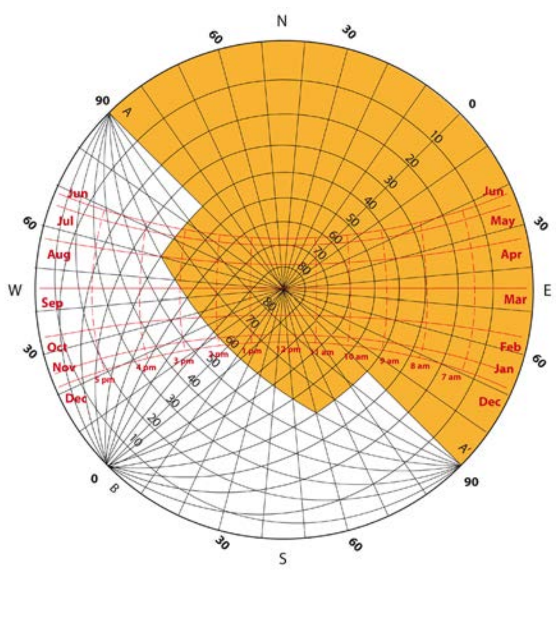


Fig. 3.7-12 – Orientation of the shading mask

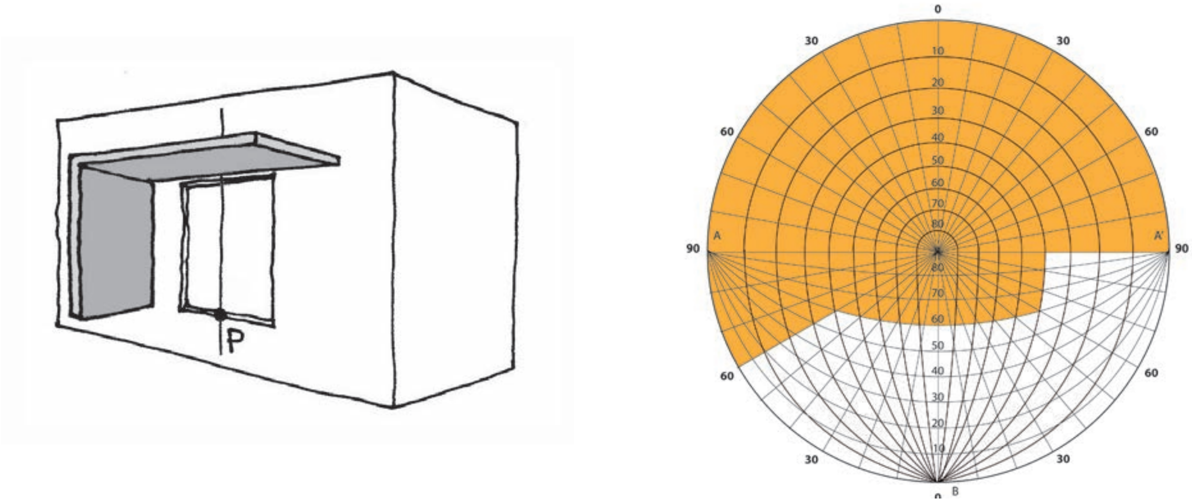


Fig. 3.7-13 – Sample of shading mask for a vertical and horizontal overhang

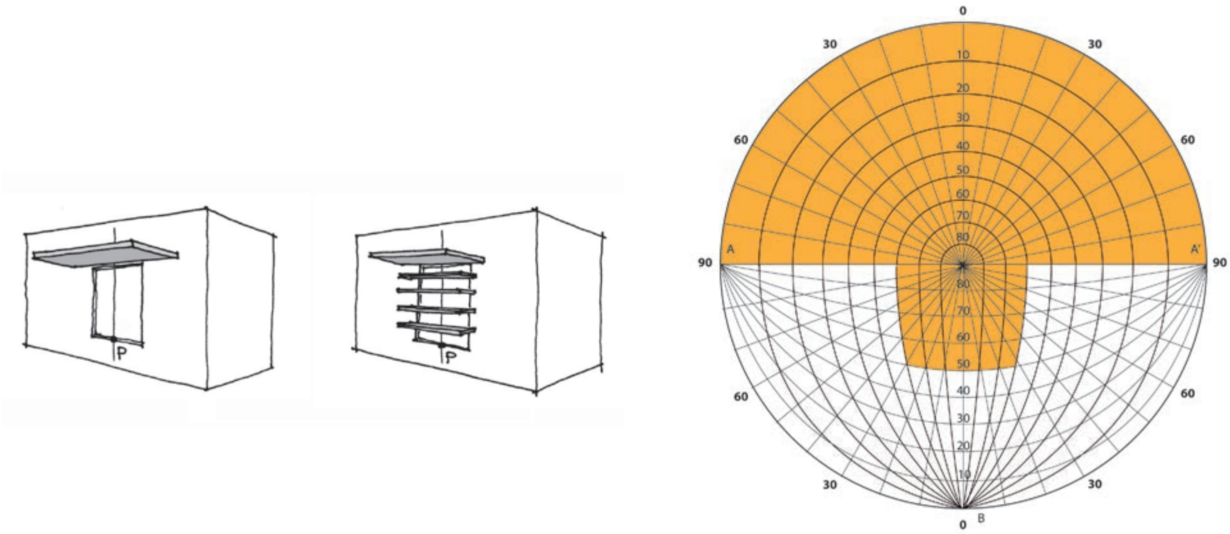


Fig. 3.7-14 – The same shading mask could be used both for a single overhang and for a series of blades

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 (e. g. the window), 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.

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).

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, louvers 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 facade 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 facade at different times of day.

As the sun is generally high in the sky at African latitudes during hottest periods, horizontal shading devices are the optimal choice for north and south-facing facades. Horizontal overhangs located above the windows on the north and south-facing facades 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.

East and west-facing facades 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, especially in tropical climates.

In any case, movable systems, although generally more expensive, prove to be more flexible and dynamic and can be applied in virtually all conditions.

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).

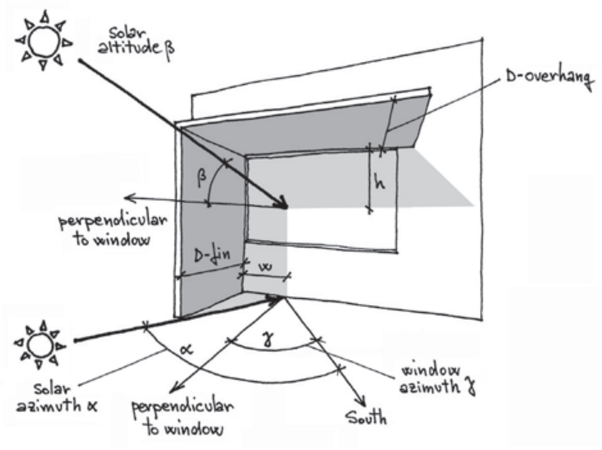


Fig. 3.7-16 – Solar protection types

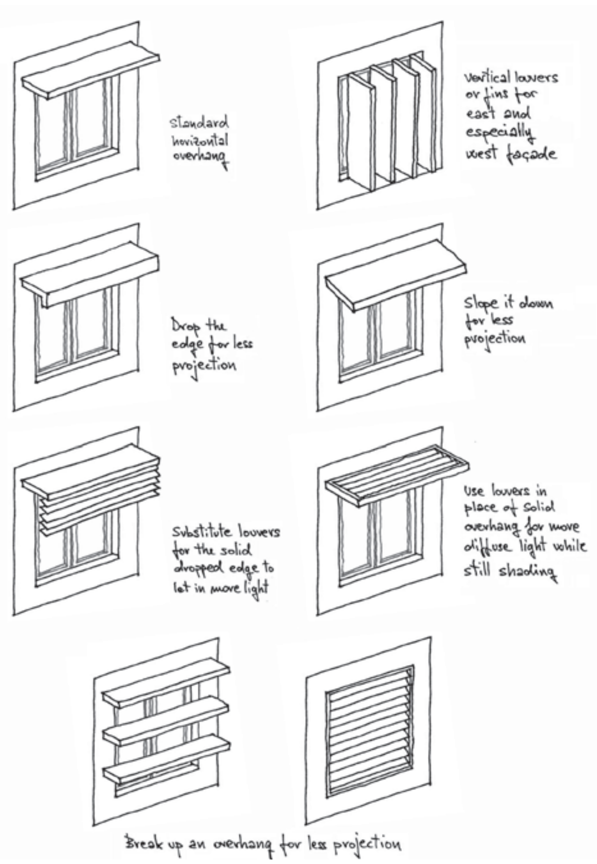


Fig. 3.7-16 – Solar protection types

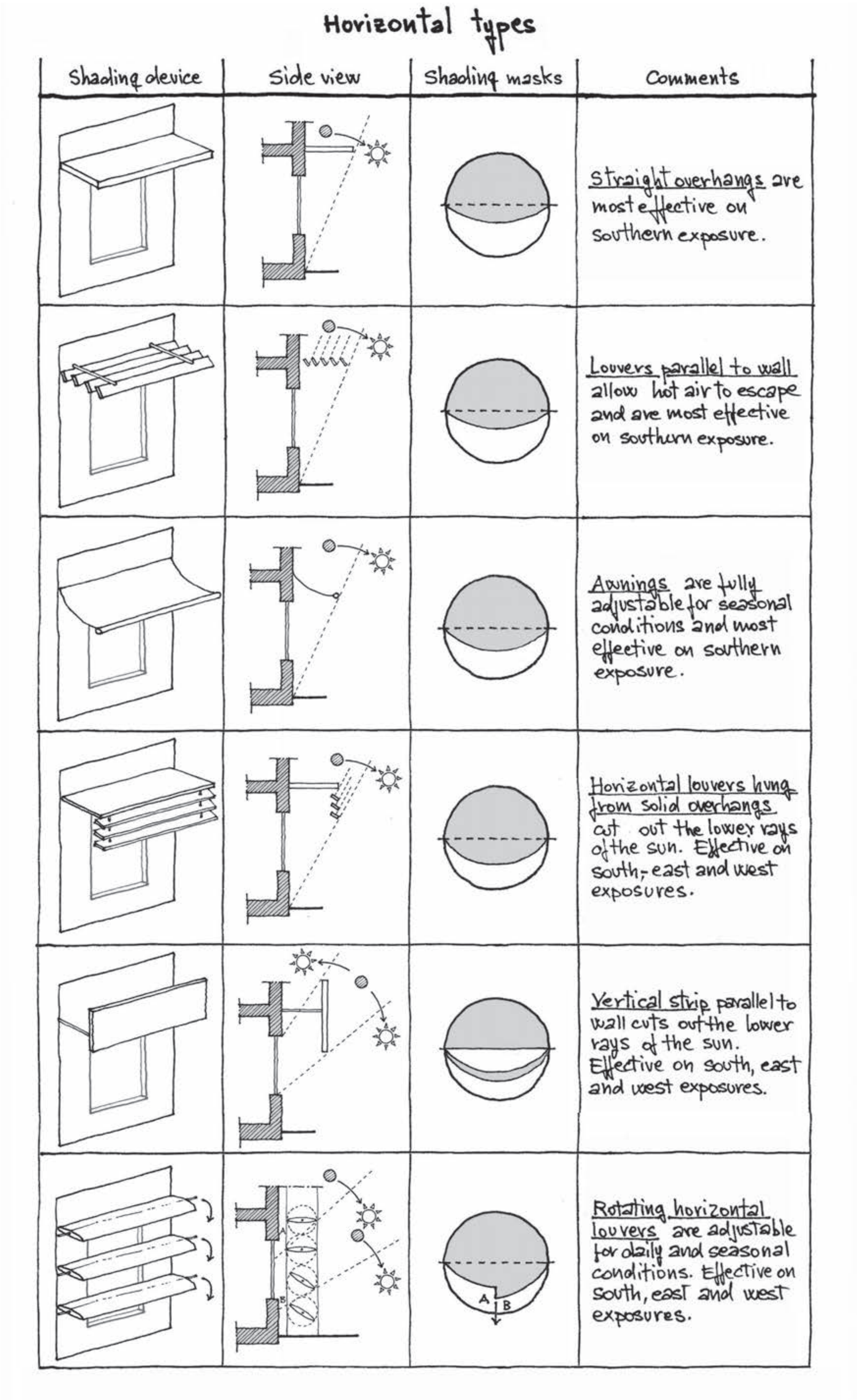
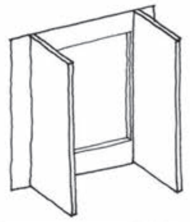
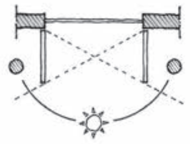
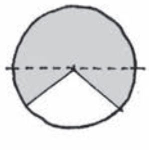
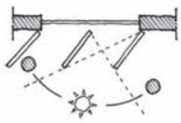
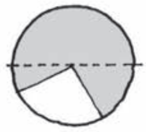
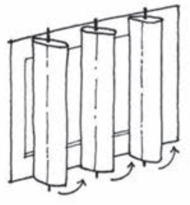
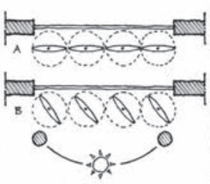
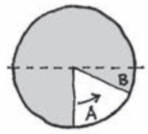


Table 3.7-1 – Characteristics of different types of shading devices

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

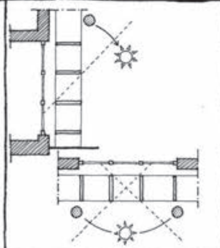
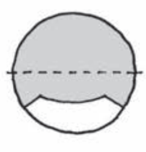
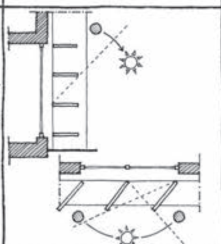
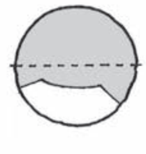
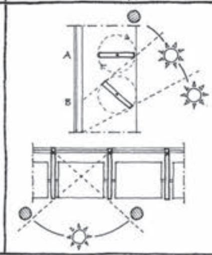
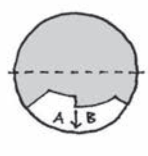
Shading device	Plan & side view	Shading masks	Comments
			Eggcrate types are combinations of horizontal and vertical types. Most effective in hot climates on east and west exposures.
			Eggcrate with slanted vertical fins (slant toward north). Most effective in hot climates on east and west exposures.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

Table 3.7-1 (continued) – Characteristics of different types of shading devices

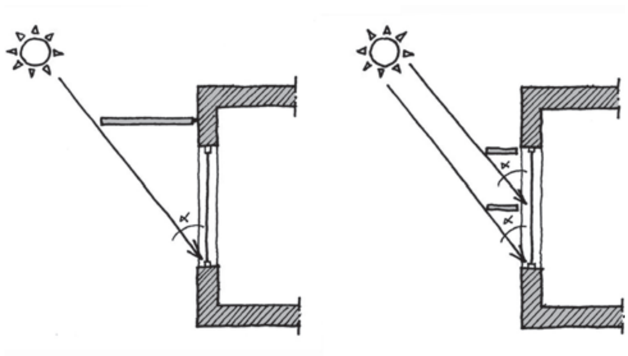


Fig. 3.7-17 – Single or multiple horizontal solar protection of a window (section). The shading effect is a function of the angle α. It is not a function of the actual size

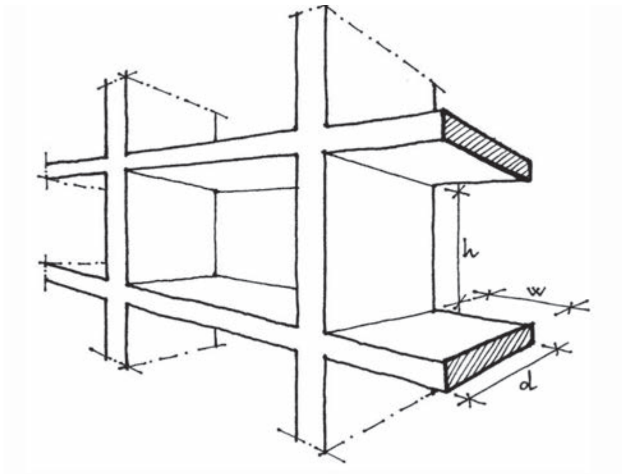


Fig. 3.7-18 – The shading effect is a function of the ratios h/d and w/d. It is not a function of the actual size

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 fixed systems if the budget is limited, but bear in mind that mobile systems allow for a more efficient use of natural light and natural ventilation. Take also 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.

- Prioritize shading of windows facing east and – especially – west.

- Use horizontal elements for openings facing south and north.

- Use egg-crate or vertical or movable elements on windows facing east and 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 and low IR emissivity because, being heated by solar radiation, they became hot and re-radiate towards the interior space, heating it up.

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 night-time, 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[1]. Alternatively, the evaporative cooling principle can be exploited as shown in the 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.

1 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.

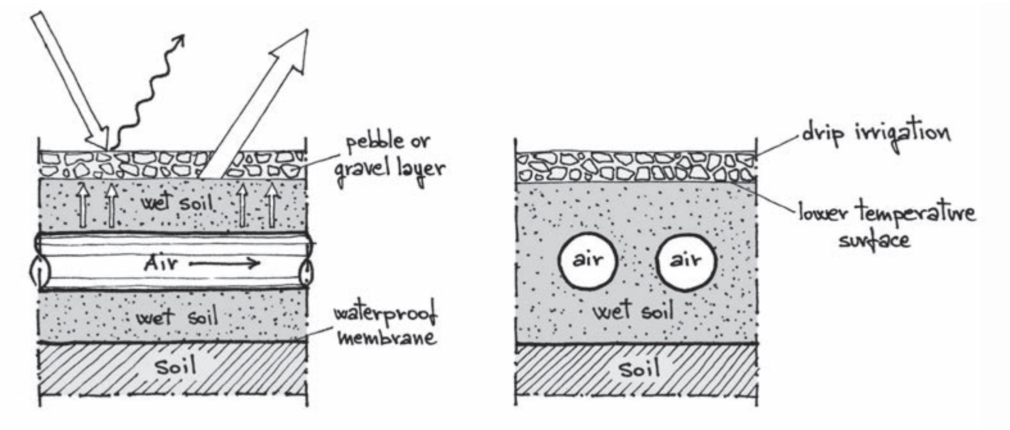


Fig. 3.8-1 – Soil treatment with wetted pebbles (Source: S. Alvarez Dominguez et al., Control climatico en espacios abiertos, Ciemat, 1992)

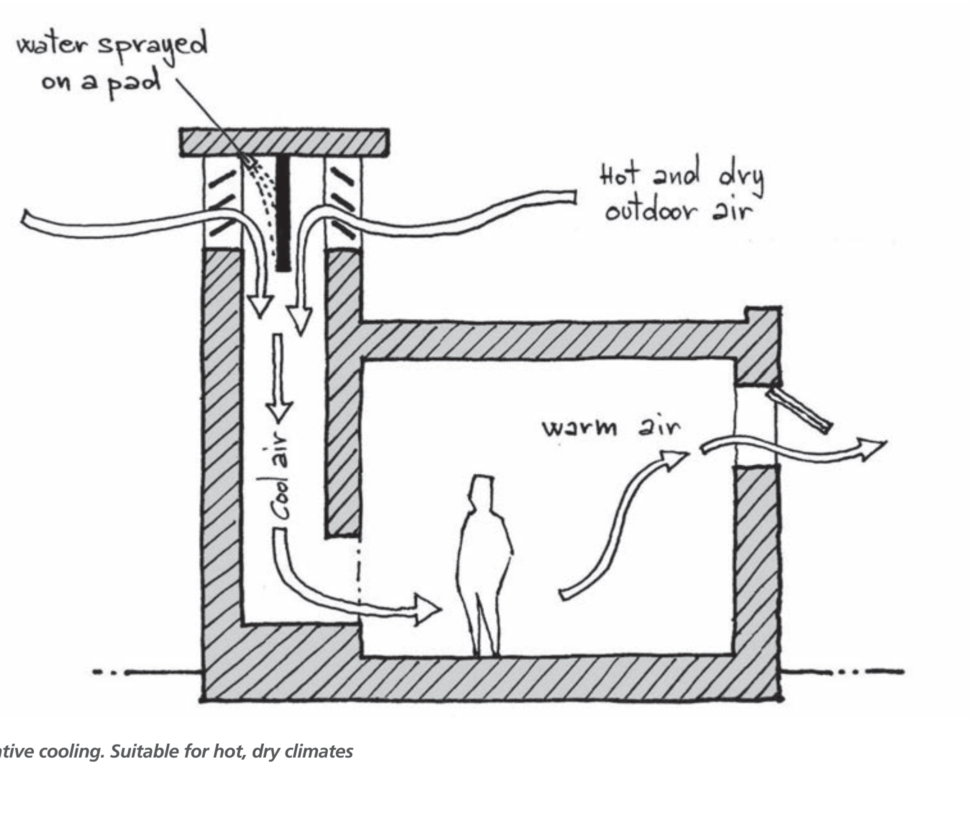


Fig. 3.8-2 – Evaporative cooling. Suitable for hot, dry climates

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 the 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 shown in the figure 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[2].

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%).

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

2 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).

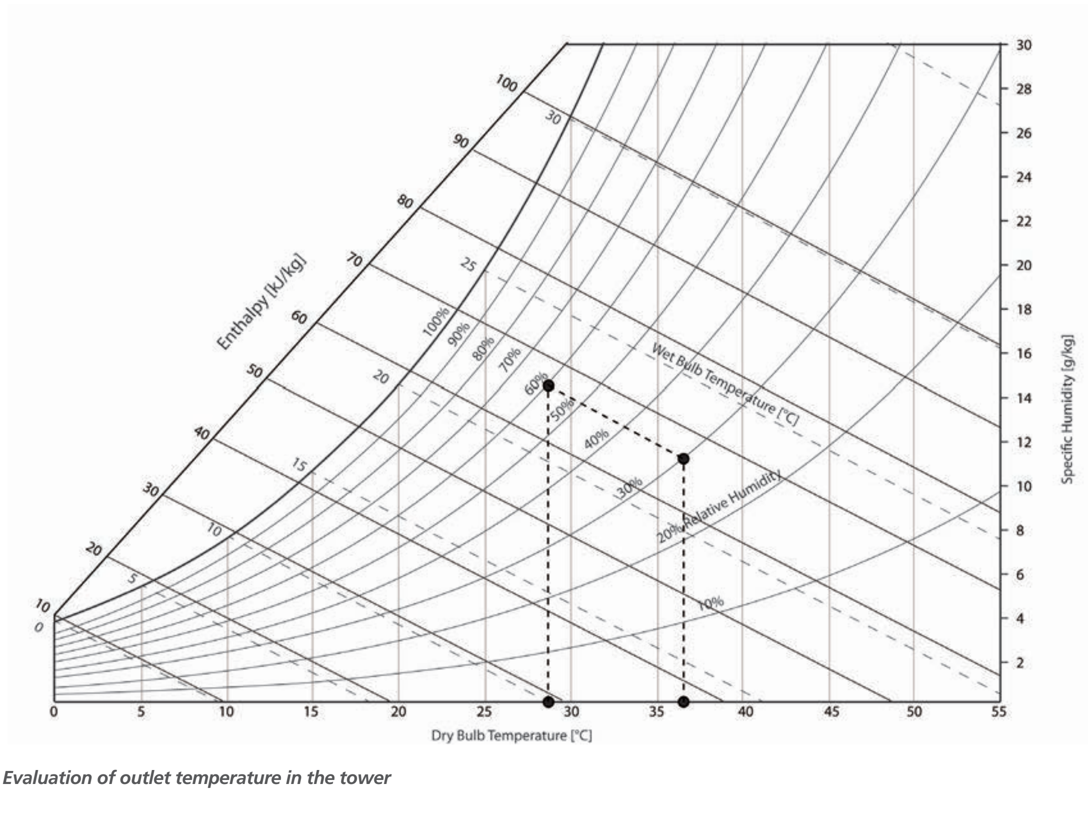


Fig. 3.8-3 – Evaluation of outlet temperature in the tower

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 a too high 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 4.2.1 HVAC System types and features).

Fig. 3.8-4 – Zion National Park Visitor Center (left) and cooling tower outlet (right)

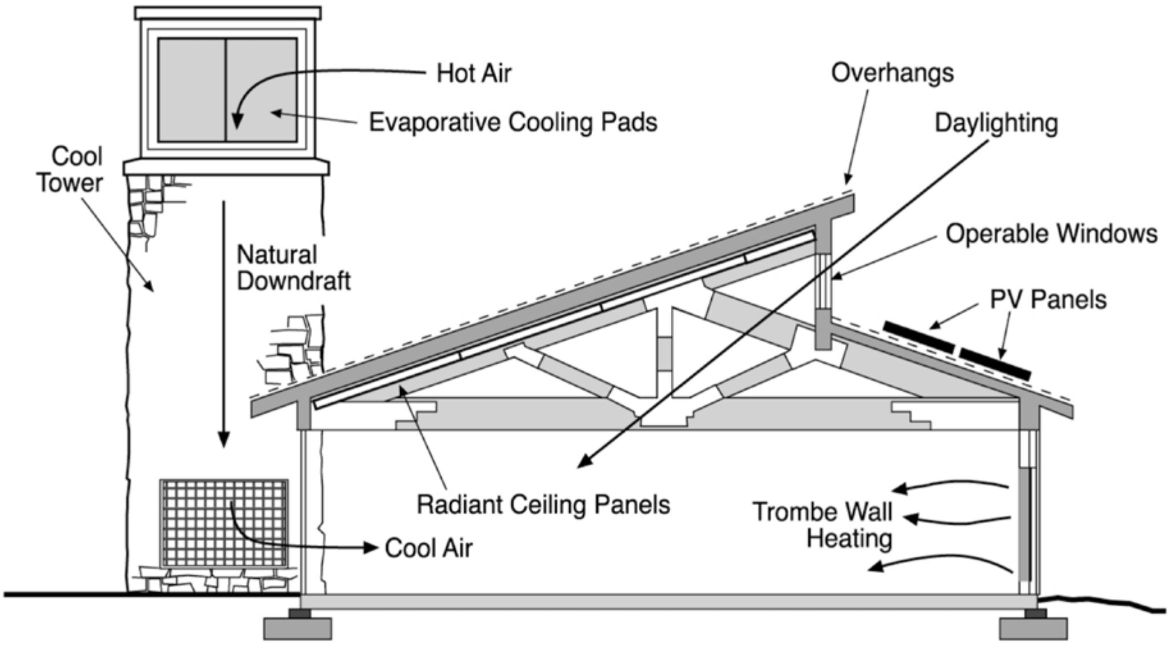


Fig. 3.8-5 – Cross Section of the Building Showing Integrated Design Strategies

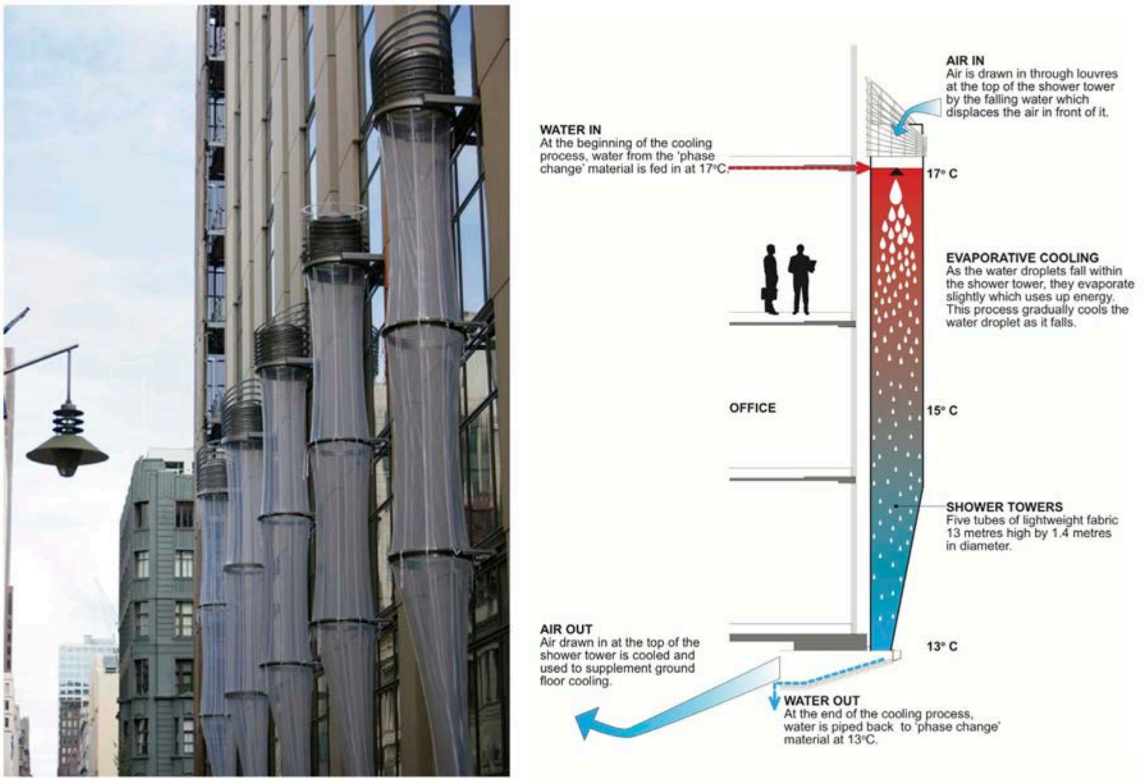


Fig. 3.8-6 – Council House 2 Cooling towers

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

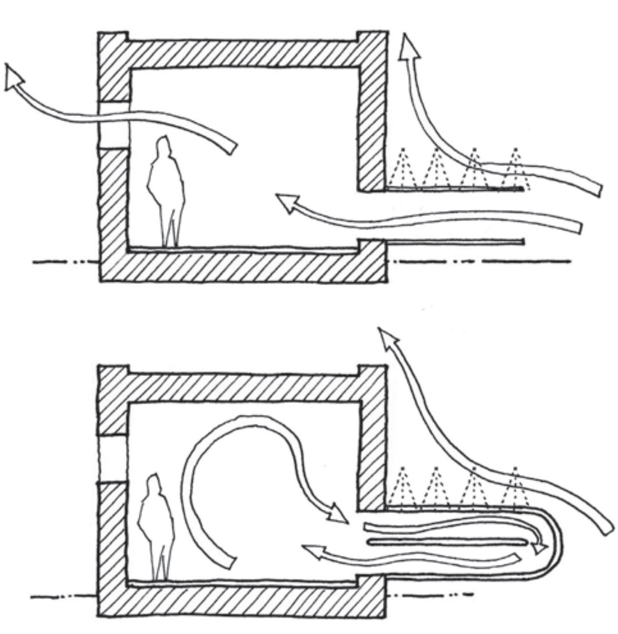


Fig. 3.8-7 – Principle of indirect evaporative cooling; a) open circuit; b) closed circuit

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. The 3.8-1 and 3.8-2 tables can be used to size ceiling fans.

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 3.8-1 – Fan diameter in function of the largest dimension of the room

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.

Room area [m^2]	Minimum fan diameter [cm]
10	90
10-20	120
20-30	140
30-40	160
> 40	Two fans

Table 3.8-2 – Fan diameter in function of space area

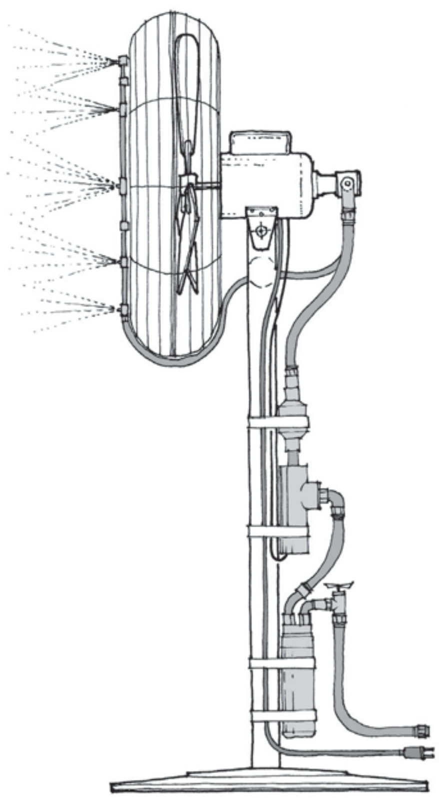


Fig. 3.8-8 – Typical misting fan

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. Such choice should be embraces the circular economy principles, mainly arise as the 3Rs principle, that can be summarized as Reduce; Reuse, and Recycle. "Reduce" point out to the action of decreasing the inputs (primary energy and raw materials) and outputs (wastes). "Reuse" means "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" and finally "Recycle" implies "any recovery operation by which waste materials are reprocessed into products, materials

or substances whether for the original or other purposes. Of course, it should be noted that the 3Rs principle follows a "hierarchical importance", as the action of "reducing" comes first as the main principle: the proper approach to reach material efficiency and generate benefits in both economic and environmental is to give priority to the "Reduction" and "Reuse" of waste. In such respect 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. In such respect, in the next paragraph, two alternative materials that combine tradition and innovation, in order to reduce costs and energy consumption are described.

3.9.1.1 Interlocking Stabilised-Soil Brick (ISSB) Technology[1]

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.

Recently a Tanzanian brick has been introduced, whose shape lies – in complexity – between the Hydroform and the Bamba bricks (Fig. 3.9-3).

3.9.1.2 Precasted hempcrete brick

Hempcrete is a construction material made from hemp fibres, lime and water. This composite can be precasted in order to obtain characterized by good thermal and acoustic-insulation properties.

Hempcrete block is a building product incorporating a large fraction of biomass, with a good performance in thermal and hygrometric regulation. The base of the binder can be hydrated lime, natural hydraulic lime or a mixture of the two. In some cases, a small fraction of cement and/ or pozzolanic binder is added to speed up the hardening process and improve the mechanical resistance. Hydrated lime is made from pure limestone and sets through the absorption of CO_2 during the carbonation process. Hydraulic lime is made from limestone with clay impurities (silicates and aluminates) and sets through reaction with water. These processes transform the mixtures into final

1 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/

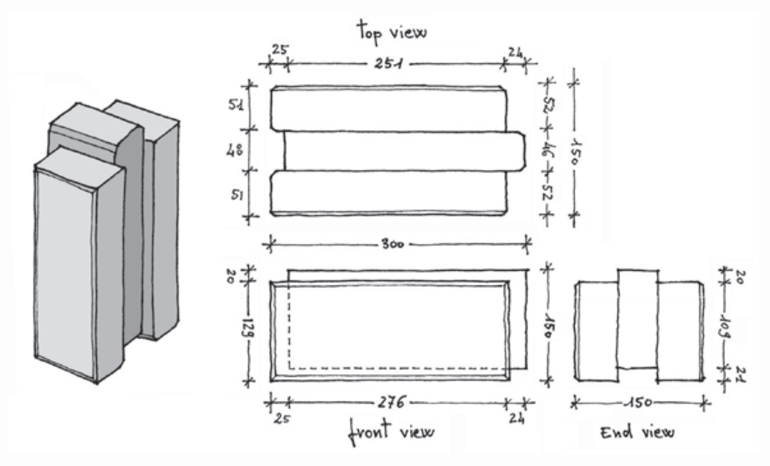


Fig. 3.9-1 – Hydraform system

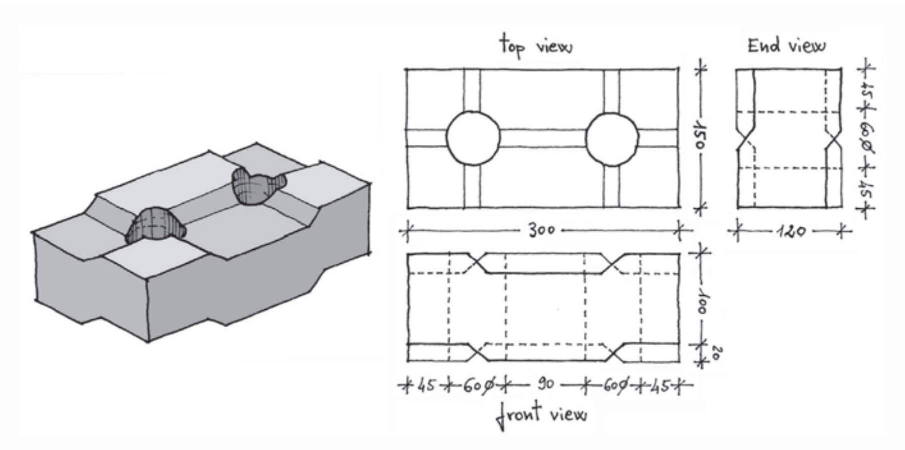


Fig. 3.9-2 – Bamba brick

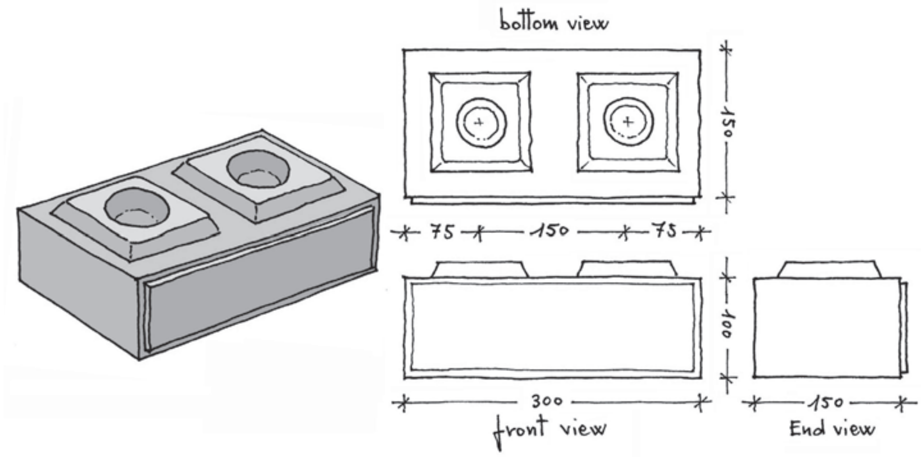


Fig. 3.9-3 - Tanzanian brick

products that are solid but light, durable and with good insulation performances. Hemp, as any crop, is considered a carbon negative material, because during its growth it absorbs CO_2 from the atmosphere. In addition, the CO_2 captured from the air via carbonation will be stored into the hempcrete block throughout its lifetime and may further improve its environmental profile.

When used in constructions, hempcrete mixtures can easily absorb or release water vapour from the air and have a good vapour permeability. These features allow a better control of thermo-hygrometric conditions in the indoor environment, decrease the risk of vapour condensation and increase thermal comfort. Thanks to the action of lime, hemp shives slowly mineralize, becoming inert and reducing the risks of rot and mould formation. The performances and properties of hempcrete materials depend on the binder, on the quality and length of the hemp shives and on their proportions in the mixtures. Different mixtures produce building materials with different functions. In frame structures, hempcrete mixtures can be used as filling materials in infill walls. If density is increased, the hempcrete mixture allows the production of roof or floor insulation materials; on the other hand, if density is reduced, insulating indoor and outdoor plasters can be produced (Fig.3.9-4).

Hempcrete block is an interesting product that can be very easily installed, generally requiring mortar to be applied between the blocks. Hempcrete block walls can be left without any covering or can be covered with finishing plasters, using the same mixture in different proportions. Blocks can be manufactured on the construction site or through an industrial process. Industrial blocks usually have more regular dimensions and a higher quality thanks to an automated manufacturing process and to the employment of more complex mixtures.

The installation of rectangular shaped blocks needs staggered and keyed joints, as with other masonry structures (Fig3.9-5). Furthermore, since a vegetal component is included in the mixture, the blocks must be protected from water and rising damp. The joints between the wall and the ground are therefore designed in order to avoid capillary rising as well as water runoff at the wall base. For the same reason, hempcrete blocks are to be installed above the ground level. External walls should be protected by the rain gale with sand and lime plasters in order to avoid rotting of shives.

Blocks are normally self-supporting. As an alternative, it is possible to produce lighter blocks with better thermo-acoustic performances that can equal those of loose mixtures (1:1 binder-to-hemp mass ratio). Lighter blocks need to be installed in a frame structure. Typically, hempcrete blocks are inserted into wood frames, but they can be used also in metal or reinforced concrete structures. Internal partitions made with hempcrete blocks need to be carefully jointed with the external walls. They will normally be thicker than typical internal brick walls (at least 15 cm instead of 8–10 cm). When performing a building retrofit or a building restoration, it is possible to use blocks in external or internal counterwalls to increase thermal insulation. Blocks are normally not used in floors and roofs because mixtures can be easily blown and they are best suited to host the electrical and heating system.

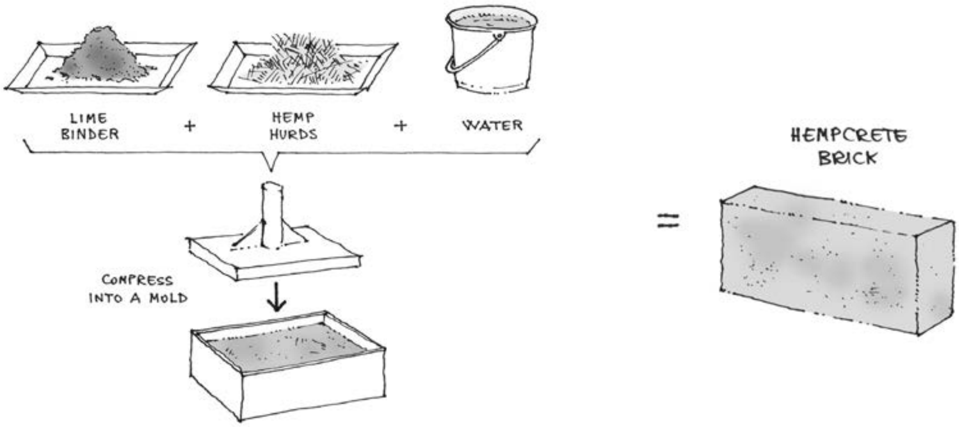


Fig. 3.9-4 Precasted hempcrete brick

Fig. 3.9-5 Details of non-load-bearing walls made of hempcrete blocks: (a) wall erection; (b) side view; (c) front view

3.10 Design guidelines according to African climates

Design guidelines for roofs, walls and openings in hot-humid, arid and temperate climates are at the vertexes of a triangle encompassing the complex variety of climates in African countries. These climates (equatorial, tropical, hot and cold desert arid, hot and cold semi-arid, and humid, dry winter, dry summer subtropical) 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 subtropical temperate climate), as described in detail below.

3.10.1 Group A Climates: 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; to achieve this, two main provisions should be made:

(1) Protect from direct and/or indirect solar radiation;

(2) Maximise ventilation.

3.10.1.1 Site plan

Sun protection

The building should be surrounded by trees, shrubs and grass, which absorb solar radiation and do not reflect it into the building. Trees should have high trunks and be appropriately positioned to avoid wind screening.

Ventilation

Sites exposed to prevailing breezes are highly desirable. The closer to the sea and the higher above 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 1 to 8 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 each other from the prevailing winds but should be spaced at a distance of 7 times their height if in row; 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-story dwellings is likely to be better than in single-storey houses. Therefore, at high urban densities, an increase in height is generally preferable, with the limits deriving by possible other constraints.

Outdoor spaces

As the outside shade temperature is the coolest available, 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[1] 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 single storey buildings 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, ventilation 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 parallel to the direction of prevailing winds, wing walls can improve ventilation (see

1 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

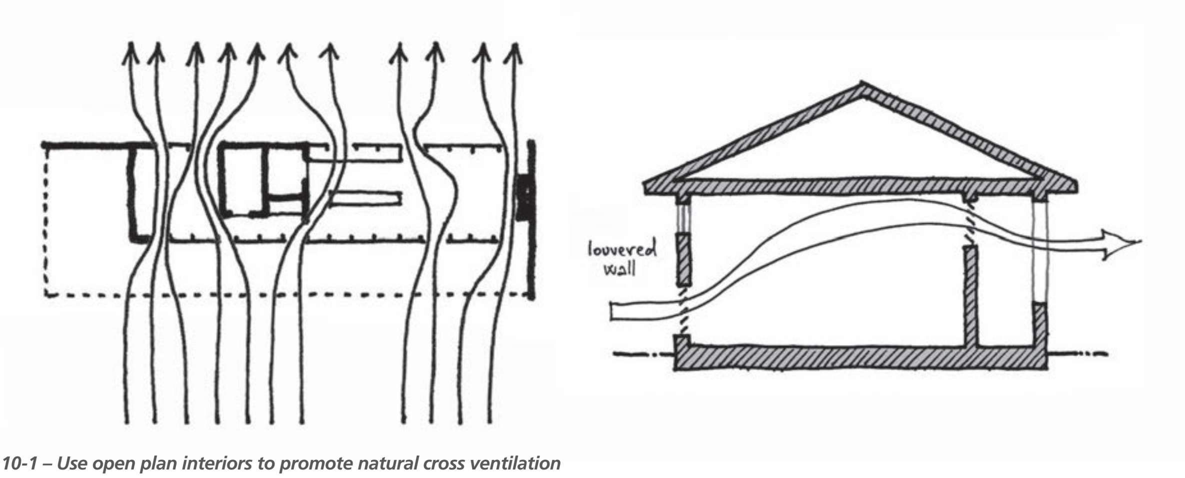


Fig. 3.10-1 – Use open plan interiors to promote natural cross ventilation

paragraph 3.5).

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. In flood prone areas, it can be helpful to have elevated floor slabs ('Stilt' building).

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 solar radiation.

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

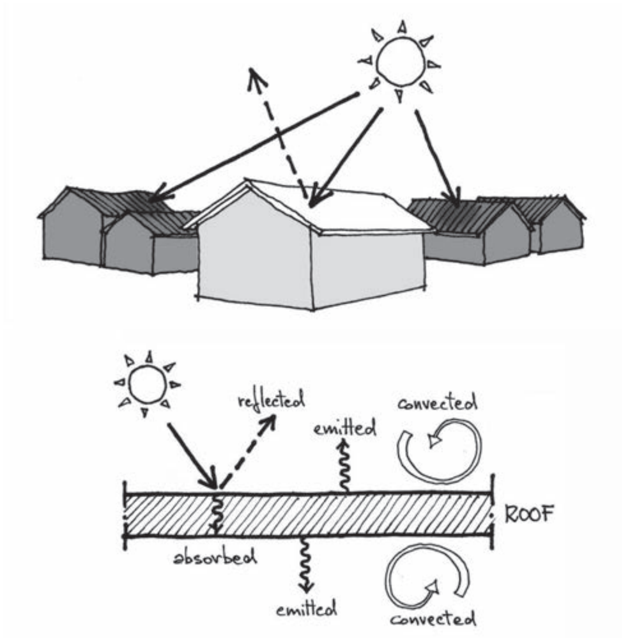


Fig. 3.10-2 – Dark, heat-absorbing roof surface increases heat transmission inside

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;

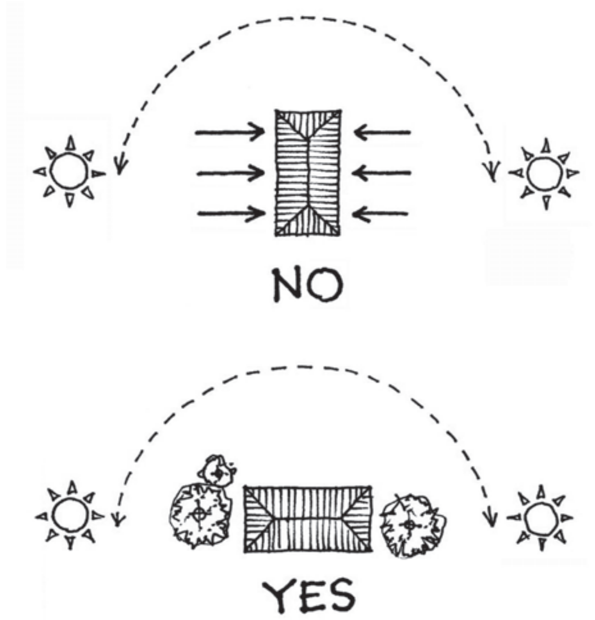


Fig. 3.10-3 – The best orientation for solar protection of walls is with the long axis east-west

- • shading with trees.

Cavity or hollow brick walls should be used for non-shaded walls. 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.

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, 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 towards 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).

(b) Louvered 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 louvers (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 louvers (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

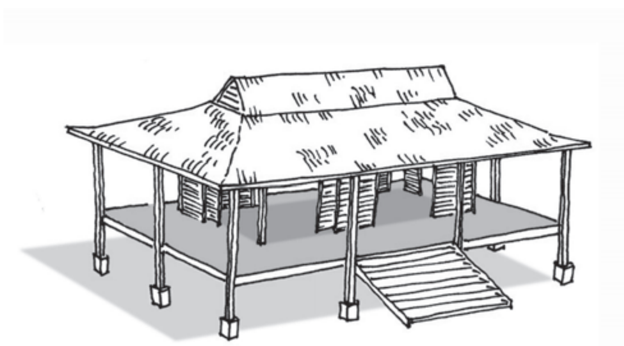


Fig. 3.10-4 – Lightweight construction with ventilated roof, operable walls and shaded outdoor porches, raised above ground

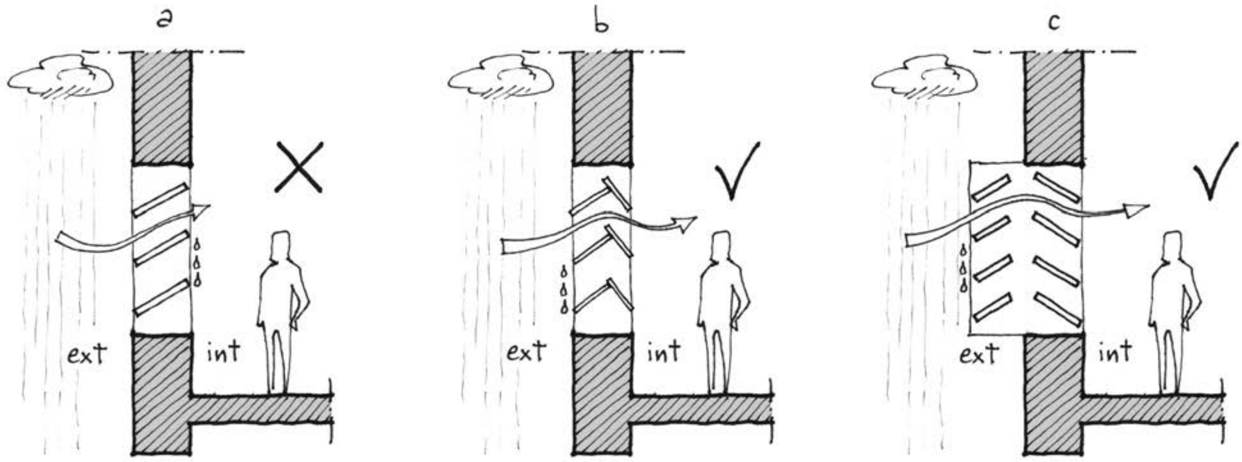


Fig. 3.10-5 – Non suitable and suitable louvres

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.

Sun protection

In Af climate, characterized by high precipitation, a specific design of the louvre should be adopted (Fig.3.10-5).

Ordinary louvres (a) in fact direct the wind upwards above the component and, furthermore, it is not safe against driving rain.

Modified louvres (b) keep the wind at lower level and provide protection from driving rain, but reduce the airflow to a certain extent. Another alternative is the use of a second set of louvres (c) to direct the air down to the occupants.

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 Group B Climates: Arid

(A) Hot-arid and semiarid climates (BWh and BSh)

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

Layout and sun protection

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 these climate, 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 heavy weight 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 facades 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 the northern hemisphere). 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 (in the northern hemisphere) 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.

Windows and ventilation openings

Wooden louver 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 louver windows, as the wind often carries dust. If louvered 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.

For hot semiarid climate (BSh), the design strategies are similar to those for the hot desert arid (BWh) climate except for the use of a mid-weight building envelope because of the lower daily temperature swings. Evaporative cooling is not as effective because of higher values of relative humidity, but still recommendable during the hottest hours of the day.

(B) Cold-arid and semiarid climates (BWk and BSk)

Present in a very limited area of Africa, the cold-arid and semiarid climates (BWk and BSk) are characterized by high thermal conditions, large diurnal contrast to low thermal conditions. Because of the low temperatures, passive heating is welcome during the cold 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 cold season;

(2) Use of medium/high thermal mass for walls and roof.

3.10.2.3 Site plan

Sites should be selected so as to provide shelter against prevailing winds and cold air pockets in ground depressions. Exposed sites, where strong winds may be experienced, should be avoided. The exposed nature of many sites in this climate makes it necessary to group houses in order to give protection and shelter against cold winds.

There is no need for buildings to be widely spaced for ventilation. Spacing of houses should be kept to be the minimum compatible with the need to exploit solar radiation.

Compact layouts are an advantage and should also be applied on sloping sites whenever possible.

3.10.2.4 Building plan

The major climatic performance criterion for houses is to provide protection from the cold. Buildings should have their main glazed elevations orientated north-south; a NE-SW orientation with most of the rooms facing north-east is appropriate.

It is an advantage to locate living room and bedrooms to the northern (in the northern hemisphere) 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/heavy 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 temperature drop.

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

Heavy-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 (according to the latitude)l. 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, with consequent overheating. The only effective solution is to put adjustable louvres or Venetian blinds outside or inside the windows. The south-facing windows (in the northern hemisphere) 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 climate, a flexible heating system should be provided. Fireplaces are needed in most areas, at least at higher altitudes. Fireplaces should be located in living rooms. Moreover, an increased emphasis on passive solar design (Fig. 3.10-6) should be given.

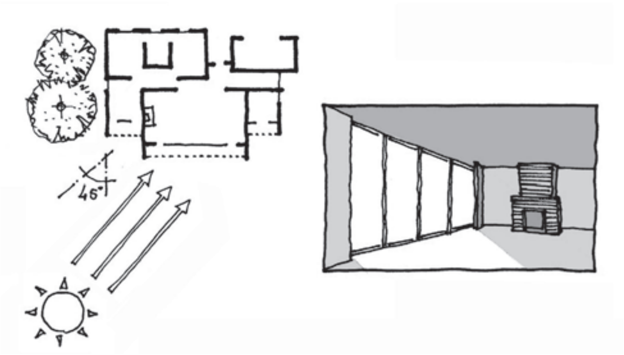


Fig. 3.10-6 – Let the sun in during the cold season for passive heating

3.10.3 Group C Climates: Temperate

With conflicting seasonal requirements, heating and cooling demand should be considered together. To achieve this, three 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) Provision of flexible heating system or fireplace.

3.10.3.1 Site plan

In general, buildings in temperate climate (C) can be arranged rather freely. Settlements should be semi-compact to provide mutual shelter from sun in hot season but also wind protection in the colder one.

Since microclimatic conditions may vary considerably from place to place, a compromise in the orientation of the building between the long axis East-West to provide effective shading and the direction of the winds blowing perpendicular to seashore may be necessary.

In subtropical temperate climate with dry summer (Cs), morning breezes from the sea and evening breezes from the land, due to the difference in temperature between water and land, should be exploited for improving the summer comfort conditions. As breezes are perpendicular to the coast line, sites should face the main body of the sea and not be inside deep bays or creeks. If possible, they should be on high ground to avoid the high humidity at sea level and to catch stronger breezes.

In colder zones which belong to Cf and Cs climates, shelter against the cold wind and a proper building orientation able to maximize the solar gain are suitable strategies all year round. Accordingly, the urban layout and thus the street patterns, should be designed according to the direction of summer winds, avoiding the direction of winter ones.

Outdoor spaces

The outdoor spaces, as in all warm regions, are actively used. It should be planned to provide a well-balanced mix of open, sunny areas for the cold season and shaded, well-ventilated areas for the warm period or wind protection from cold wind. The vegetation should be planned accordingly, to provide a dynamic space according to the season. In such respect deciduous trees are an excellent strategy to achieve this goal. Such shading trees should be located on the south or north side of a building (according to the emisphere) as well the west façade should have sun protection during the hottest hour of the day. To counteract the winter winds, evergreen trees are also desirable (especially in Cw).

In temperate climate, the vegetation moderates summer temperatures and promotes by cooling the air through the evapotranspiration. Similarly, fountains, pools offer pleasant cool exterior spaces because of the evaporation of water with consequent benefit in terms of comfort with particular reference to subtropical temperate climate with dry summer (Cs).

3.10.3.2 Building plan

In this zone, buildings should be preferably compact. However, due to the conflicting climatic needs, specific solution can be arranged according to local topographical conditions and functional requirements. For example, in Cw climate, since heating in winter becomes more important than cooling in summer, rather compact structures with minimal but proper sun-oriented exterior surfaces are desirable. In Cs climate, where the sun is desirable in the winter while cooling and ventilation is pivotal in summertime, the courtyard is an advisable layout to be adopt.

The orientation of the building highly affects its energy demand, thus, it should be carefully considered.

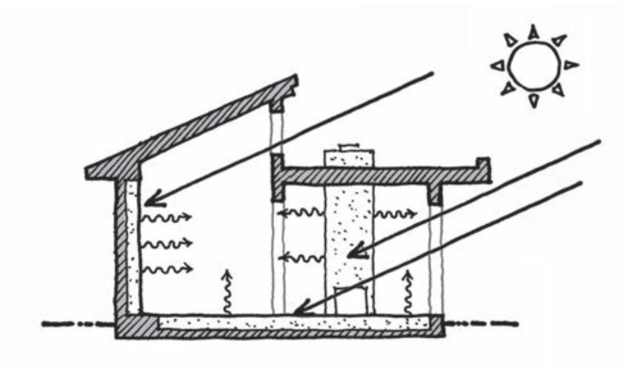


Fig. 3.10-7 – Provide solar access during the cold season and mid-weight envelope

In general, buildings should have an elongated shape along the east-west axis. The façade towards sun can easily be designed for proper utilization of the winter sun and for the protection against the summer gain. For this, arches, overhangs and porches are able to provide sun protection and, at the same time, to enhance wind breezes are appropriate (especially in Cs climate). Windows on the eastern side receive substantial heat during the morning, which may be useful in winter time. Usually, larger windows on the west side should be avoided, as the solar heat gain coincides with the highest air temperatures.

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. 3.10-7).

A moderately compact internal room arrangement is adequate for most of the year. In cooler areas (Cw and Cf), the exposure of the main rooms to the winter sun is essential, whereas in warmer areas (Cs) these rooms can also be north facing.

In subtropical temperate climate with dry summer (Cs) it could be reasonable to conceive one part of the building for the cold period and another one for the warm period. One solution would be a building type consisting of a ground floor characterized by massive walls and an upper floor with lightweight one. The ground floor would be relatively cool in the daytime and relatively warm at night. The light structure on the upper floor would perform the opposite way. As a consequence, in the winter time the inhabitants would use the upper floor in the daytime and the ground floor at night. In the summer time the pattern would be reversed.

Roof

The construction of the roof should be characterized by medium heat storage capacity to balance temperature swings between the daytime and evening hours. The mass should be placed in the inner part of the construction. The insulation material is required especially in colder climates (Cw and Cf). In Mediterranean climate (Cs) an outer layer characterized by high reflectivity and emissivity could be adopted as finishing of the roof.

Walls

Medium-weight walls, floors and ceilings are recommended for the best exploitation of passive solar gains: night temperatures are often below the comfort range. Thermal insulation should be placed on the outer layer of walls in order to not decrease the beneficial effect of the thermal capacity.

In general, external walls should be light-coloured. In some climates also a green cover (due by vegetation) on outer walls can be adopted since it protects surfaces against driving rain, reduce the convective losses on the walls and reduce the glare probability. However, it should be noted that, vegetation which is too dense and too close to the building could be affected by dampness effect. The use of deciduous plants should be considered.

Openings

The average area of the openings should be about 30% of the area of north and south facing walls to ensure sufficient ventilation for comfort and for cooling the structure at night. Preferably, openings can be placed mainly above the staircase or overhangs. Higher openings area is allowed in Cs climate while lower in Cw one.

Sun protection

In the hot period, windows must be protected from solar radiation and glare. In the cold season, however, solar heat gain through openings is desired. Hence, movable shading devices could be the best, even if they involve a somewhat complicated mechanism and also the attendance of the inhabitants. In general, shutters, screens and pergolas that allow ventilation, lighting and view and simultaneously control the penetration of the sun in the summer period should be considered.

Deciduous trees are also suitable for shading purposes (Fig. 3.10-8).

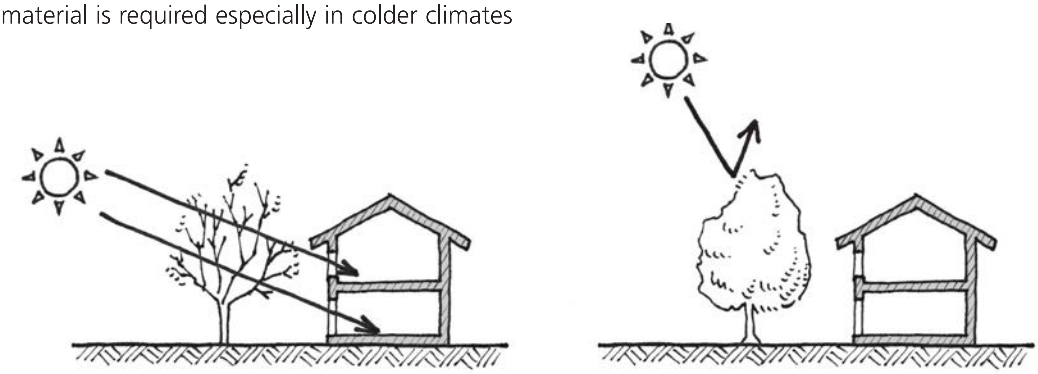


Fig. 3.10-8 – Deciduous trees for shading in hot period.

04 | ENERGY EFFICIENT BUILDINGS DESIGN

4.1 The envelope

Building envelope consists of all building components and technical elements that morphologically and functionally define the boundary between a building's interior and exterior environment. In addition to contributing to the definition of the architectural character and appearance of the building, it guarantees thermo-hygrometric control, acoustic insulation, mechanical stability, protection against intrusion, weathering and fire resistance.

Primarily, the building envelope (Fig. 4.1-1) consists of transparent and opaque components (walls, slabs, roofs and windows), the layout, distribution, and composition of which heavily influence the building's energy performance.

Despite fashionable trends in contemporary architecture, excessive use of glazing often results in high consumption, mainly due to the greenhouse effect in indoor spaces and associated cooling needs. There are building types, 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 is designed according to the guidelines given in Chapter 3. This condition is common in commercial buildings, because of the usually significant internal loads (people, office equipment, artificial lighting), but – at a minor extent – it applies also 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 of this special care derives from fact 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, which can cause severe internal overheating;

- 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

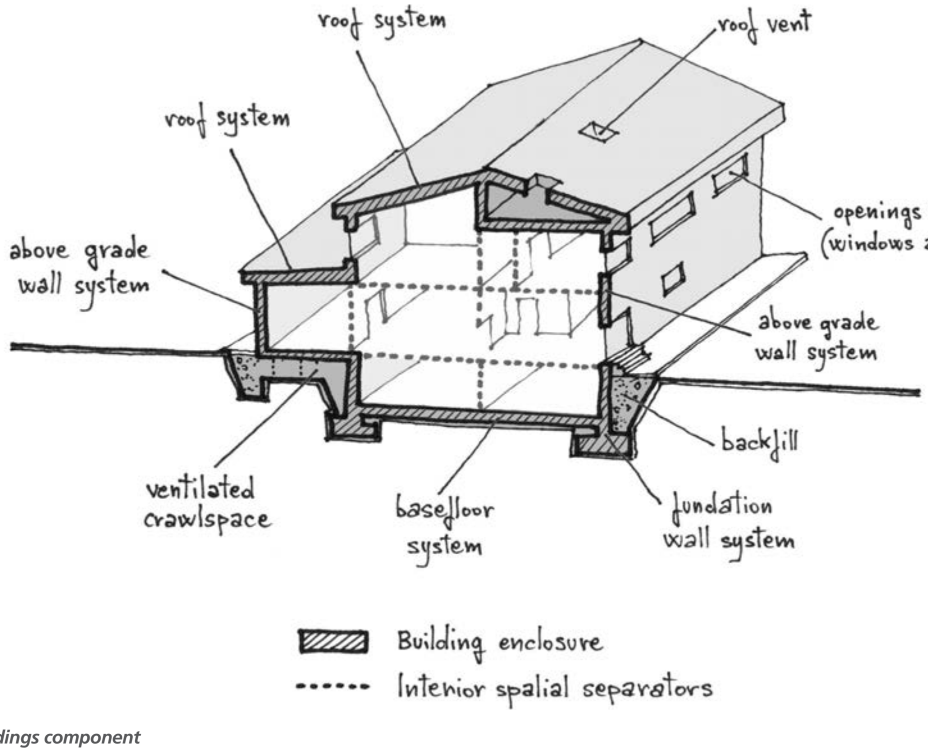


Fig. 4.1-1 Main buildings component

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).

For these reasons, the balance between opaque and transparent surfaces, as well as their interaction with climatic factors and technical features, must be the basis of sustainable building design.

4.1.1 Opaque envelope

Opaque building envelope is composed of all the non-transparent elements, separating the interior of the building from the exterior, which are responsible for most of the performance regarding boundary, structural stability, weather protection and filtering of climate conditions.

Regarding energy performance, the opaque envelope is an essential element to ensure proper building's operation and use in order to prevent unwanted heat gain, to enable heat loss in warm seasons and to limit it in cold seasons. Thanks to careful design and appropriate selection of materials and technologies, external weather conditions could be mitigated, filtered and dynamically exploited to improve indoor comfort and lower consumption.

4.1.1.1 Physical properties of the opaque envelope

To ensure correct energy design, opaque envelope's physical properties[1] to be considered are:

- Thermal transmittance U, which indicates the ability of a material or a layering of different materials to allow heat to pass through. As its value decreases, thermal insulation increases. In general, unless there are particularly favourable climatic conditions, it is always useful to keep the value below 0.8, but in energy-efficient buildings it can be as low as 0.2. Of course, the choice must be made in relation to a careful cost/benefit assessment, avoiding unnecessary over-insulation that could lead to internal overheating.

- Vapour permeability, which expresses the capacity of a building element to be crossed by vapour, depending on the differences in vapour pressure between inside and outside. Building elements where vapour permeability is poorly designed can result in condensation and moisture stains, that can cause mould, plaster deterioration or even damage to structures and materials.

- Mass-related inertial properties, expressed by the time-lag ϕ and the decrement factor ψ which indicate, respectively, the ability to attenuate and retard the heat flow through the layer under consideration. In general, except in hot-humid climates, a good level of thermal inertia contributes positively to the building's energy balance.

- Surface albedo, which expresses the ability of the outer finish to absorb solar radiation. In general, in hot climates it is advisable to use light colours and materials, so as to limit solar gains and internal overheating.

4.1.1.2 Elements of the opaque envelope

The main elements of the opaque envelope are walls, horizontal partitions and roofs.

Walls can be load-bearing or infill structures, depending on construction technologies and materials used.

In the first case, we refer to more traditional construction methods, where the task of supporting the various floors is assigned to the perimeter walls and some of the interior walls of the buildings. In order to bear the load, the masonry must generally be built with considerable thicknesses, which also results in an increase in mass that benefits the inertial properties. The most commonly used materials are stone, cement, brick, clay and rammed earth, generally installed in blocks or bricks. Reinforced concrete panels, prefabricated or manufactured on site, can also be used. When additional thermal insulation is required, an outer or, in concrete panels, intermediate insulation layer can be added.

In more recent and widespread practices, walls do not have a load-bearing function, but are inserted or superimposed on the structural apparatus of the building. The materials to be used in this case are diverse (brick, wood, sheet metal panels, etc.) and layered structures are generally used to achieve the desired performance by combining different materials (e.g. bricks - thermal insulation panels - plaster).

Horizontal partitions are essentially represented by external slabs facing downwards or lying on the ground. They must be designed in coherence with the structural framework of the building, with particular attention to thermal insulation and waterproofing functions.

Roofs are the upper closing element of the building envelope. They consist of slabs, often added with insulation layers to improve their function as separation element between inside and outside of the building. Depending on their geometry, they are divided into flat or sloping roofs.

Flat roofs are advisable in very hot climates with moderate rainfall, because they allow reirradiation at night, contributing positively to the building's energy balance. The slabs are similar to interior floors but have

1 See Appendix A1 for specific values and calculation methods and Section 3.4.4 for design tips.

greater thicknesses, more thermal-acoustic insulation and waterproofing. Different materials can be used, depending on local building techniques and traditions. The load-bearing structure can be made of reinforced concrete, wood or, more rarely, steel with planks, bricks, or panels of various types to fill gaps in the structure. The outer layer, usually made of concrete, is overlaid with waterproofing layers, to prevent infiltration, and thermal insulation layers. The flooring must also be resistant to the long lasting action of solar radiation and have a slight slope to allow rainwater drainage.

Sloped roofs, more effective in rainwater protection and drainage, consist of one or more inclined planes, depending on whether the roof is single or multi-pitch. Again, the materials used for construction vary according to the type of architecture and building technologies.

A widespread and traditional material for the bearing structure of pitched roofs is wood. The main structure is then stabilized with other wooden beams and rafters, to which the roof covering, made of shingles, tiles or sheet metal, is superimposed.

In more recent construction techniques, on the other hand, sloping roofs are built with a reinforced concrete or steel bearing structure, on which layers of waterproofing and thermal insulation are superimposed and, as a finishing element, again shingles, tiles or sheet metal.

4.1.2 Glazing

Glass panes were perhaps the most important technological discontinuity in the history of buildings, which has allowed an extraordinary leap in the quality of life indoor, making possible other innovations. No longer the forced coupling between light and outside air, cold in winter and hot in summer, which pass through the openings (in fact the word window in English is derived from the analogous Icelandic word meaning "eye of the wind"). And not just light without "wind"; the sun penetrating through the glass heats the room, thanks to the greenhouse effect. Of course there is the problem of the summer, but is easily solved with external protection and/or opening the windows.

4.1.2.1 Glass, climate and energy

To ensure adaptation to external and internal conditions, glazed windows had evolved into an optimized system, according to the different climate. In central and northern Europe relatively large glass surfaces are found, partially operable (typically the sash window) and internal sunscreen (curtains), often dark. In the Mediterranean the optimization process has led to quite different solutions: glass surfaces smaller than in central and northern Europe, windows that open fully to better benefit of natural ventilation in summer, external sun protection (shutters, often with movable slats). And it is entirely reasonable that this is so: 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, and sunscreens should only serve to adjust the intensity of the entering light; better not to exceed with the ventilation because the air is cool. In the Mediterranean, is a different story: sun protection and ventilation are the prerequisite for a comfortable environment in summer, but in winter ventilation must be precluded and some solar gain in is welcome.

In hot-humid tropical climate the jalousie window, instead, has been the most popular and appropriate technological solution to allow the fine tuning of natural ventilation.

These rules were adopted until to the nineteenth century in all types of building, residential or commercial, with few exceptions. Then, with the beginning of the twentieth century a revolutionary tsunami hit architecture, a revolution which tended to make a clean sweep of all the rules of the past by imposing a new slogan: lightness and transparency (cultured translation of the expression "envelope made of glass").

So, in the midst of brilliant insights, the abuse of the glass developed and consolidated, which led, as an inevitable consequence, to the abandonment (often the contempt) of the principle of adaptation to climate, and buildings - glittery jewels - became equal everywhere, from Oslo to Dubai.

Lightness and transparency. At that time it was little known, but it is a lightness that weighs thousands, millions of tons of CO_2, due to the enormous waste of energy for heating them in winter in cold climates, for cooling them in hot seasons/climates and for the artificial lighting necessary even when the sun is shining, as it is experienced every day.

A transparency, inter alia, existing only in the pictures in the magazines, because in the reality the curtains are always lowered by the occupants, trying to restore a visual and thermal comfort that such transparency precludes.

4.1.2.2 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 wavelength less than 2.5 microns), but blocks the long waves[2]. 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 so called thermal radiation, which - being of a wavelength greater than 2.5 microns - are retained in the indoor environment, blocked by the glass,

2 Visual and thermal performances of glass panes are treated in detail in Appendix 1 – Principles of building physics.

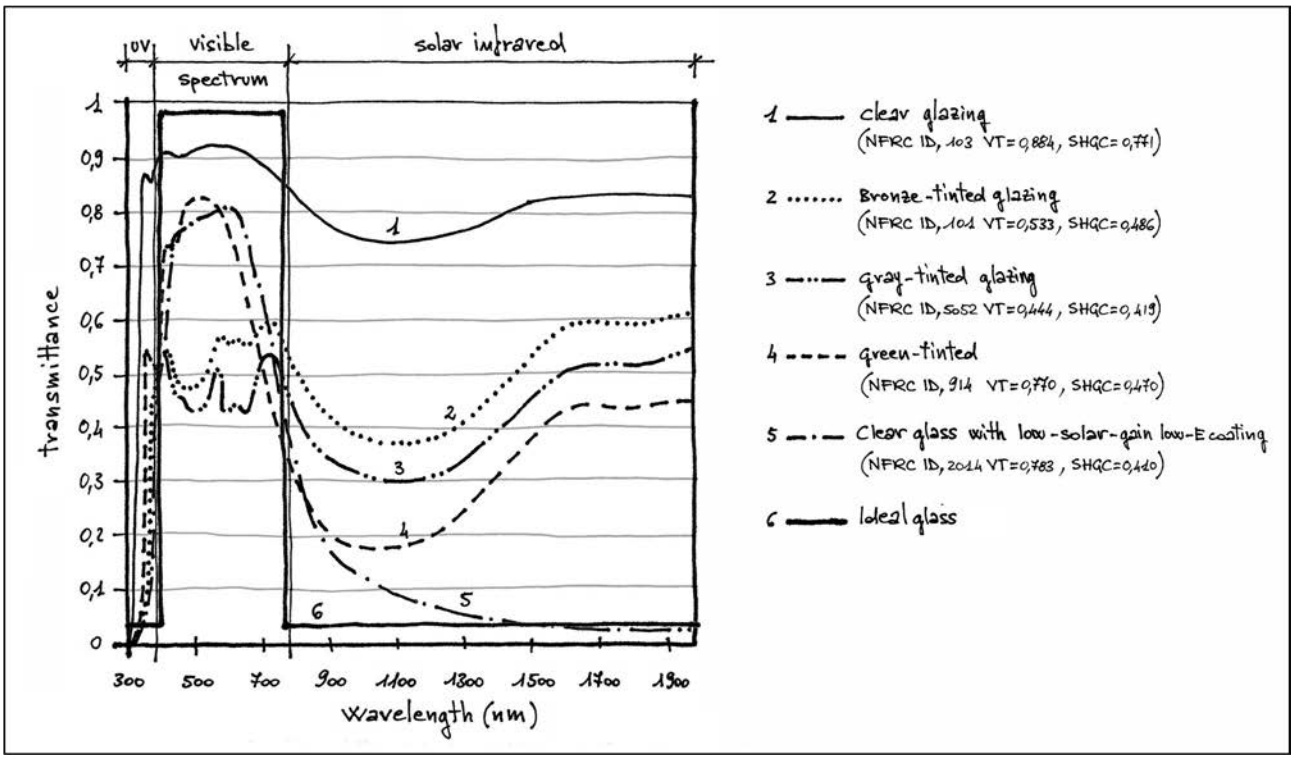


Fig. 4.1-2 – Solar radiation transmittance through different types of glass. Legend: NFRC = National Fenestration Rating Council; SHGC = Solar Heat Gain Coefficient; VT = Visual Transmittance

and generating a temperature increase.

The feature of transforming solar energy into thermal energy is an ambivalent factor; if, on the one hand, it allows heating the room with solar energy in cold climates, on the other hand causes an energy gain that must be removed to avoid overheating in hot climate and seasons.

Figure 4.1-2 shows that the 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 considered: the spectrally selective glasses, for example, attenuate a little the transmission in the visible range and very much in the near infrared, where a part of the solar radiation (about 50 %) lies. Reflective glasses show strong disadvantages from both the thermal and visual points of view. If the reduced transparency in the infrared is advantageous, the benefit is heavily outbalanced by the poor transparency to visible radiation, resulting in the need of use of artificial lighting even in the brightest days. These glasses are not recommendable from the energy point of view.

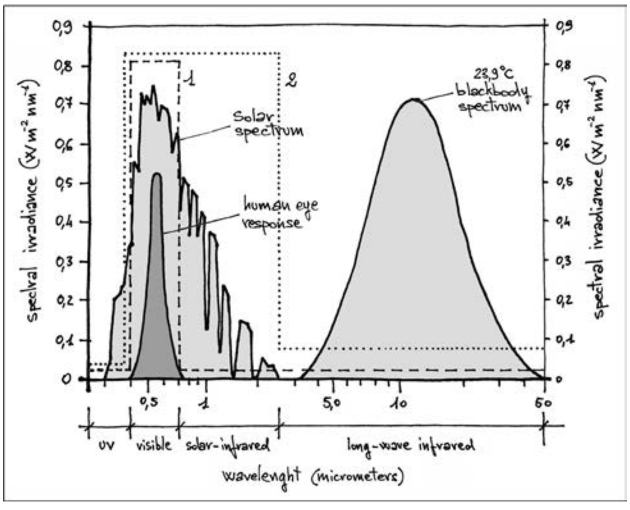


Fig. 4.1-3 – Spectral transmission of electromagnetic radiation of an ideal glass in different climates

Long-wave radiant heat has a considerable weight in the overall energy balance of a glass, thus its reduction improves dramatically glass performance in cold climates. For this reason low-emissivity films are used. The standard glass has an emissivity equal to 0.84 in the far infrared, which means that 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 hits it, it absorbs 84% of radiant energy and reflects 16%. A glass protected by a low-emissivity film, instead, has an emissivity of about 0.04, so this glass emits only 4% of the radiant energy that can theoretically emit, and reflects 94% of the radiation in the far infrared that hits it; the radiation that comes from the inside is therefore almost totally returned, greatly reducing the losses. This property, extremely positive in cold climates and seasons, make the low-e glass unsuitable, or at least useless, in hot climates and seasons and constitutes an unjustified cost.

Since the solar radiation spectrum extends from ultraviolet to near infrared, while objects at room temperature emit radiation in the far infrared, an ideal glass should be capable of transmit the radiation in the visible range leaving unchanged the spectral distribution, so as to ensure the same colour perception that would occur in the absence of glass and capable to meet other different (and contradictory) needs in the cold and the hot season. The ideal glass, in fact, should be able to transmit indoors the near infrared fraction of solar radiation to contribute to space heating, and to block the far infrared radiation emitted by heated rooms in the cold season (Fig. 4.1-3, line 1); in the hot season, instead, 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).

In order to meet the ideal requirements, glazing have evolved a lot in recent years, but still have 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), as shown in 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 - as outside;

2. the glass is also crossed by the radiation which falls in the near infrared: 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 the pros and cons. The pros are in cold seasons, when it is good that all the energy of the sun penetrates through the glass surface, contributing to reduce energy consumption. The cons in hot climate/ seasons, when this energy is unwanted, because it requires to be extracted, by cooling, to maintain comfort conditions.

Tinted glasses are such because, crossing them, the solar spectrum is changed. As it can be seen in figure 4.1-2, green glass is less transparent than clear glass in correspondence of wavelengths greater than 520 nanometres, i.e. those that characterize the colour orange-red. It follows that this colour is attenuated, and in the resulting light – deprived of much of the red component – the green dominant prevails. This glass, however, reduces the amount of solar energy passing through it, since the transmission of the radiation is lower, on the whole spectrum, of that of the clear glass.

The grey and bronze glass, instead, 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 glass, said "spectrally selective", has been developed, which has the capability to attenuate the infrared component of the solar spectrum, while maintaining a good transparency to visible radiation (glass n. 5 in Fig. 4.1-2): the result is that the ratio of light transmission to solar gain is greater than 1. It is defined spectrally selective, according to the Department of Energy of the United States, a glass whose index of selectivity is ≥ 1.25 (Table 4.1-1).

In principle in hot climates with high solar radiation, like in the tropics, the ideal would be to use glasses with low SHGC. This would correctly apply if the glass properties were those of the "ideal glass" described above. Unfortunately, real glass with low SHGC show also a poor light transmission (which forces to use artificial lighting), or poor light quality (too "cold", with the consequence of the need for blend it with the artificial one). If they are bronze or grey, light quality is little altered, but the low light transmittance leads to high WWR (Window to Wall Ratio), which outbalance the benefit of a low SHGC. In conclusion, the best choice would be to use clear glasses, low WWR, and well-designed sun shading devices.

Thermal Comfort

Glazing and shading systems design strongly influences

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

Table 4.1-1 – Indicative values of the characteristic parameters of some types of glass

thermal comfort conditions of building occupants, because thermal comfort in a space depends also on the radiant temperature of the interior surfaces. Glass, for its characteristics, often works as a radiating plate (cold or hot) and regardless of the air temperature creates discomfort in the perimeter zones. A coloured glass, for example, hit by solar radiation can reach significant surface temperature – especially in warm-hot climates/seasons – and create heavy discomfort conditions, even if the air temperature is comfortable. The occupants react by adjusting the thermostat to a lower temperature, wasting energy, and eventually not being able to obtain satisfactory comfort conditions.

Visual comfort

One often underestimated consequence that derives from the use of green and blue tinted glasses is that the luminous flux entering the room has a shift towards green-blue, corresponding to that of a light source with a very high colour temperature (over 7000 K). It follows that, for the usual values of the of illumination level (300-500 lux), the occupants have the perception of a "cold" environment. At this unpleasant sensation they respond by turning the artificial light on, which not only increases the level of illumination but which, mixing with the natural one transmitted by the glass, results in a reduction of the colour temperature, the artificial being more "warm". This results in a more comfortable visual environment, according 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 external conditions, resulting in waste of energy and in poor visual comfort.

Selective glasses have similar problems to those of non-neutral coloured glasses. In fact, as shown in figure 4.1-2, they absorb a large amount of the solar spectrum in correspondence of the orange-red wavelength range, giving rise to a light that turns into the 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 experienced also 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.

4.1.2.3 Smart Windows

They are systems capable of changing the optical and thermal properties under varying climatic conditions, 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 ones, which respond to a single environmental variable, as light or temperature, and the active ones that respond to multiple variables such as the preferences of the occupants or the air conditioning system request.

Passive devices are the photochromic and thermochromic glazing; 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. These materials, for example, are used in eyeglasses that become totally transparent in the presence of internal penumbra and dark in sunny outdoors.

Photochromic glasses may be used for the adjustment of the natural light, avoiding the effects of glare, and for the overload control 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 crystal and the glass becomes transparent in a fraction of a second, allowing the 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 colorants can be added to darken the system when it is off. Products offered by some companies are available in various colours, either flat or curved glass. Stability to ultraviolet (UV) allows use in external applications, but their cost is still a problem.

Electrochromc glazing

Electrochromic glass is at present the most promising technology for windows changing optical properties. 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 low voltage power supply (0-10 volts DC), remain transparent in the full range of properties change and can be modulated from transparent to completely coloured. The high initial price of electrochromic glass is partially offset by the reduction in the consumption of the air conditioning system and the elimination of external sunscreens or internal blinds, because electrochromic windows give the possibility to modulate solar gains and reduce glare; however, they have a limit about colour: losing transparency they shift towards a cold colour.

4.1.2.4 Glass architecture

First to change must be architectural fashions such as fully glazed buildings, whose diffusion is cause of energy waste, especially in hot climates.

What's wrong with glass facades? 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 light and transparent also in physical terms, affecting heat gains and thermal inertia in a way that makes them energy voracious (Fig. 4.1-4). But it is not the only problem. Let's summarise how these full glazed envelopes are used, and their effect on energy consumption and comfort.

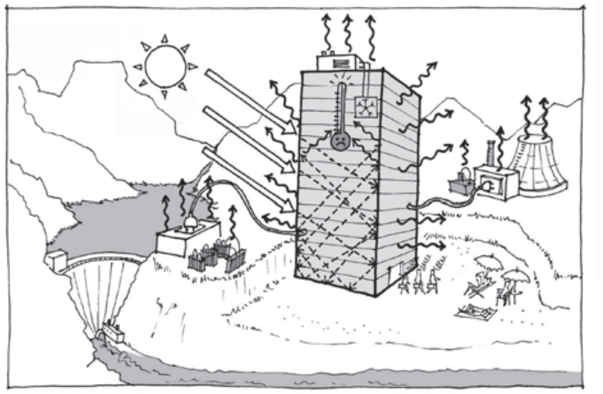


Fig. 4.1-4 – Energy and glass buildings

Since part of the solar spectrum is absorbed, in sunny hot days the glass warms up to 30-40 °C, and the infrared radiation emitted makes uncomfortable the nearby spaces. 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 the comfort is improved, but at expenses of higher heat gains.

There is another environmental drawback when tinted glass facades are used, especially if the colour is blue-green, the most appreciated and used by architects. The drawback is evident having a look to such buildings during clear days: in spite of the brilliant sun shining and the large amount of natural light available, artificial lighting is on. The reason 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 it is well known since more than 60 years – the occupants feel the luminous environment uncomfortable; as a result, they switch on artificial light, warmer, that compensates the cold natural lighting.

Another visual comfort related issue is to consider when clear glass is used. The benefit of a large aperture that lets come in a flood of natural light is entirely cancelled by the effect of glare on occupants' behaviour: they restore their visual comfort by obscuring the glass surface with curtains, venetian blinds or whatever it 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: high and uncontrolled solar gains in hot climates (the curtains inside, even if white, absorb solar energy that is transferred to the room) and lights always on.

To temperate this undesirable effect in more recent times some leading architects use to protect the large glazed curtain walls with external shading devices. It seems a good idea, but unfortunately if they cut off glare also light and outside vision is cut off, and artificial lighting must be on all the time.

Glass is potentially a very effective material for low energy buildings, especially thanks to the most recent technological developments, but fully glazed buildings exacerbate the problem of air conditioning in hot seasons/climates, increasing the energy demand both because of the large solar gains and for the induced need of artificial lighting in spite of natural light always available.

The most effective way to stop the proliferation of energy wasting buildings is to develop and put in force appropriate building regulations dealing with energy conservation. In some countries, such as France, Spain, Portugal in Europe, and California in US, there are limits to the maximum glazed area allowed in each façade, unless it is demonstrated that the energy required for heating and cooling is less than a pre-set limit value.

Glass Double skin

The claimed advantages of glass double skin facade 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 possibility to enable controlled natural ventilation, all while maintaining the architectural value of a light and transparent envelope.

The problem is that many of these claimed benefits are controversial or even denied by experimental evidence, sometimes conflicting with each other and in many cases lacking of scientific evidence.

A study carried out under the EU "Intelligent Building" program, named "Best Facades[3]" showed that:

- the cost of the double skin glass is 20-80% higher than the single one, and 100-150% higher than a normal facade (wall and windows). So, to economically offset this extra cost, significant energy savings are required;

- maintenance costs in the double skin are obviously higher than those in 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;

- if it is true that the reduction of traffic noise is one of the advantages offered by the double skin, it is also true that in many cases an increase of noise transmission between indoor environments was reported, due to the reflection of sound in the cavity;

- from the point of view of fire safety the double skin presents very strong critical elements, since the firemen would be forced to break two glass panes before they can enter the building from the outside, and because of the possible spread of fire through the interspace;

- double skin facades require, compared to the traditional ones, more space, more resources and more energy for the production and construction (see Appendix 1). Their environmental impact is also higher and reducing it requires compensation 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 facade is designed. A building with a double glass skin well designed for the Swedish climate would not work in Nairobi, and vice versa. Furthermore, the design solutions must be different for each facade. Consequently, to obtain good performances with a double skin it is necessary to carry out complex dynamic simulations, sometimes with models developed "ad hoc": it is an indispensable precondition;

- experiences in southern Europe show that the milder is the climate the worse the glass double skin facade performs.

These evidences indicate that any application of this technology in tropical climates should be excluded.

3 *BESTFACADE, Best Practice for Double Skin Façades (EIE/04/135/S07.38652, 2008), Publishable Report, WP5 Best Practice Guidelines,* http://www.bestfacade.com

4.1.3 Opening sizing and design summary

Designing a window is not just architect's matter, because the impact of the glazed surfaces design on the design of the HVAC system is very high. Windows have a significant impact on energy consumption in a building's perimeter spaces. The most direct impact is on cooling and fan energy 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 energy during the day by providing daylight, but this benefit may be counterbalanced by solar gains. Solar heat gain accounts for the majority of the cooling load in perimeter spaces with windows and there is to consider that as the glass area increases, electricity consumption for artificial lighting is decreasing until the glass area does not reach the 25% of the entire facade; beyond this value a sort of saturation is reached, and electricity saving achieved by continuing to increase the area is very small, while instead consumption for cooling continue 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; this equipment savings, in turn, can help offset some of the additional cost of the solar protection.

Window and shading design are strongly 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 naturally ventilate the building also reduces HVAC energy consumption by reducing the number of hours during which the HVAC system operates. In temperate 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 cost;
- lower lighting energy cost;
- 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.

4.1.3.1 Recommendations and tips for windows design

Begin daylight design early in the design process. 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 sunlight penetration via overhangs or other fixed shading devices. Any window orientation more than 15 degrees off of 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 of exposure toward 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, that should provide the maximum light and the widest view lets also enter a large amount of solar radiation, with its consequent solar gain, and – if it is not properly designed – causes the very unpleasant phenomenon of glare.

Windows are a most complex component; they are a critical component for the quality of internal spaces, since they play a very important role in determining the comfort (thermal and visual).

Consider 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 it is not only matter of size and shape, it is also 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 a glass surface depends on several factors. First the climate of the place in which the building will be built must be considered and should always be balanced both the functional and the aesthetical 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) must be selected which is a compromise between glare and light. This is a compromise however favouring the electrical consumption for artificial lighting and represents a defeat from the design point of view.

To maximize lighting and HVAC energy benefits, conduct a whole building simulation to evaluate the total glazing area used for daylighting before finalizing a daylight scheme

4.1.3.2 Windows 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 - by the distance, the type of glass, by the presence of curtains or other protections and the position of the window relative to the floor level. Figure 4.1-5 shows that the first meter, from the floor level, does not bring an advantage for the purposes of natural light (and is a disadvantage for solar gains). On the contrary, moving the window to the top, to touch the ceiling, the daylight factor increases.

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.

Clerestory side-lighting can save energy by reducing electric lighting energy use, assuming that appropriate manual or automatic controls are used for the space's 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 window should be sized to provide the illumination required in the space when the view windows curtains are drawn.

A sloping ceiling at perimeter raises the window head without increasing floor-to-floor height (Fig. 4.1-8)

Size the windows and select glazing at the same time.

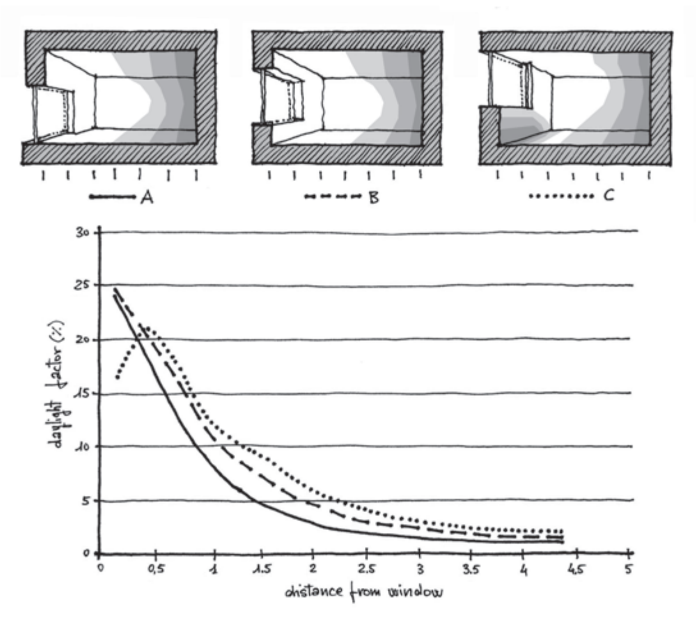


Fig. 4.1-5 – Daylight factor on a vertical plane crossing the centre line of the window, at the height of 0.8 m from the floor

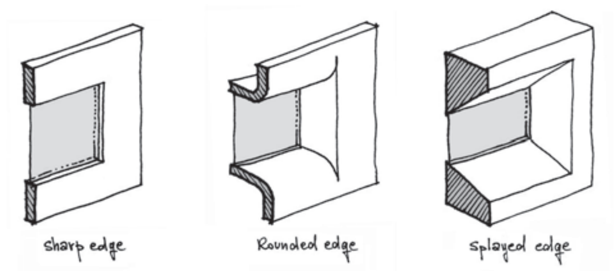


Fig. 4.1-6 – Traditional vs. splayed windows to reduce glare

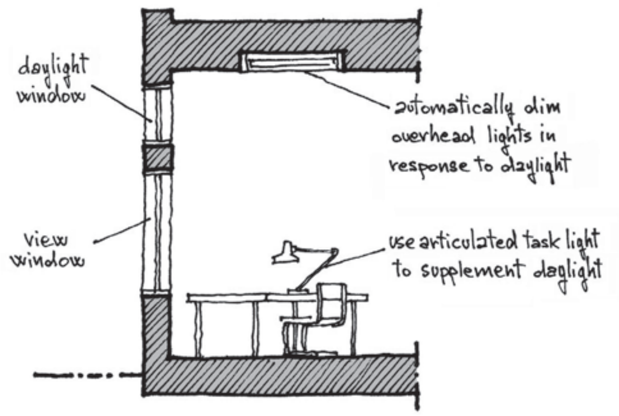


Fig. 4.1-7 – Separate aperture for view and daylight

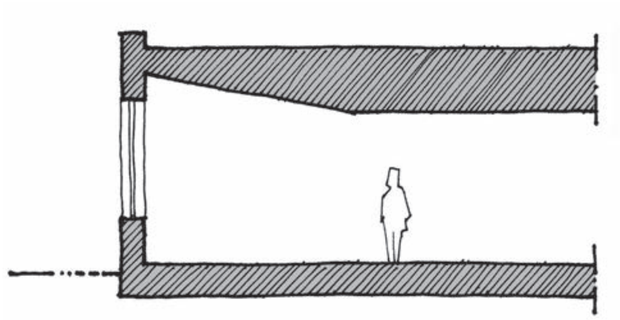


Fig. 4.1-8 – Sloping ceiling

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. For this we need to keep in mind when sizing a window, 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 must be solar factor and visible transmittance. The larger the window, the greater the need for high performance glass properties.

4.1.3.3 Glazing

Clear single-pane glass is generally the least expensive type of glazing providing the best colour quality indoors. Check carefully the real need to use other type of glasses. In tropical climate high performance low-e glazing may be a waste of money.

Do not believe that tinted glass provides good solar control. Many tinted glasses block more the light than the heat, and then reduce the air conditioning load very little, while force to use more artificial lighting. Tinted glass can create a gloomy atmosphere and it can affect the temper in residential buildings and the productivity and absenteeism the commercial ones. The colour quality of natural light is preserved only with the use of clear glass or tinted with neutral colours.

Tinted glass, if it is really necessary to use 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 into a furnace the space around who is close to it.

Spectrally selective glasses reflect some of the red component of solar radiation, and the resulting light in

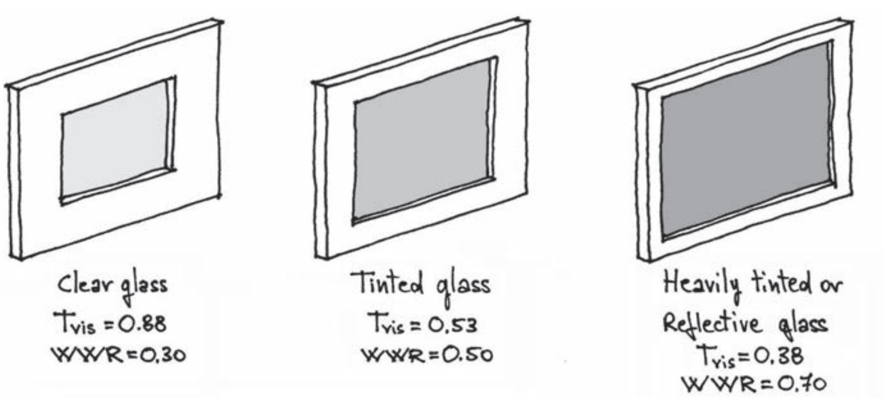


Fig. 4.1-9 – Variation of the size glass area as a function of the type of glass, with the same natural lighting obtained

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 "cold" of the visual environment, the selective glass can be replaced by a mobile solar protection.

Do not rely solely on the type of glass to reduce solar gains, thermal discomfort and glare. If the solar rays enter the building, they create discomfort to occupants who are in their trajectory and increase the thermal load for cooling. External shading systems combined with carefully chosen glasses are the best strategy. Even the interior shading systems are possible options to reduce solar gains, but result in higher energy consumption than external ones. Avoid, as much as possible, the use of reflective glass; they reduce the quality of the outside view and the mirror effect after sunset is unpleasant for the occupants.

4.1.3.4 Shading

Exterior shading makes more of a difference when used with clear glass; it has much less of an 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, in this respect, perform better (Fig. 4.1-10).

Exterior shading is recommended for windows on all buildings. It will be most cost effective when used with 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.

Before selecting the external sunscreen to use, it is advisable:

- check if it would be possible/appropriate to reduce the glass areas towards values that optimize 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 consumption for artificial lighting;
- check the costs and benefits of mobile sunshades;
- take account of the fact that - struck by the sun – the sunshade heats up and emits in the infrared, in turn heating up the glass, which heats up and radiates inward, especially if the solar protection is made of metal or glass. The heat gain reduction resulting for this attenuated. This phenomenon is particularly critical when the sunshade is located in the cavity of a glass double skin.

Before selecting the interior sunscreen to use, 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 can't be relied upon. It is advisable:

- specify light-coloured blinds or louvers 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;
- do not use dark components unless external shading is present. 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 carefully this option: the blinds warm up and, in turn, by infrared radiation warm the interior glass pane that radiates energy toward the internal space: the heat gain is still high and thermal comfort low.

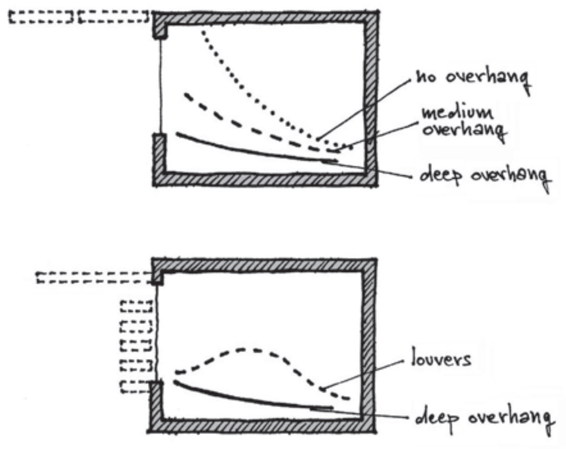


Fig. 4.1-10 – For the purposes of glare control at equal sun protection capability, horizontal blades result in a more uniform illumination

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')".

This is still true today, unfortunately, and must be changed; moreover, the growing concern about the environmental issues makes the change terribly urgent.

Sustainable building design implies integrated design which imposes that architects and mechanical engineers interact, as both have to interact with the energy expert. There is no interaction possibility if the architect does not have some basic information about the technologies that are handled, with deeper knowledge, by mechanical engineers.

4.2.1 HVAC systems types and features

HVAC (Heating, Ventilation and Air Conditioning) systems include a large variety of active technologies to provide thermal comfort and appropriate air quality in an enclosed space. Sustainable HVAC system should be capable to control air temperature, humidity and air quality, minimizing the primary energy needed to carry out such task.

HVAC systems play a fundamental role in architectural design for several reasons. First of all, they can occupy a not negligible part of space in the building. After that, they constitute an important part of the budget for construction. Further, the operational costs of HVAC could 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 that it is able to provide to the occupants. In this sense, the HVAC system should be considered as an integral part of the overall building system and has to be designed to work in synergy with building passive systems. For these reason architects should be aware of the principles underlying the layout and the operation of HVAC systems, the way energy conversion units work and the function of principal components. Architects should not leave all the decisions to mechanical engineers; they should be able to interact with some knowledge base: 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 the figure below, in order to properly manage the HVAC system.

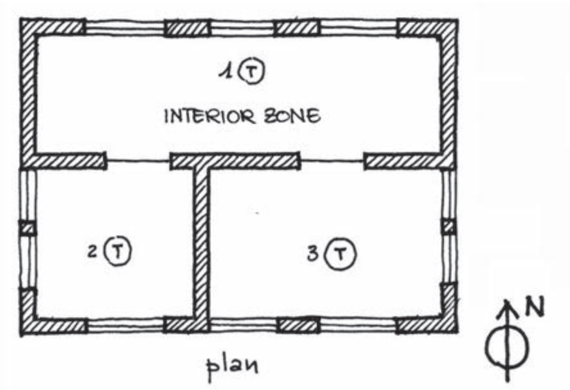


Fig. 4.2-1 – Example of a thermal zones division in a large office building

The functions of a HVAC system 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, transferring the produced thermal energy to the thermal zones of the buildings, by means of a heat transfer fluid;

3. emitting units, which have the task to exchange thermal energy with the thermal zone;

4. ventilation subsystem, which has to provide the optimal air exchange rate in the thermal zone; it can be fully/partially integrated in the above mentioned subsystems or separated;

5. control subsystem, controlling 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 above-described architecture is shown in figure 4.2-2.

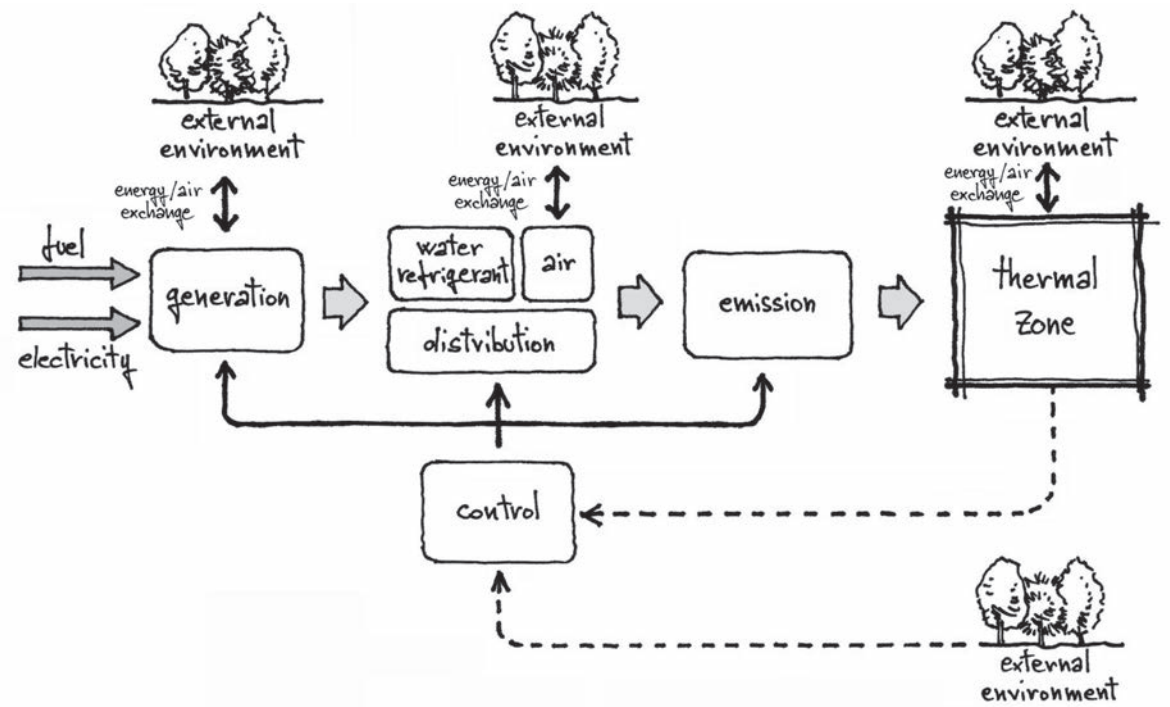


Fig. 4.2-2 – General architecture of an HVAC system

In centralized systems the different subsystems are typically well separated, with a tree structure that considers 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 subsystem or at least a part of them are compacted in self-contained equipment units working independently and located in the thermal zones or next to them. Compact systems are generally used in small buildings.

HVAC systems (Fig. 4.2-3) are categorized according to the type of fluid used to transfer thermal energy, as follows:

- all-air systems: they provide HVAC using only air as fluid; the air flow channelled to a thermal zone provides both ventilation and heating/cooling;
- all-water systems: only water is used to distribute hot/cold water to the terminals and ventilation must be supplied separately through openings/windows or mechanical devices;
- direct expansion systems: instead of water, is the refrigerant fluid to be distributed to the terminals; also in this case ventilation must be supplied separately through openings/windows or mechanical devices;
- combined systems: they are a combination of two or more of the above mentioned categories; the most common are the air-water systems, where usually sensible heating/cooling is 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. To distribute heated/cooled water in the building, from the generator to terminal units, pipes and pumps must be provided. The basic configuration is a two-pipe system: a main-flow pipe, in which water flows from generator to 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 if 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 always 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 inside building thermal zones, it must be exchanged with the air conditioned spaces through several types of water terminal units.

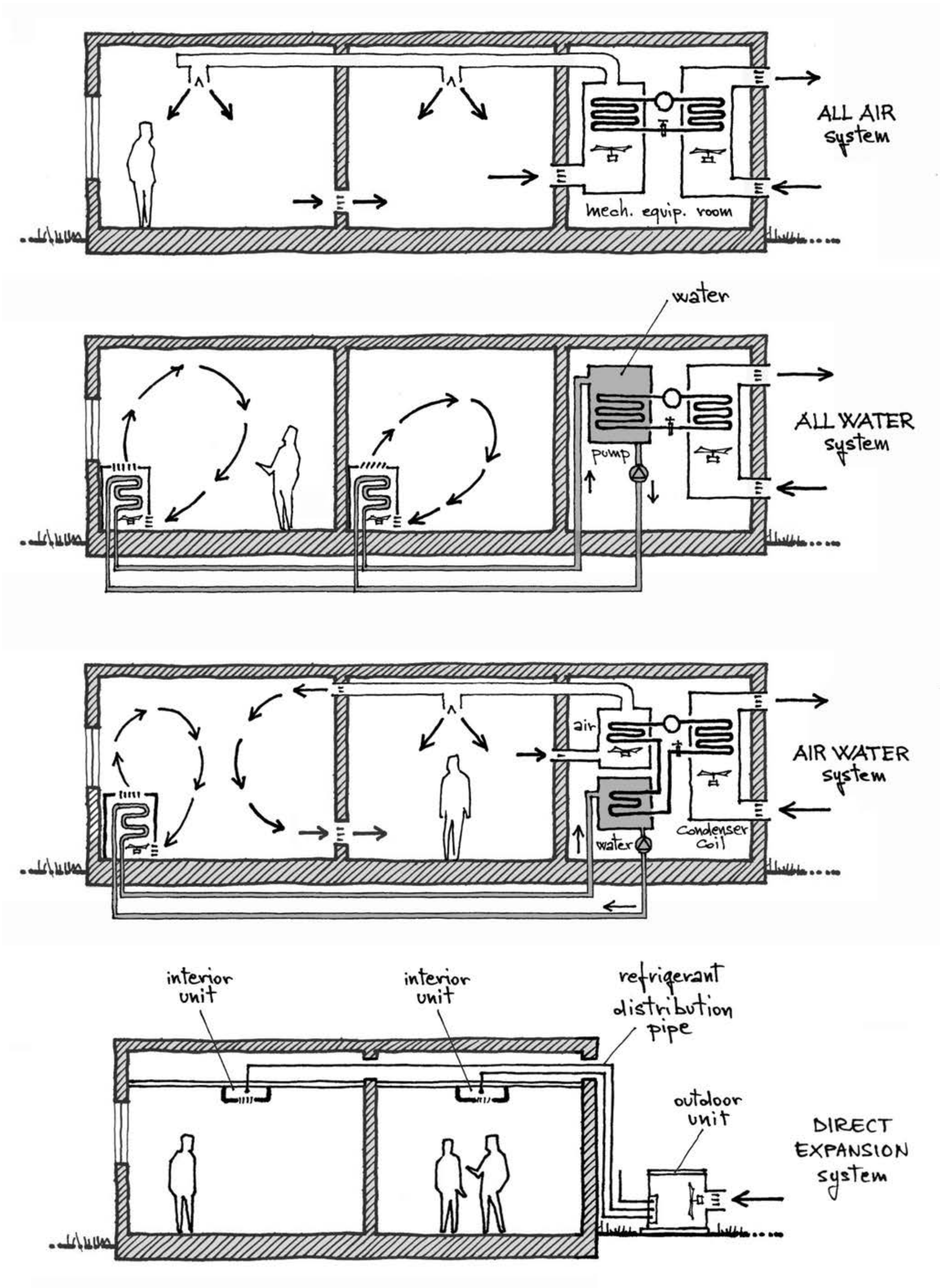


Fig. 4.2-3 – Schematic diagram of all-air, all-water, air-water systems and direct-expansion

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[1].

Fan-coil units

A fan-coil is a terminal unit with a heating/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 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 a condensation of the water vapour, that 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, that 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 separately ventilation and air handling (Fig. 4.2-5).

Specific room spaces for fan-coils must be carefully considered and 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 aesthetical and technical solutions (Fig. 4.2-6), easily adaptable to heterogeneous application contexts.

In general, fan-coils are appropriate for buildings with small thermal zones, where high flexibility in thermal needs is required.

Chilled beams and induction units

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 in the false ceiling of a room. As the beam chills the air around it, the air becomes denser and falls to the floor,

1 Radiators are not included in the list since heating only is not an option in commercial buildings in Africa and are not a competitive option in residential buildings in climate zones requiring heating.

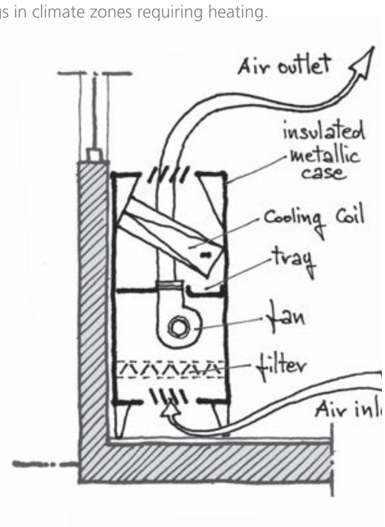


Fig. 4.2-4 – Fan-coil unit

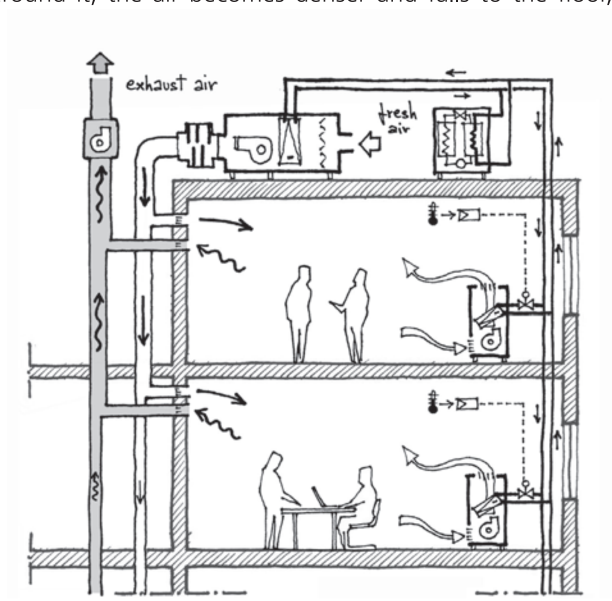


Fig. 4.2-5 – Fan coil and primary air system

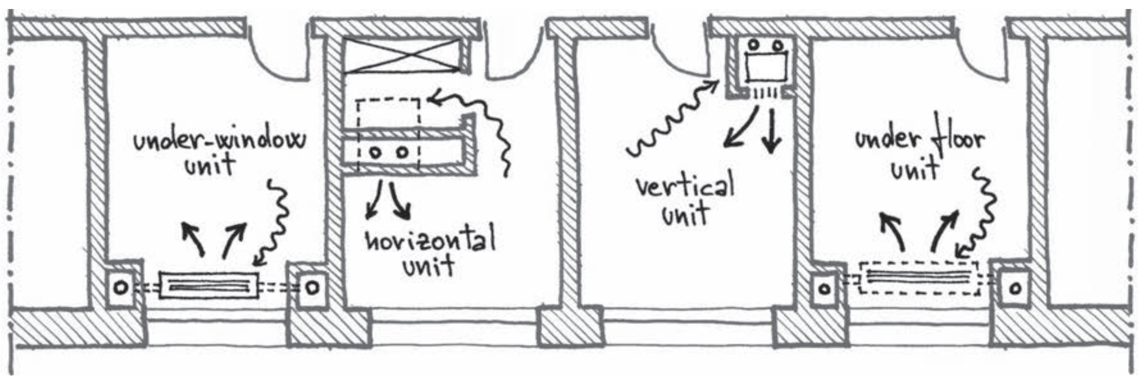


Fig. 4.2-6 – Four different fan-coil uses

being replaced by warmer air moving up from below, causing a constant convection flow and cooling the room (Fig. 4.2-7, a). 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.4.2-7, b); 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 with 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.

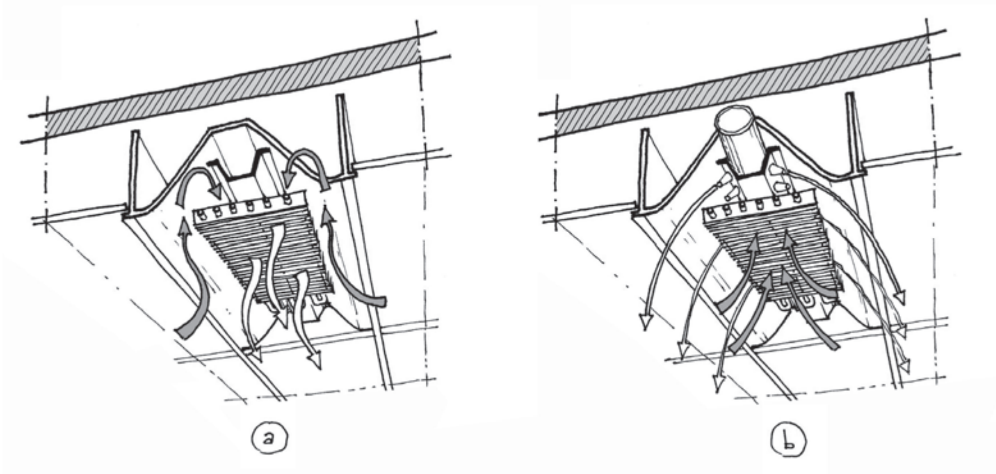


Fig. 4.2-7 – Chilled beams working principle. Passive (a); active (b)

Similarly, also 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, as shown in the figure 4.2-8. Despite the absence of fans, induction units may still present noise issues from the induction nozzles.

Currently, they are rarely used in new buildings since increased power, and consequently, significant energy amounts are required to compensate for the high pressure drop levels in these terminal units. Also, they are not designed to handle condensation and must operate dry. Therefore, they must be avoided in humid environments and used only for replacement in renovations when the installation of other systems may not be compatible with the original architecture. Modern, energy-efficient induction units for replacement include the variable air volume (VAV) induction systems and chilled beams.

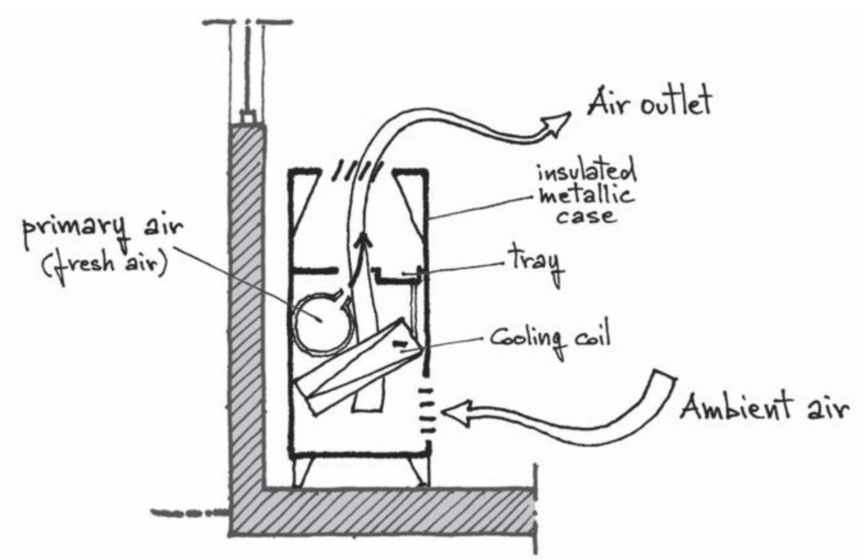


Fig. 4.2-8 – Induction unit

Radiant ceilings

Radiant ceilings are constituted by panels with embedded pipes (Fig. 4.2-9). Pipes can be either embedded in customized construction elements or in pre-cast construction components, such us false ceilings.

These type of heating/cooling systems are virtually maintenance-free and allow energy saving as long as water temperature is higher (in summer) and lower (in winter) than in fan-coil systems, with reduced losses in distribution subsystem and higher efficiency in generating heated/chilled water. Radiant ceilings, by performing the cooling effect primarily through radiation, can provide a comparable comfort level acting on the mean radiant temperature, thus enabling a more efficient operation. Anyway, a disadvantage is that an accurate humidity control is required to avoid condensation. Since these systems have no condensation drain, when too cold water is circulated in the pipes 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).

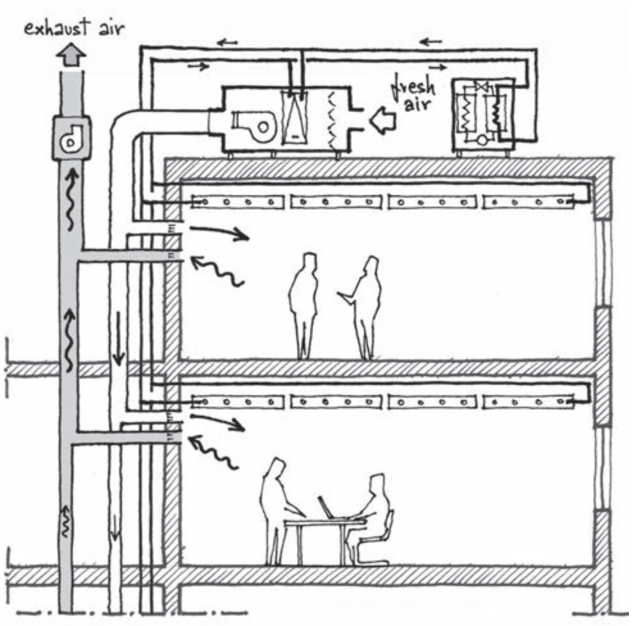


Fig. 4.2-10 - Radiant ceiling and primary air

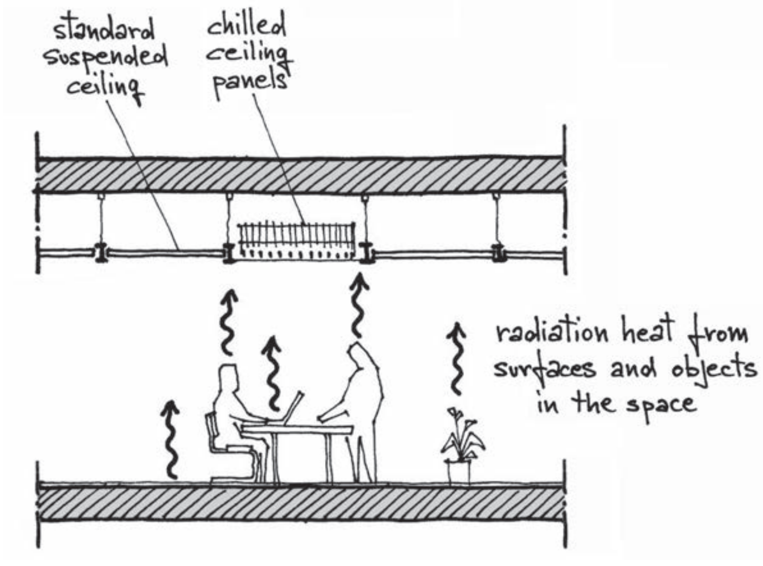


Fig. 4.2-9 – Radiant ceiling

4.2.1.2 Air systems

In all-air systems, air is supplied to the target zone at certain temperature/humidity conditions that ensure the proper treatment of the sensible and latent space loads while maintaining the room at the desired comfort level. In this sense, air systems can cool/heat, dehumidify/humidify, or provide ventilation air without additional systems.

The air system configuration is generally based on an air handling unit, which serves as a distribution and ventilation subsystem, and different types of emission subsystems, i.e., air terminals (passive or active devices). In contrast with water systems, air systems require more space for supply and return ducts, exhaust duct, and piping. As a consequence, their integration in the architectural design must be carefully assessed.

Air handling and heat recovery

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. 4.2-11). 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 serving the whole air distribution subsystem, or decentralized, i.e. subdivided into multiple units nearby the different building zones and connected to them. In case of high air relative humidity levels, the design and dimensioning of AHU 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.

Control devices such as mixing dampers and valves are often part of air handling units.

In commercial buildings in hot climates, air-conditioning may be necessary throughout the year. For this reason, in order to increase energy efficiency, the recovery of sensible heat or of the enthalpy (both sensible and latent energy) of the exhaust air is essential.

In AHU this can be usually performed by using:

- an energy recovery unit (Fig. 4.2-12);

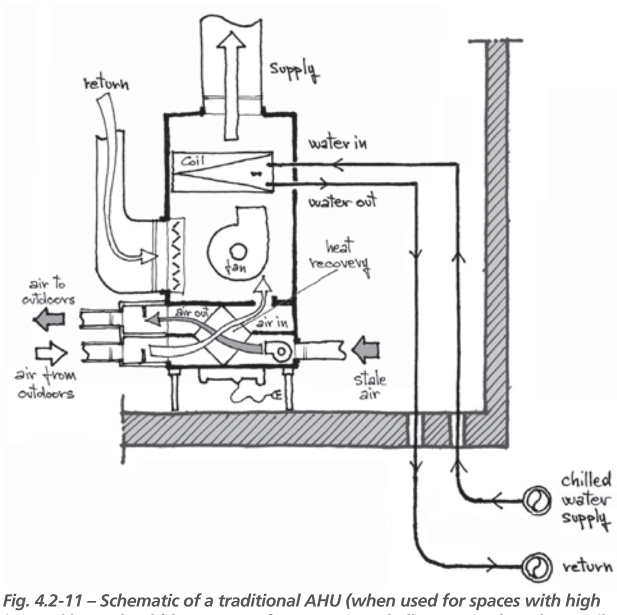


Fig. 4.2-11 – Schematic of a traditional AHU (when used for spaces with high internal latent load (theatres, conference rooms, ball-room, etc.) a reheat coil may be necessary after the cooling coil)

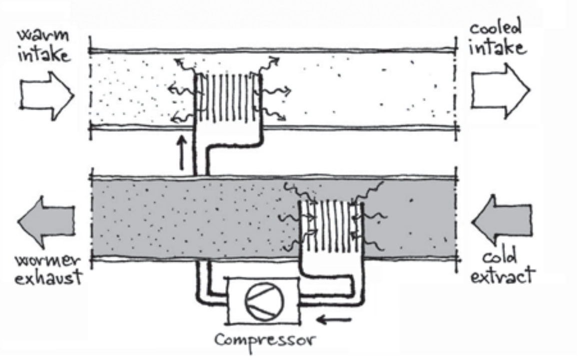


Fig. 4.2-12 - Run-around coil heat recovery system with heat pump

- a fixed plate energy exchanger (Fig. 4.2-13);

- an enthalpy wheel (Fig. 4.2-14).

An energy recovery unit (ERU) is a type of mechanical equipment that includes a sensible and/or latent heat exchanger combined with a ventilation system, which reclaims energy from exhaust airflows. If just sensible heat must 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 efficiently may transfer energy from cold extract to warm intake, as illustrated in figure 4.2-12.

Some standards present guidelines for the use of energy/heat recovery devices under specific outdoor air percentage or supply airflow rate. For instance, the ASHRAE Standard 90.1 establishes that ventilation systems that operate less than 8000 hours per year shall have energy recovery if the outdoor air at full design airflow rate is ≥50%. This is relevant, especially in high occupancy buildings, such as hospitals or schools, which require high amounts of outdoor air intakes.

In some applications, where the outdoor conditions are not too extreme or the indoor conditions are not too restrictive, it is possible to reach comfortable conditions just using ventilation systems that integrate active energy/heat recovery devices.

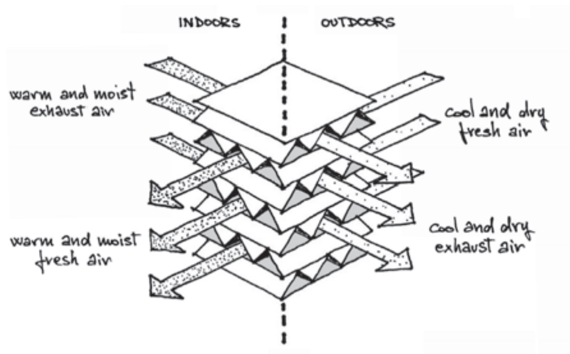


Fig. 4.2-13 – Cross flow heat exchanger

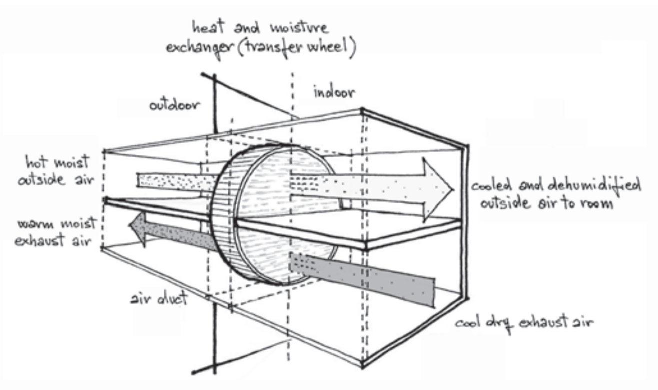


Fig. 4.2-14 – Enthalpy wheel heat recovery system

In the fixed plate energy exchanger, two air-streams (inlet and outlet) flow in adjacent but separated ducts exchanging sensible and latent heat by using special materials which transfer sensible heat and are water vapour-permeable.

Lastly, the enthalpy wheel consists of a rotating cylinder filled with an air permeable material resulting in a large surface area, representing the medium for the sensible energy transfer. As the wheel rotates between the ventilation and exhaust air streams it picks up heat energy and releases it into the colder air stream. At the same time, the use of desiccants 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.

Actually, enthalpy wheels are the most effective devices for energy recovery but accurate system design and selection of appropriate components should be done to guarantee wheel's durability.

The enthalpy wheel can be used also in desiccant air handling units to cool down and dehumidify air like in traditional AHU (Fig. 4.2-15). More in detail, the rotary wheel with solid dehumidifiers (e.g., silica gel) coupled in the AHU dehumidifies the incoming air and, to keep the system working continuously, the amount of water vapour adsorbed in the process must be discharged by heating the desiccant material to a certain temperature (regeneration), generally in the range of 50-100°C, until it returns to its initial adsorption capacity. In this sense, three main components of a desiccant cooling system can be identified: the dehumidifier, the regeneration heat source, and the cooling unit. The key advantage of these systems is that they can operate with different thermal energy sources, even low grade, such as solar energy or waste heat from industries, decreasing the dependence on primary resources. On the other hand, such systems can present some technical limitations, particularly in hot and humid regions, due to the high latent loads to be handled by the wheel, which could imply higher regeneration temperatures. Therefore, it is possible to provide pre-cooling before the wheel and to properly select desiccant material to improve the moisture removal capacity and avoid large heating plants for regeneration.

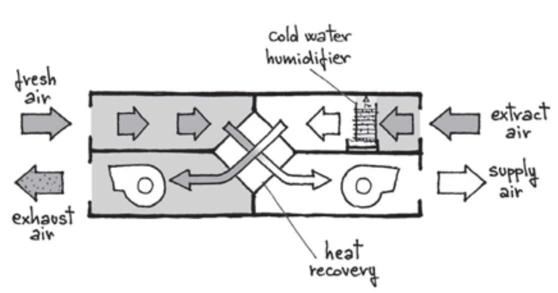


Fig. 4.2-16 – Evaporative Cooling heat exchanger

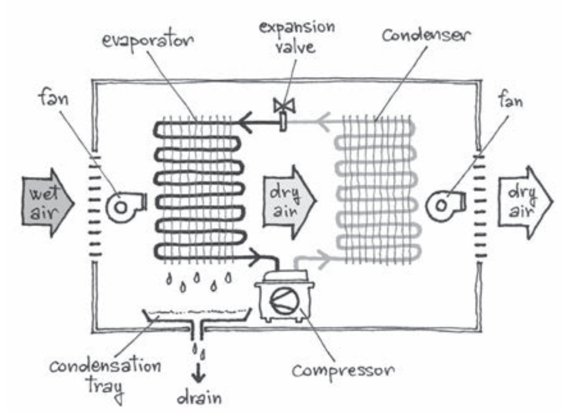


Fig. 4.2-17 – Air dehumidifier

Evaporative cooling can be used to enhance the heat recovery; in evaporative cooling heat exchangers exhaust air is cooled by spraying water before entering the heat exchanger (Fig. 4.2-16).

Air dehumidifiers

For applications in humid climates, dehumidifiers must be used to dry the outdoor air enough to compensate

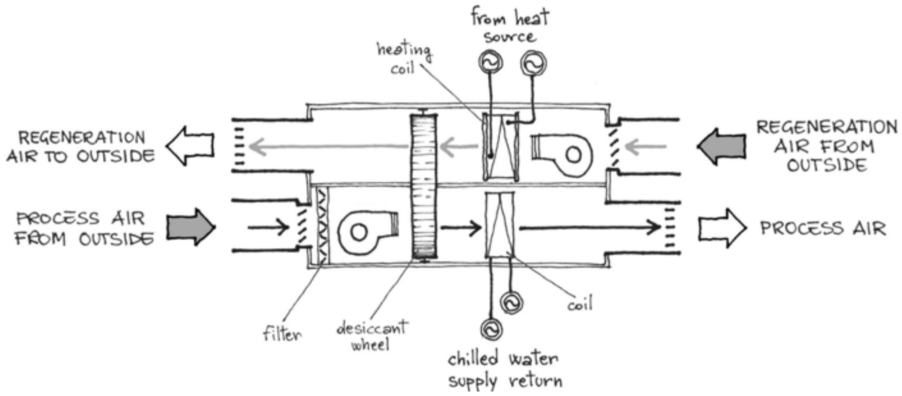


Fig. 4.2-15 – Desiccant air handling units

for the space latent loads and reduce the risk of mould. Generally, mechanical dehumidifiers (dehumidifying + reheat coils) or desiccants are used for dehumidification purposes. In case of mechanical dehumidifiers (see Fig. 4.2-17), the dehumidification is carried out by cooling the air below its dew point temperature (dehumidifying coil) to remove its moisture and subsequently, the dry air is reheated (reheat coil), usually using recovered heat, to avoid overcooling.

The dehumidification process requires the installation of a drainage system (pan and piping) to remove the condensate.

Dedicated outdoor air systems

Dedicated outdoor air systems (DOAS) are a special type of ventilation systems that provide fresh air to the building independently from heating or cooling, thus differing from the traditional air-handling systems. The airflow rate in the DOAS is sized to meet the minimum ventilation standards (e.g., ASHRAE Standard 62.1), or to meet 100% outdoor air demands. DOAS can serve different zones and is designed not necessarily to control space temperature but to bring thermally neutral air into those spaces (ventilation only operation). Therefore, DOAS is usually composed of a high efficiency energy recovery unit (ERU), which significantly reduces the heating and cooling loads. Generally, other systems are used to control space temperature while working in parallel with the DOAS in other to provide ventilation and active cooling, and the combination of both technologies is included in the so-called "separate sensible and latent cooling" (SSLC) systems. A common example may be the use of radiant panels to control the space temperature of the zone, while the DOAS is used to provide the minimum outdoor air ventilation as well as to handle the latent loads.

Air Distribution

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 much as possible, thermal losses and condensation. The most common shapes of ducts have rectangular, square, circular and oval section. Circular section is the most economical with respect to material and pressure losses, but the rectangular one is more suitable for architectural integration.

Ductworks are usually completed by 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; there is to consider, however, that air -as energy carrier- is not as efficient as water and 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 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 appropriate temperature is circulated throughout the building in a single branching duct, as shown in the figure 4.2-18. 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, such system is appropriate for small buildings or for buildings with few zones.

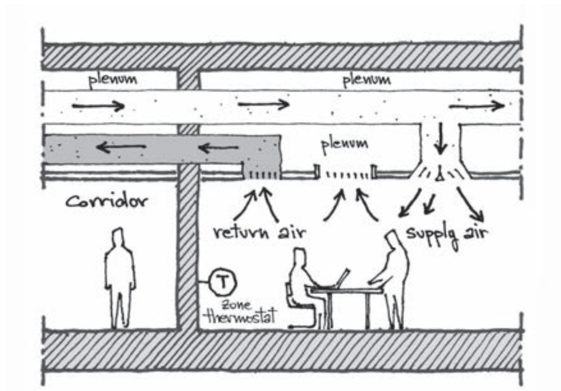


Fig. 4.2-18 – Single-duct configuration

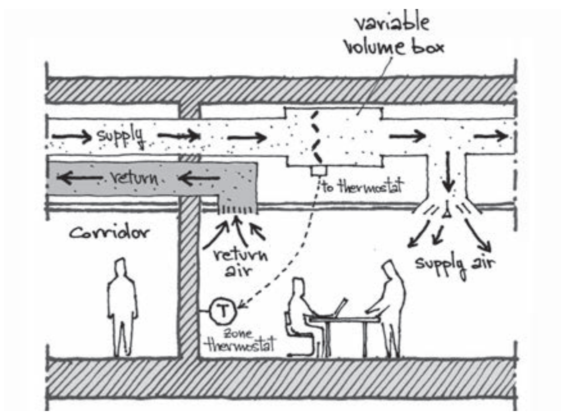


Fig. 4.2-19 - Single-duct VAV

Single-duct systems can integrate also terminal reheat systems: a single duct for air supply is combined with some type of heating devices, 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 as long as the supply air is conditioned to cool the zone with the greatest cooling load and may result 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 air temperature of the stream depending on the needs.

Any zone requiring less than maximum cooling will have its supply air temperature increased by its terminal reheat device. As can be easily imagined, cooling all supply air to the lowest temperature required and then reheating most of the air to produce comfortable conditions is an energy waste, thus this solution should be preferably avoided.

Single-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. 4.2-19). This is a major operational difference from the constant volume systems, in which supply temperature 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 spaces conditioned and each zone is provided with a VAV box (terminal control box) that adjusts the air supply volume; by this way both air temperature and flow rate can be varied separately in response to the zone requests.

Multi-zone systems

Multi-zone air configurations are composed by an individual supply air duct for each thermal zone in the building (Fig. 4.2-20). 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 with separate ducts to the different zones.

A key advantage of the multi-zone control approach is the capability to adequately air condition several zones, usually avoiding the energy waste associated with 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. 4.2-21).

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. In principle, a dual duct system has the same advantages and disadvantages of a multi-zone system, but it can be considered more flexible to changes in zoning requirements.

Like single-duct systems, dual-duct configurations can be operated with constant volume or VAV terminals. In dual-duct VAV systems, cold and warm air travelling in separated ducts are blended in a dual-duct box in different volume combinations, depending on the changing load of each zone.

These systems can be either single or dual fan, of which the dual fan configuration presents more opportunities for air treatment energy savings and less energy for fans

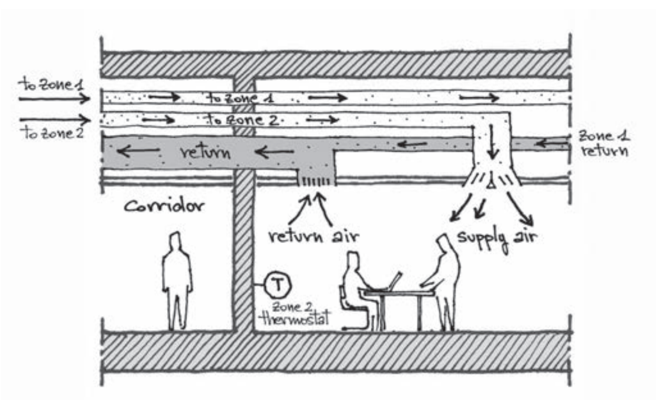


Fig. 4.2-20 – Multi-zone configuration

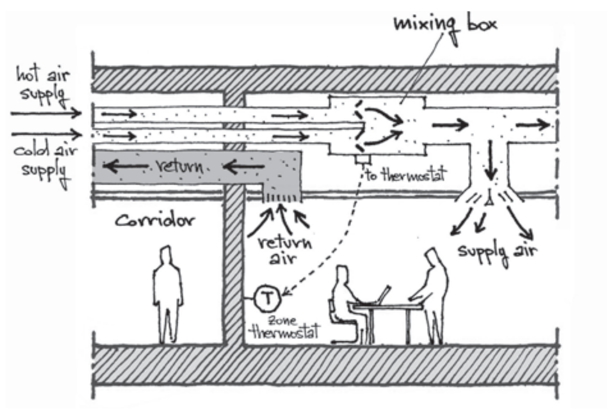


Fig. 4.2-21 – Dual-duct configuration

power. Overall, these systems, as well as all VAV units, must be carefully controlled to avoid introducing more outdoor air than the required minimum, especially when humidity is high.

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. 4.2-22). The position of supply-air outlets is related to the comfort level for occupants, and it has to assure that the air stream homogeneously circulates in each space without directly striking persons. Inlet and outlet air terminal will be positioned considering also the most economic and easiest routes for ducts according to building structure.

In general, in spaces with normal height ceilings, a good stratification typically occurs; for this reason, displacement ventilation technique, which supplies low-velocity cool air at floor level and extracts warm air from ceiling outlets, can be particularly efficient.

Several types of air terminal devices are available (Fig. 4.2-23). The most common are:

Grille

A grille is an opening with several slits in a wall or metal sheet or other barrier for 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 zone.

Register

A register is 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 drafts that would cause discomfort for occupants. Diffusers should be selected carefully, as they are the point where the effect of a 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.

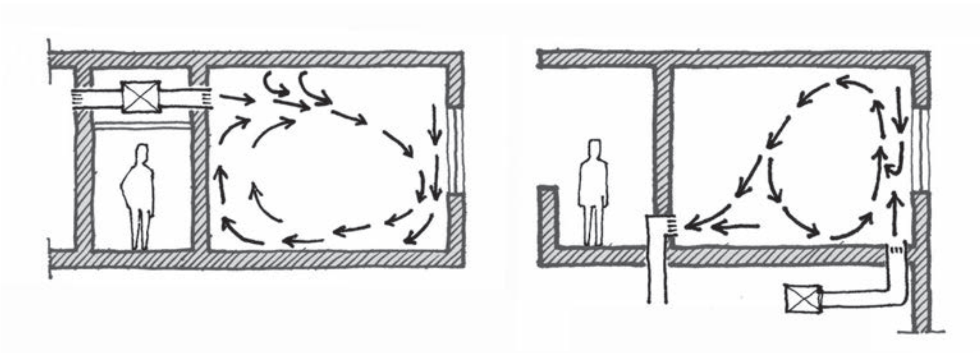


Fig. 4.2-22 – High air terminal outlet (a) and floor air outlet (b)

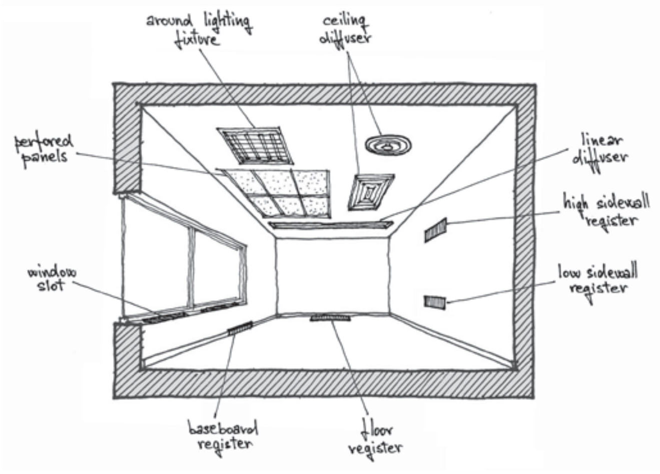


Fig. 4.2-23 – Diffuser and register types

4.2.1.3 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 are called split systems). Such solutions are usually suitable for small or medium size buildings, or for those contexts in which ducts and/ or pipes are difficult to be installed (e.g. existing historical buildings).

The simplest DX configuration is the single-split system, which 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 system is typically reversive to provide also heating to the rooms.

The two parts of the system, that can be distant many metres each other, are connected by refrigerant distribution pipe, thus guaranteeing a better flexibility with respect to window air conditioners, unitary air-conditioners and packaged rooftop units.

The internal evaporator unit can be also provided in a self-contained element, with different dimensions and features, similarly to fan-coil units but fed by the refrigerant. They are designed to meet the cooling/heating needs of a single room or small space of no more than 10-12 kW, and therefore, the refrigerant distribution pipe is not too long as in the multi-split systems.

A multi-split system (Fig. 4.2-24), instead, is generally composed by one or multiple exterior units, which always include the compressor and condenser elements, and multiple indoor units.

Modern split systems can also have variable refrigerant flow (VRF) o variable refrigerant volume (VRV), modulating the amount of refrigerant being sent to each evaporator. By operating at varying speeds, VRF/VRV units allow a substantial energy saving at part-load conditions and can represent an interesting technical solution also for many small-size applications.

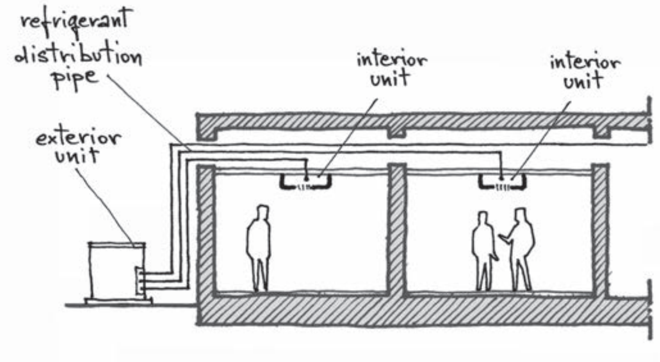


Fig. 4.2-24 – Multi-spilt system

The use of split systems can be considered when different cooling loads are requested in neighbouring spaces and a central system is not suitable. The subsequent table summarises advantages and disadvantages of multi-split systems compared with centralised HVAC systems.

The advantage of DX system is that they are fully reversible and can provide heating/cooling in every room with an independent set point.

4.2.1.4 Control Systems

The control systems regulate the operation of the HVAC and must be generally applied to all previous types.

The word "control" is intended 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 following the thermal load of building zone and contrasting it. Incorrect zoning of buildings may result in a poorly controllable HVAC system with high energy use and low comfort for the occupants, due to the difficulty in managing the oscillations of internal environmental conditions. The basic control element in a thermal zone is, of course, the thermostat (set-point for internal temperature).

One problem faced by this type of control is short cycling (frequent on/off), which keeps the system operating inefficiently and wears the component 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. Under this concept, if just a fraction of the cooling rated 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 using multiple sensors, such as external and internal air temperature/humidity sensors, occupancy sensors, CO_2 level sensors etc.

Collected information must be adequately analysed and handled by the HVAC controller, which consequently sends command signals to different subsystems.

	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.

Table 4.2-1 – Centralised vs. decentralised heating and cooling systems (Source: adapted from: Energy Conservation Building Code User Guide, Bureau of Energy Efficiency, 2009)

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. to move with continuity heat 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 across the middle of 19th century, after the scientific advancements about thermodynamics took place.

The second principle of thermodynamics teaches us also another important lesson: if the aim is to produce heat at about 20 °C – the comfort 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 low 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 unavoidably is released in the operation of a thermal engine producing mechanical power.

Efficient energy conversion technologies are the ones based on the exploitation of the second principle of thermodynamics.

4.2.2.1 Refrigerating machine and heat pump

The refrigerating machine 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 higher temperature (Fig.4.2-26). The same process can be used to extract heat from a room and to release it to 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

The 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. 4.2-26). 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

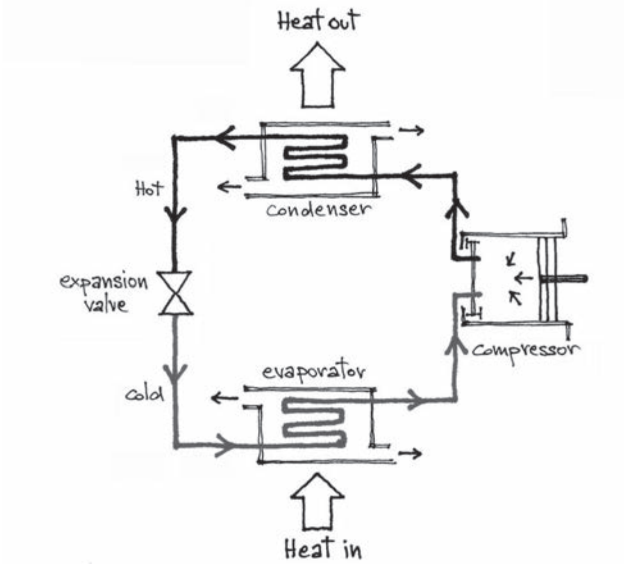


Fig. 4.2-26 - Vapour-compression refrigeration cycle

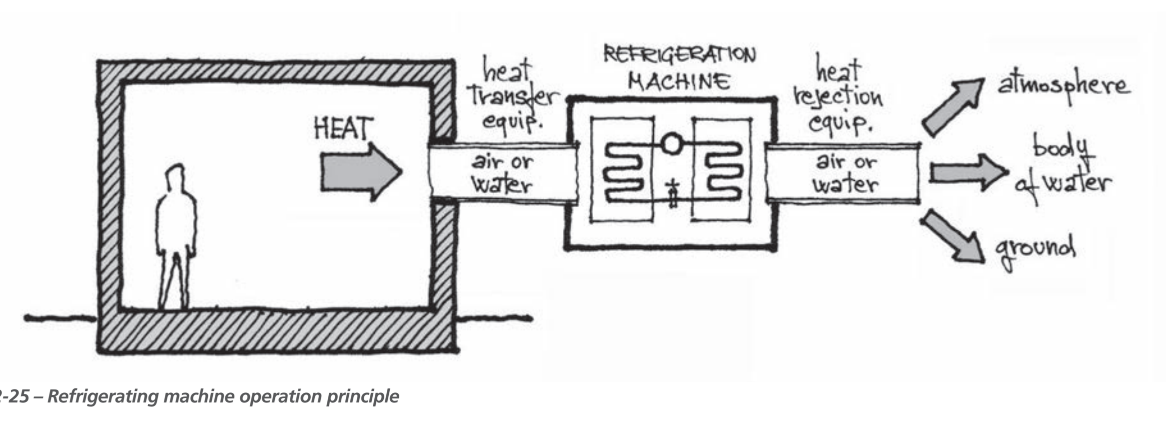


Fig. 4.2-25 – Refrigerating machine operation principle

either water or air.

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 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. 4.2-27) requires no compressors or other moving parts to operate the thermodynamic cycle but it 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.

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

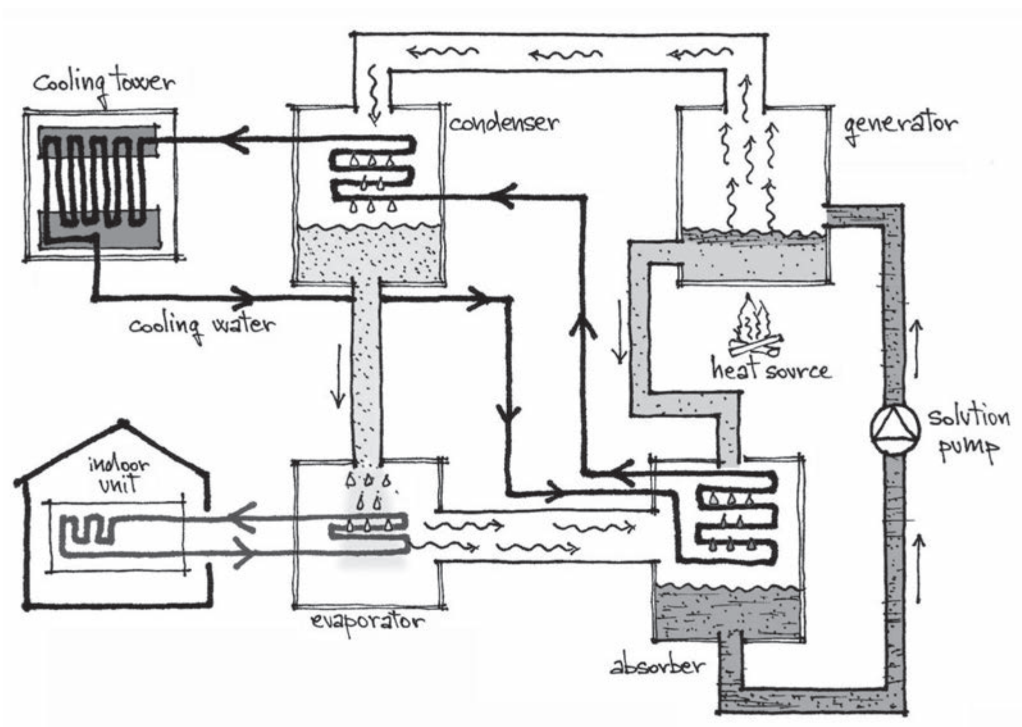


Fig. 4.2-27 Absorption refrigeration machine cycle

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 directly the room air through an evaporator and transfers heat to the external environment by means of an air cooled condenser;
- air to water: the refrigeration machine cools directly the room air and transfers heat to the external environment by means of a water cooled condenser; such 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 to the temperature of the heat source: the higher is the temperature, the higher is the system efficiency. In this sense, the EER of an absorption machine is variable depending on the type of heat pump and the operating conditions and has, in general, a value lower than 0.6; only in presence of high-temperature sources (>160-180°C) double-effect machines can be used, with an EER up to 1.2.

Overall, although the definitions of EER in the two systems are different, vapor compression machines always outperform absorption machines in cooling mode.

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 from 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. 4.2-28). 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.

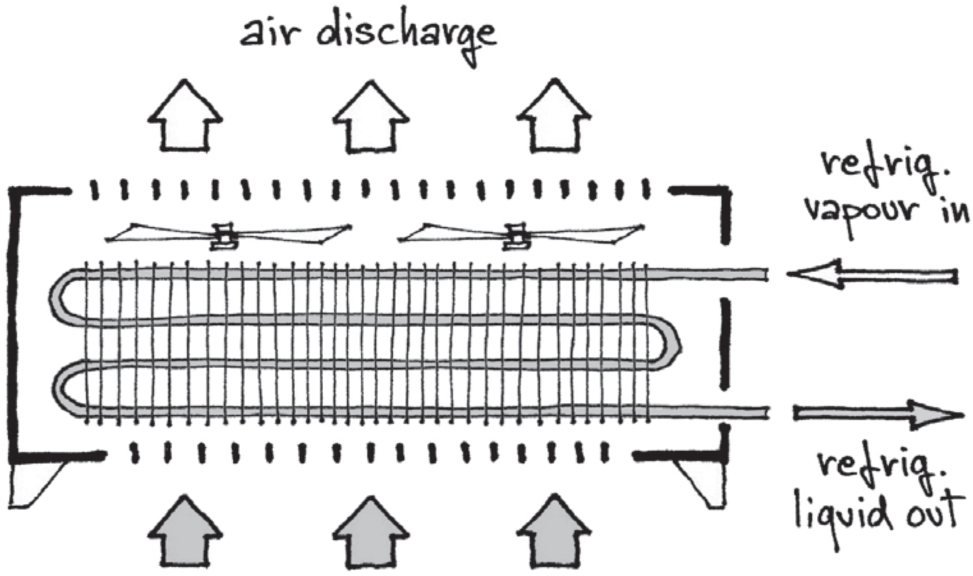


Fig. 4.2-28 – Air cooled condenser

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. 4.2-29, left) 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.

A closed cooling tower (Fig. 4.2-29, 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

For improving the energy efficiency of the air cooled condensers, several systems have been developed.

Evaporative Condenser

An evaporative condenser (Fig. 4.2-30) is a device that is meant for cooling the refrigerant in the condenser coil by evaporating water. Water is sprayed on the condenser coil and evaporates, cooling the coil.

Evaporative pre-coolers

Typical air-cooled condensers lose efficiency significantly during hot outdoor conditions. Evaporative pre-coolers reduce air conditioner load by cooling the air that surrounds

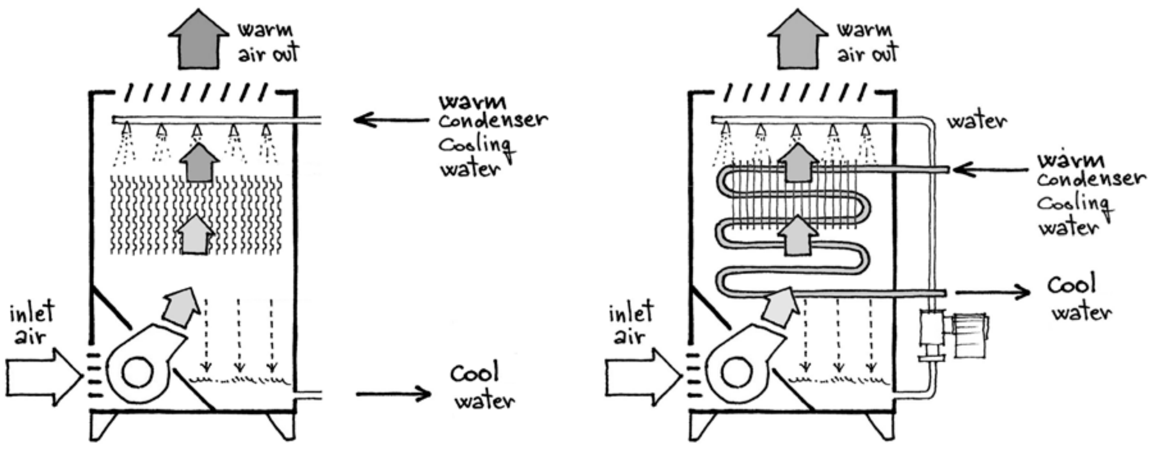


Fig. 4.2-29 – Open cooling tower (left); closed cooling tower (right)

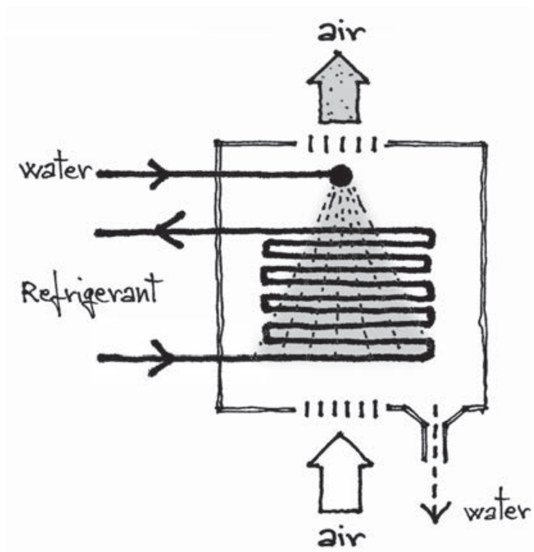


Fig. 4.2-30 – Scheme of evaporative condenser

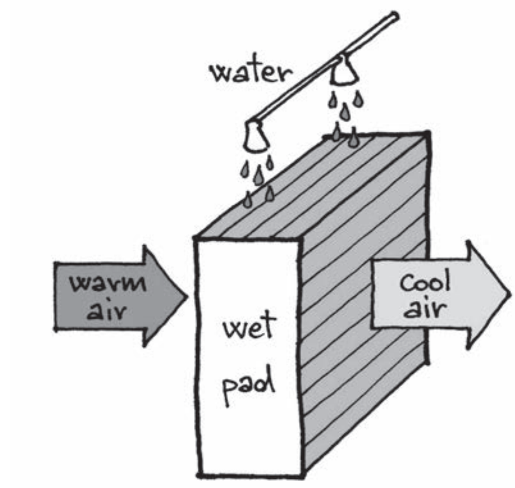


Fig. 4.2-31 - Direct evaporative cooling.

air conditioner condensers. The principle of evaporative cooling technique described below (Fig. 4.2-31) 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 the system to operate at a much higher efficiency during peak conditions.

Peak demand can be reduced by 40%. These systems provide the greatest benefit in climates that have significant hours of cooling during 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 period 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. 4.2-31). The cooled air is circulated by a blower.

The air, cooled by 10 to 20 °C crossing the water-soaked pad, is then directed into the room, and pushes warmer air out through windows.

When operating an evaporative cooler, 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 m^3/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. 4.2-32). 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.

Two-stage

Two-stage evaporative coolers (Fig. 4.2-33) 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

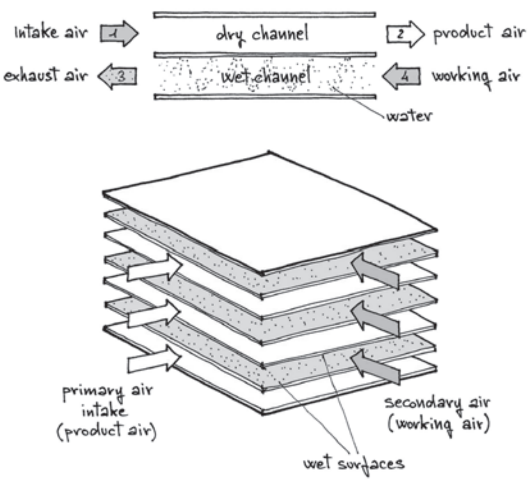


Fig. 4.2-32 – Indirect evaporative cooling

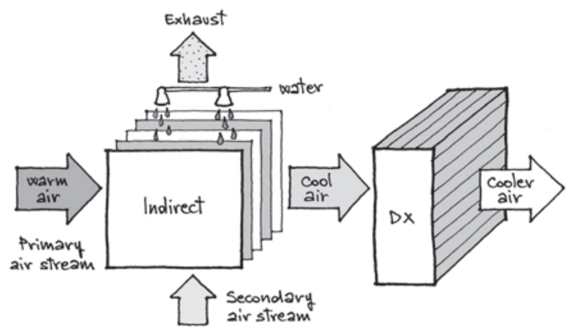


Fig. 4.2-33 – Two-stage evaporative cooler

air is pre-cooled in an indirect evaporative cooler. In the second stage, the precooled 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.

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 coupled with DX backup

Indirect evaporative cooling can be coupled with conventional DX (direct-expansion) cooling to lower refrigeration loads to meet cooling demand during hot and but not very dry outdoor conditions (Fig. 4.2-34). 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.

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.

Desiccant-enhanced evaporative air conditioners

DEVap (desiccant-enhanced evaporative) air conditioning systems consist of two parts: the liquid desiccant dehumidifier and the IEC (indirect evaporative cooler). This system can be arranged to provide total fresh air or work in recirculation mode. The working principle is as follows: the inlet air passes through the desiccant dehumidifier, and its moisture content is reduced based on the absorption capacity of the desiccant unit; the latent loads are handled in this first stage. Then, the hot-dry air enters the IEC and is cooled until it reaches the supply conditions; the sensible loads are handled in this second stage. Since the air is sufficiently dry after the first stage, the evaporative process is not dependent on the climate anymore; therefore, this system can be implemented in hot climates, either dry or humid.

Moreover, this system combines the benefits of both technologies, lowering the energy consumption and the environmental issues since it uses only water as the refrigerant.

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

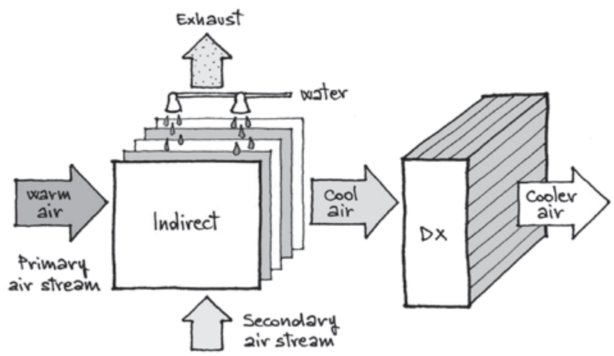


Fig. 4.2-34 – Indirect evaporative cooling coupled with direct-expansion (DX) cooling system

be some concern about the water-use impact of adding an evaporative cooler.

The evaporative cooler water tank is a common place for mosquito breeding. To avoid this negative effect chemical larvicide must be used or, better, sealed water tanks to prevent mosquito eggs.

Odours and other outdoor contaminants may be blown into the building unless sufficient filtering is in place.

Mold 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.

4.2.2.3 Co-generation and tri-generation systems

Co-generation or CHP (combined heat and power) and Tri-generation or CHCP (combined heat, cooling and power) refers to the simultaneous generation of electricity and useful heating (CHP) and also cooling (CHCP). The most common technical configuration is made of a reciprocating engine or a micro-turbine powering an alternator; then, in CHCP an absorption chiller is added, which is powered by the waste heat from the generator. This technical solution can be economically viable in contexts characterized by a constant need of 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 be noted also that the lower is the national electricity generation efficiency, the more the application of a tri-generation systems must be considered in comparison with electric chillers, especially if also heat is needed and it 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.

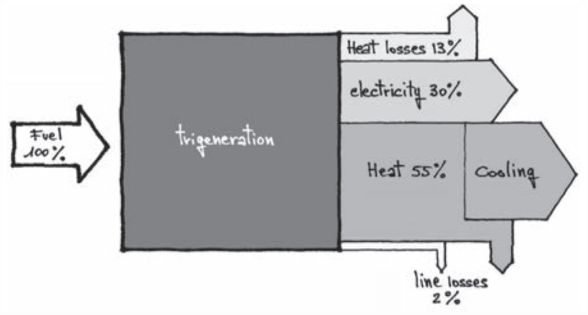


Fig. 4.2-35 – Energy flows in a typical tri-generation system

In Fig. 4.2-35 energy flows in a typical tri-generation system are illustrated.

The described configuration is that of a typical tri-generation system. A further upgrade can be obtained adding also a vapour compression refrigeration unit working in parallel with absorption refrigeration unit; by this way, thought an 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 dispatching of the produced energy.

4.2.2.4 Decentralized devices

For heating or 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 packaged condenserless air conditioners.

Window air conditioners

A window air conditioner is a packaged direct refrigerant unit constituted by 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, evaporator and condenser are placed respectively on the interior or 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.

Anyway this element presents several drawbacks concerning performance, aesthetic, noise, space utilization and air infiltration. The application of window air conditioners should be limited to provisional installations or in such contexts where other technical solutions cannot be applied for technical constraints.

Packaged condenserless air conditioners

Wall-mounted air conditioners differ from window air conditioners and split units since they have no external/outdoor units or condenser. Instead, the exterior wall must be drilled in two small holes or grilles (typically, 160 mm diameter each), which allow air to flow in or out (Fig. 4.2-36). Considering their design and their installation, this option offers more energy savings compared to window air conditioners, which require proper sealing around the unit to prevent infiltration/exfiltration issues. These systems can be used for heating, cooling, ventilation and dehumidification with no external units; just a condensate drain pipe must be added. Other benefits also include improved aesthetic appearance and noise reduction regarding traditional room air conditioners.

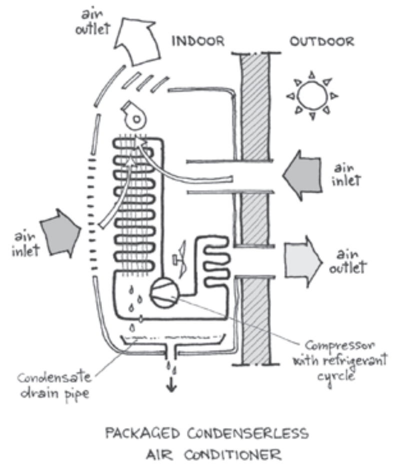


Fig. 4.2-36 – Packaged condenserless air conditioners

Packaged rooftop air-conditioner

A packaged rooftop air-conditioner (Fig. 4.2-37) is typically composed by a vapour compression refrigeration unit cycle, an air handling unit (fan, filter, dampers) and control devices. This kind of system, as suggested by his name, is typically placed on the flat roof of a building and conditioned air is typically directly injected inside the conditioned space with short ducts. The typical capacity for a rooftop packaged unit is much bigger than for a unitary air-conditioner and, thanks to the bigger size of this solution respect to windows air conditioners, the working efficiency is typically higher; moreover, many efforts have been made by manufacturers in recent years to improve energy efficiency. On the contrary, drawbacks related to aesthetic, noise and space utilization must be considered. The application of packaged rooftop air-conditioner could be considered in commercial buildings where air conditioning of large enclosed spaces is requested, also if the performance of the system with high outside air temperature and humidity must be carefully analysed.

Similar to air handling units in central systems, packaged rooftop units can operate in two cycles: open and closed. The open cycle corresponds to the 100% outdoor air mode in which no recirculation occurs and the return air is removed by an exhaust fan. On the other hand, the closed cycle refers to the recirculation mode, where the outdoor air intake can be partial to mix with the recirculation air or zero for applications that no require ventilation. In case of 100% outdoor air applications, these systems can be coupled with energy recovery units to obtain energy savings or an economizer for free cooling, depending on the outdoor conditions.

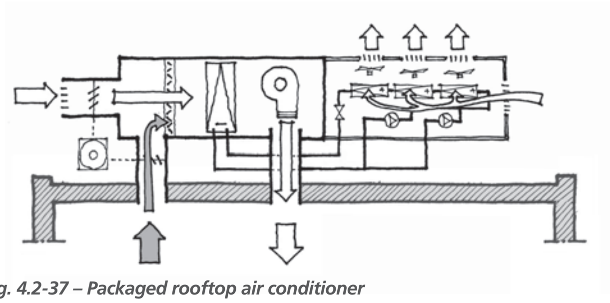


Fig. 4.2-37 – Packaged rooftop air conditioner

Evaporative coolers

In hot arid and hot semi-arid climates decentralized/ potrable evaporative coolers are a good alternative or complement to windows air conditioners and to split systems. For a detailed description of available solutions see section 4.2.2.2.

Fireplaces

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 or well-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 (Figure 4.2-38), which is typically low due to the large losses through the chimney. 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

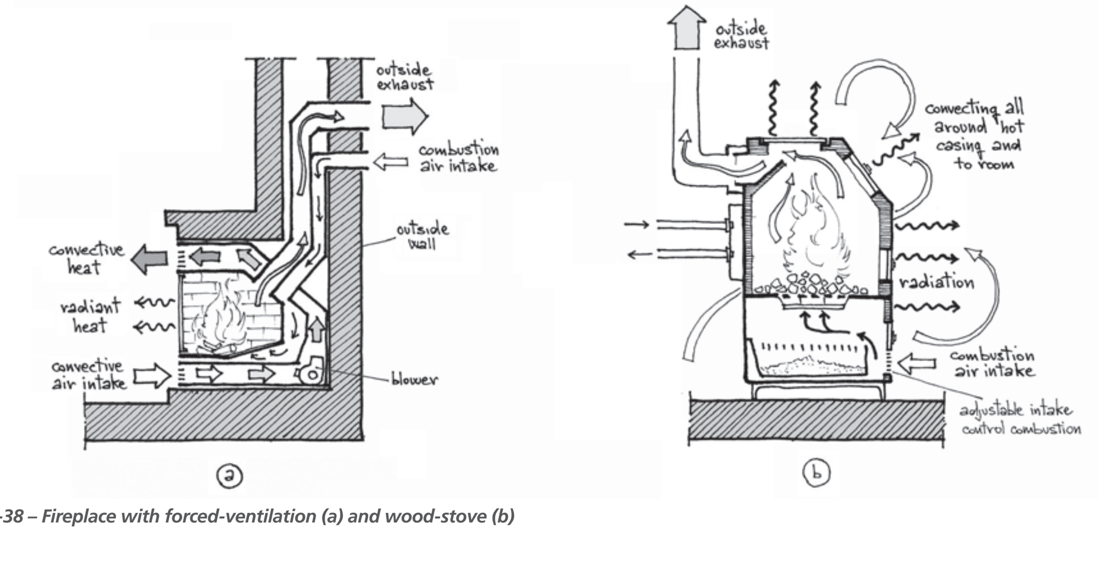


Figure 4.2-38 – Fireplace with forced-ventilation (a) and wood-stove (b)

produced by fireplaces, especially if naturally vented, must be carefully taken in account.

Wood Stoves

Wood stoves (Figure 4.2-14b) are on-site combustion devices, normally self-contained, that provide higher efficiency than fireplaces. Better control of combustion air permits a more complete combustion, resulting in improved resource utilization.

Recently, many technical solutions working with woodchips are available in the market; these systems could have an automatic woodchips loading system, an electronic combustion control and can easily heat also large spaces, reducing also the pollution due to incomplete combustion.

In many cases wood stoves can also integrate other functions, as cookers and an oven, and their application in residential contexts can be considered, if biomass is locally available.

4.2.3 DHW production

Energy consumption share of DHW (Domestic Hot Water) systems may be significant in many types of users such as hotels, sports centres, gyms, hospitals, and in residential buildings.

Such systems can be centralized, thus with a unique generation system for the whole building, or decentralized, with multiple generators installed close to the DHW supply points.

The network is single (only cold water) if water heating takes place locally (domestic water heaters) while it is double if DHW production is centralised, as illustrated in the figures 4.2-39 and 4.2-40.

The water coming from municipal water supply must have sufficient pressure to reach the most disadvantaged users and exit the dispensing tap with a certain residual pressure.

If the pressure is insufficient (common situation for tall buildings) it is necessary to install an appropriate pumping system. The distribution circuits may be one or two depending on how the hot water is produced.

Decentralized DHW systems with heat pump

A heat pump water heater (HPWH) works using the same principles as a refrigerator but in reverse. Instead of rejecting heat from the interior to the environment, HPWHs use the heat from ambient air to transfer it to water in a storage tank (Fig. 4.2-41). These systems can achieve significant energy savings in a factor of 3-4 compared to traditional water heaters. Apart from being used for water heating purposes, HPWH systems can also be incorporated in space conditioning systems due to the cool dry air at their outlet. Moreover, these technologies can be compact units, where the compressor and storage tank are packaged in the same unit, or split units, where the compressor and storage tank are separated.

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.

Hot water circuits may favour the growth and dissemination of legionella, considered that the range of proliferation of the bacterium is between 15 °C to 50 °C (up to 22 °C the bacterium exists but is inactive). There are critical places in the DHW systems: inside the pipes, especially if old and with deposits inside, or in storage tanks, in shower heads and in the taps.

An additional source 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, from time to time, is heated to 60 °C and over, to kill the possible germs.

4.2.3.2 Correct use of potable water

The basic resources are obviously essential in every building, but what has changed over the last several decades is the realisation 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 purposes for which it may

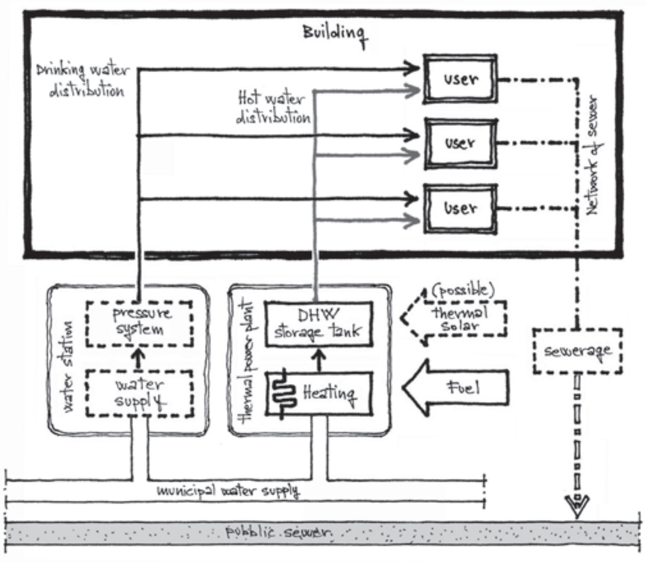


Fig. 4.2-39 – Schematic diagram of a centralised DHW system

be used, is not uniformly distributed.

Drinking water is a precious resource and its saving is one of the features of a sustainable building. The reduction of the use of drinking water can be obtained in two ways:

- with a more conscious use of it (for example installing saving devices as aerator valves, taps with timers, etc.);
- by replacing drinking water with non-potable water for the uses in which drinking water quality is not needed (e.g. for toilets, irrigation, etc.).

The first strategy implies the introduction of devices reducing the quantity of hot water used, whilst still maintaining the quality of service.

In the second case, instead, it is necessary to provide a dual supply system, one for drinking water and one for non-potable water. We define as drinking water the water that can be used for human consumption without harmful consequences to the health.

Non-potable water is water that, while not responding to chemical, physical and biological characteristics of drinking water does not contain anything that is polluting or otherwise dangerous for people coming in contact with it.

The distinction between drinking water and non-

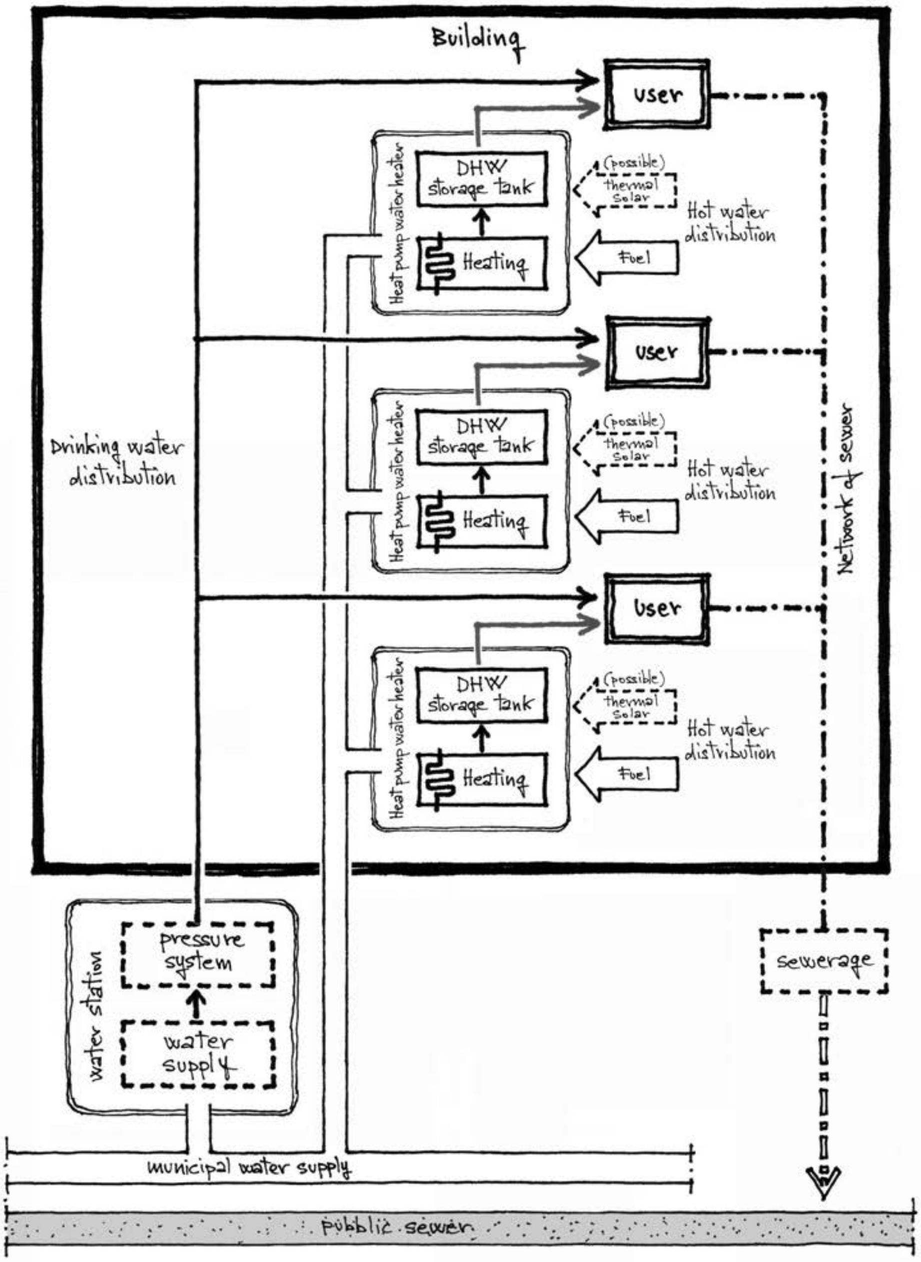


Fig. 4.2-40 – Schematic diagram of a decentralised DHW system

potable water is defined by the local health regulations whose compliance is monitored by the in charge authority. Non-potable water may be used for many applications and the list below gives some examples:

- urinals or vessels;
- industrial laundries and industrial cleaning in general;
- watering plants;
- supply of fountains, ornamental pools and similar;
- make-up circuits of cooling towers;
- heating circuits for heating or cooling of other fluids;
- fire systems (hydrants, sprinklers, etc.).

The distribution of non-potable water must be distinct in each point of the related piping and terminals from that of drinking water. No connections are allowed between a drinking water supply and a distribution system of non-drinking water even when equipped with shut-off valves. All components of the distribution networks of non-potable water should be notably and indelibly marked with words and symbols in accordance with local regulations.

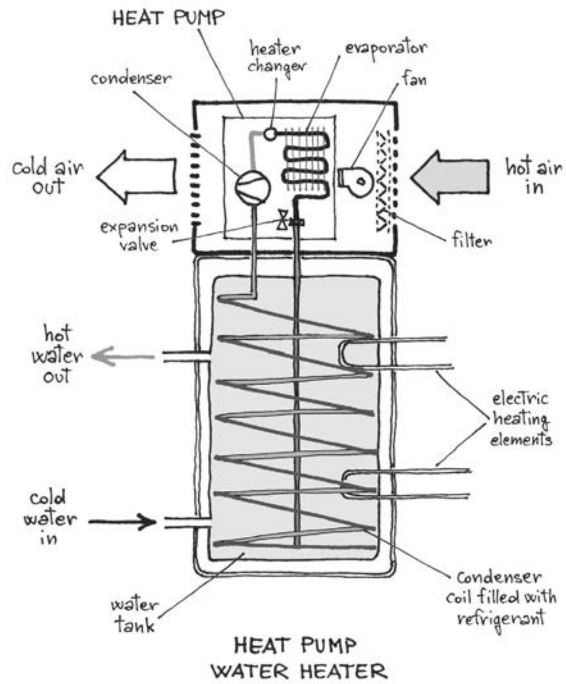


Fig. 4.2-41 – Heat pump water heater

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 Africa, 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.

Table 4.2-2 – Improving the performance of DHW systems

4.2.4 Artificial lighting

Lighting is an important issue in minimizing overall energy consumption. For the industrialized countries, lighting accounts for 5–15% of the total electric energy consumption.

Besides direct savings, indirect energy savings can be realized due to a reduced consumption for air conditioning.

The energy consumption of a lighting installation is strongly 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 measure for the 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 high temperature filament heated through electric current. The 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 backward: instead of light generating electricity, electricity generates light.

The factors that characterize a light sources are (see also Appendix 2):

- luminous flux, expressed in lumen;
- luminous efficacy[1], 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[2];
- 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, low colour temperature. Because of their low luminous efficacy, incandescent lamps production is going to be stopped all over the world. Fluorescent lamps have higher luminous efficacy, long life and lower luminance, but their colour rendering is worse than that of incandescent lamps.

LED lamps are currently the most widespread as they are characterized by high efficiencies and excellent colour rendering. In this sense, only the LED lamps will be described in this chapter.

Light emitting diode (LED)

A new and promising development are the light emitting diodes (LEDs) as light sources. 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 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 of what is used by incandescent lamps to produce the same quantity of light and their life expectancy is 100 times greater.

The performance operating characteristics of different type of lamps is summarised in Table 4.2-3.

4.2.4.2 Luminaires

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 luminaires have the task to modify, in relation to the specific requirements, the characteristics of flux and the luminance of lamps received by them.

The control of the luminous flux distribution is obtained by exploiting the optical properties of some materials (Table 4.2-4).

The 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).

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 expressed usually as in %. This may be divided into upward and downward parts (divided by the horizontal plane across the centre of the lamp).

1 *The luminous efficacy of a source can be defined as the ratio of the lighting power to the electric power used to obtain it.*

2 *All kinds of lamps, to a greater or lesser extent, are subject to a process of gradual decay of the emitted flux prior to fail prematurely.*

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

Table 4.2-3 – Lamp performance and operating characteristics[3]

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

Table 4.2-4 – Transmission coefficients of some materials

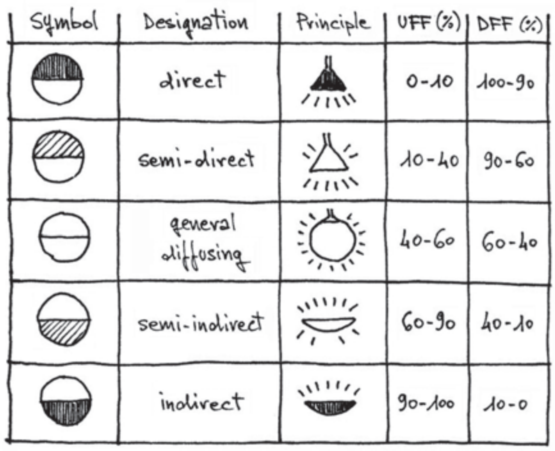


Fig. 4.2-42 – Luminaire types and their flux fractions

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 direction 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 symmetric (e.g. luminaries 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 asymmetric, the greater the departure from symmetry, the more planes needed for accurate calculations (Fig. 4.2-44), such as with fluorescent luminaires, where at least two planes are required (Fig. 4.2-45).

4.2.4.3 Lighting control systems

The further one moves from the window, the more difficult it becomes to maintain the daylight illumination levels required for some tasks. When those tasks are localized, like deskwork, 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, 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.

Properly designed artificial lighting control can yield functional, aesthetics, psychological, economic and environmental benefits. Lighting control allows for the flexible use of spaces, as well as the creation of interesting and varying lighting environment. Lighting control is also is one of the best ways to save large amount 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).

Artificial lighting can be controlled by a photosensitive cell so that it is automatically switched on or off when daylighting reaches at 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).

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 computer at a central location to control the lights. This central control of lights is a part of energy management system.

Dimming is another powerful tool for energy savings. When daylighting is used, switching and dimming are especially important.

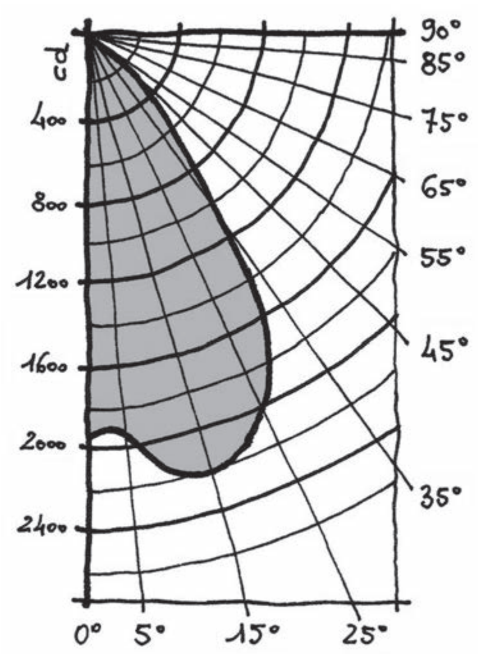


Fig. 4.2-43 – Photometric curve of a spot-light

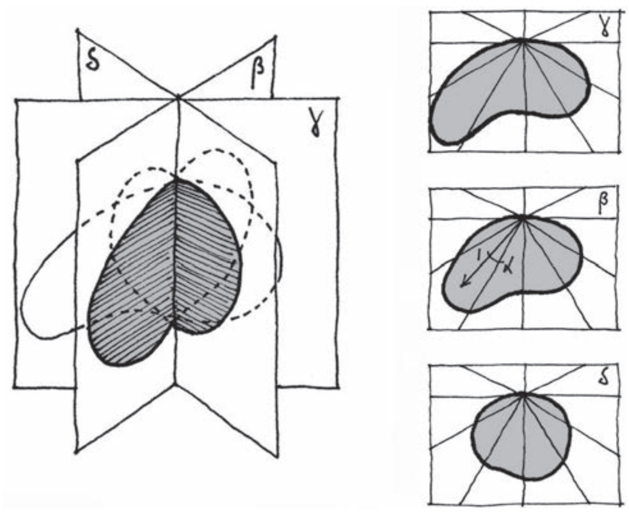


Fig. 4.2-44 – Photometric curves of asymmetrical lighting source

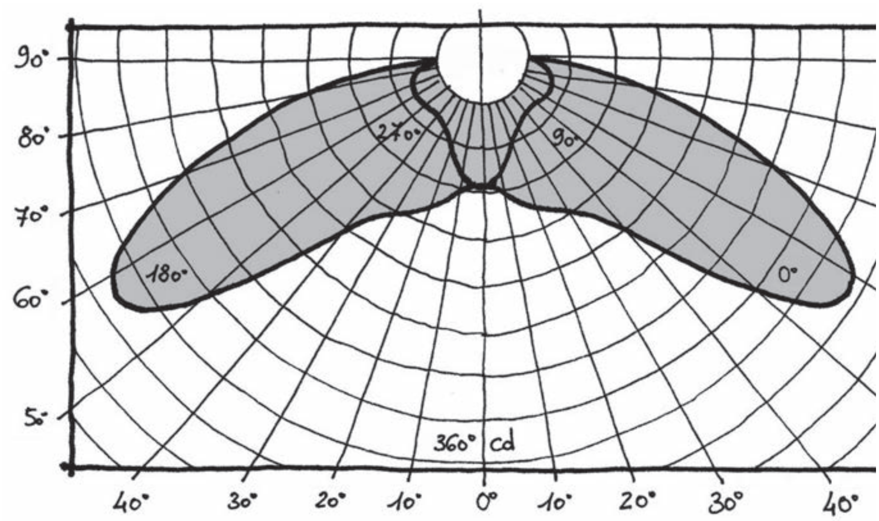


Fig. 4.2-45 – Photometric curves of a luminaire with fluorescent tubes. The angles 0°, 90°, 180° and 270° indicate the position of the planes on which the curve is plotted (see Fig. 4.2-44)

4.2.4.4 Lighting systems design

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 that are used at different stages of the design process.

The final design of lighting systems today is performed with the aid of the computer[3]; a reasonably reliable estimate can be made, however,with simply rule of thumb as a starting point for more accurate evaluations. It can be applied to rooms characterized by standard shape and color finishing equipped with direct lighting devices. In such respect it can be assumed that 270 lumens (provided by lighting devices) are required for every 100 lux per each square meter of surface to be illuminated; considering a LED device with an average efficiency this means 2 W/m^2 of electrical absorption per 100 lux. The system design

3 *The software which allows the lighting evaluation generally are able to import the general layout of the building via CAD files. Then lighting elements are added, finally, each lighting objects are associated with a photometry via IES files. Once this process is completed, the illuminance and luminance produced by each fixture in the space can be calculated. The output is typically a diagram indicating these by means of colors or numbers. The most adopted open-source software is Radiance.g*

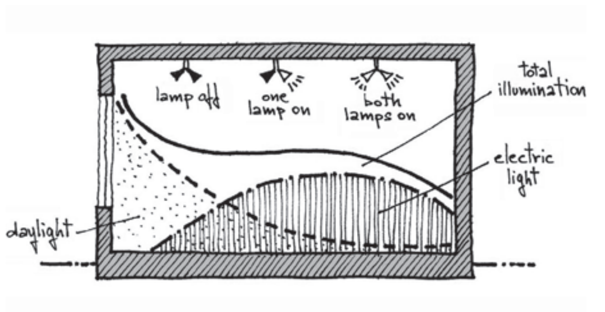


Fig. 4.2-46 – Maintaining design illuminance with electric light switching in layered zones

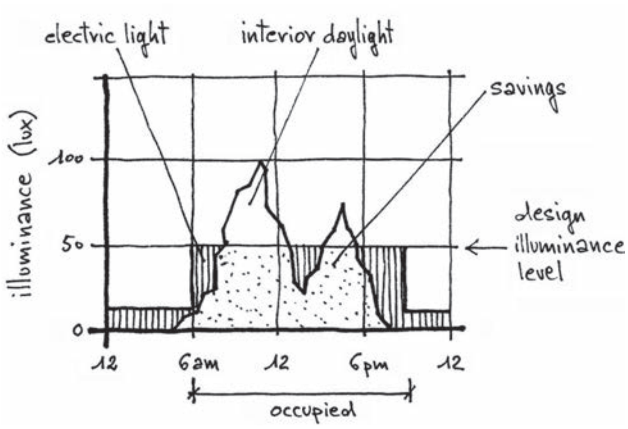


Fig. 4.2-47 – Potential energy savings from daylighting

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

Table 4.2-5 – Recommended illumination level (EN 12464-1 Standard)

requires that, once the activities to be performed in the room is defined, the designer must take initial decisions; are as follows:

- 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, also in relation to the optimization 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 4.2-5 shows the values of illumination recommended in relation to the activities[4]. It should be noted, however, that recent investigations showed that 300 lux, instead of 500 lux, is the most appropriate value for office buildings.

- the type of illumination (direct, semi-direct, diffuse, etc..) motivated by the technical, economical, aesthetical parameters, and the choice of the type of illumination is accompanied by the choice of the type of luminaries, which is also conditioned by glare control;

- the type of source, according to economic parameters (cost, duration) and technical (quality of light).

The illumination of the working plane depends both to the direct flux, from lighting fixtures, that by indirect, re-diffuse-from walls and ceiling-which depends on the colours and geometry of the room.

4.2.4.5 Tips for artificial lighting

For minimising energy consumption, the integration of daylighting and artificial lighting should be considered since 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 required ambient lighting for most operating hours. User-controllable task lights should be provided to assure 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, design 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 produced, should be used very carefully: it is very inefficient from the point of view of energy consumption. Better use luminaires providing semi-direct illumination with UFF < 20%: it is a good compromise between energy efficiency and visual pleasantness.

4 *EN 15251 Standard*

Lamps

- Use fluorescent lamps and dimming ballasts. Fluorescent Most dimming fluorescent ballasts dim to 10-20% light output, but "architectural" dimmers dim to 1% (these dimmers come at a cost premium).

- Use LED sources, especially for task lighting. LED 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. Even if more expensive they are dimmable and have a very long life-time.

- 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 fluorescent lamps with a colour temperature of 4000 K. If, otherwise, daylighting is sufficient for 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 suffer 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.

- 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): 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 sources to avoid glare. Direct/indirect lighting is one method.

- Use lighting strategies to balance window glare if anticipated. Keep luminance of 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 slight 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.

4.3 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 the 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 approaches 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/time. 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 size of the natural components of the system.

In hybrid systems a strong interaction exists between the ventilation system and the control strategy. It is essential 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 architect is essential.

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 deviations 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 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 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 not to be able to predict airflows, and different tools must be used.

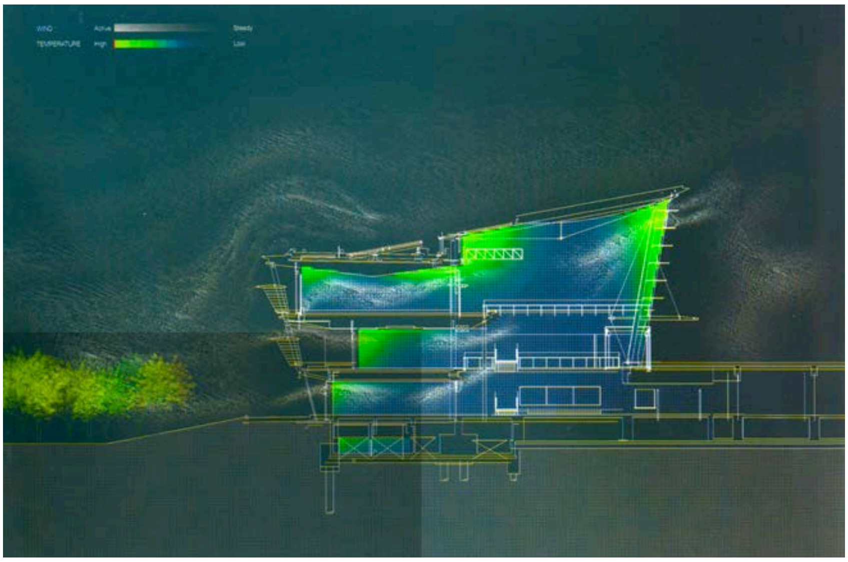


Fig. 4.3-1 – CFD analysis of airflow around and through a building (Source: Sustainable Architecture in Japan – The continuing challenge 1900-2010 & beyond, Nikken Sekkei, 2010)

Until a few years ago, the only tool available for a reasonably correct prediction of natural ventilation in complex buildings was the wind tunnel. Today it is not so, because simulation models are available allowing calculating and predicting exactly 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, windows surface temperature, air temperature, heat load, wind velocity, etc. Only a dynamic computer simulation of the energy behaviour of the building can provide this information.

Simulation that is also necessary for optimising the building components. This implies that hybrid ventilation design cannot be carried out without sophisticated design tools and appropriate expertise.

Hybrid ventilation proved to be quite effective in achieving good indoor air quality and thermal comfort, in spite of diffuse fears held by potential users and designers.

Energy performance was generally good but not excellent. The application of hybrid ventilation to retrofitted buildings achieved good results but was problematic in some cases.

Providing users the possibility of manual control during occupied hours and utilizing their preference for adapting their clothing and using window opening before using mechanical equipment, suggests that hybrid ventilation exploitation can be optimized in cellular offices.

The past experiences show that it is difficult to avoid comfort complaints in open plan offices; this is also seen in buildings with natural or mechanical air-conditioning systems. It was difficult (or perhaps impossible) to control the local conditions, which was probably perceived by the users as a personal limitation, and which influenced their thermal comfort evaluation. Hybrid ventilation systems have proved to be suitable for schools[1].

Hybrid ventilation is well practised technology, but several problems are still to be solved. Many hybrid ventilation components are designed for a specific building project, and the use of advanced technologies to develop hybrid ventilation-specific components and systems could significantly improve the performance. Further development of robust control strategies and more reliable and cheap CO_2 sensors (or alternative sensors for demand control) is also very important.

1 *IEA (2002). Principles of Hybrid ventilation, P. Heiselberg (Eds.), IEA Energy Conservation in Buildings and Community Systems Programme, Annex 35: Hybrid Ventilation in New and Retrofitted Office Buildings.*

4.4 Existing Buildings

For existing buildings equipped with HVAC systems, in African climates a substantial part of the electricity consumption is associated to the uses related to the summer air conditioning. This consumption can be reduced by:

1. reducing the energy demand of the building, i.e., improving the performance of the envelope by reducing the heat gains;

2. reducing the energy consumption of the air conditioning system, eliminating energy wastes and redesigning it in a more appropriate way.

The objective of a HVAC system is to maintain in the indoor spaces the design operating conditions, such as the air temperature, relative humidity and air purity.

To ensure the healthy environment of the internal spaces it is necessary to maintain suitable IAQ (Indoor Air Quality). A correct ventilation of internal spaces is therefore necessary but, on the other hand, it contributes significantly to increase energy consumption, since a 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 Envelope improvement

4.4.1.1 Pitched and flat roofs

The measures to reduce heat gains through the roof depend upon the type of it: flat, pitched or domed.

For the thermal insulation of a single leaf pitched roof two retrofit measures can be considered (Tables 4.4-1 and 4.4-2):

- from outside: removal of the tiles and replacement of the existing roof with a new, better insulated, one: this measure is specially 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).

If the spaces under the roof are not used, action must be taken to improve the energy performance of the attic, by adding an insulation layer on its floor.

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.

Table 4.4-1 – Pitched roofing thermal performance improvement strategies

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.

Table 4.4-2 – Flat roof thermal performance improvement strategies

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.

Table 4.4-3 – External walls thermal improvement performance strategies

The improvement of the energy performance of the building envelope requires a check of the HVAC sizing and control system as the original energy balance has changed.

4.4.1.2 External walls

The energy performance of external walls can be improved by (Table 4.4-3):

- painting external walls with a light-coloured finish;
- decreasing the U-value through the application of a layer of insulating material;
- shadowing the walls.

The above strategies may also be adopted together.

External insulation is to prefer to internal because better comfort conditions are provided. They should be avoided in Hot-arid and tropical wet and dry climates.

The improvement of the thermal resistance is a barrier during the day, when the effects of the higher external air temperature are added to the effect of the solar radiation, heating the outer surfaces of the walls.

Since solar radiation effect on vertical walls dominate on external temperature effect, insulation is mostly appropriate in east and west facing walls, whereas south and north can be easily shaded.

4.4.1.3 Fenestration

For renovation of existing buildings, in order to reduce the effects of solar radiation on windows facing east or west, it may be cost-effective to install external sunscreens. Internal blinds, even opaque, have too high solar factors; these types of devices are not effective in preventing overheating due to solar radiation and are normally used for protection from glare. For effective solar control purpose there are several solutions, as shown in Table 4.4-4.

4.4.2 HVAC system improvement

The retrofit measures of mechanical systems on the basis of a careful analysis of the existing plant and components (through field surveys and monitoring) have the objectives of reducing the primary energy consumption by increasing the system's efficiency without compromising the required indoor comfort condition.

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 perform 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

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.

Table 4.4-4 – Thermal performance improvement strategies for fenestration

achieving two objectives: to reduce operating costs for lighting and to reduce 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 4.4-5 shows a list of possible retrofit actions for lighting systems and the approximate energy savings that can be obtained.

It should be also considered that the colouring 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 by 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 using chillers that use environmentally compatible refrigerants should be carefully considered, even if 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. Just the conversion of the chiller to operate with non-CFCs may probably be the most economical option. However, the non-CFC refrigerants (e.g., low-GWP refrigerants) may reduce the chiller cooling capacity 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 examining the cooling capacity of chillers in existing buildings, their usual oversizing 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 of the thermal insulation, implementation of sun protection strategies, etc.) are planned, the capacity of the cooling system can be significantly reduced. A precise calculation of the real cooling demand of the system is important, also because its reduction involves a reduction in size of the other components of the plant (e.g., pipes, pumps, terminals, cooling tower, etc.).

In Table 4.4-6 the possible actions for improving the energy performance of HVAC systems are summarised.

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 in the conditioned spaces. The types of HVAC systems can vary greatly depending on the needs of users.

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

Table 4.4-5 – List of possible retrofit actions for lighting systems and the approximate energy savings

Table 4.4-7 shows how the energy consumption due to the Air Handling Units (AHU) can be reduced.

4.4.2.4 Improvement of control systems performance

It is important for the auditor to assess, through measurements and monitoring, the existing indoor air temperature controls for evaluating 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 the performance, since the set-point values can be modified by the users. Only a control system, properly chosen, properly installed and properly adjusted and maintained, can guarantee the energy performance and the thermal comfort over time.

Possible control systems improvement strategies are shown in Table 4.4-8.

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 can be large, cube-like devices that may be noisy and difficult to screen.

To reduce 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

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%.

Table 4.4-6 – HVAC system improvement

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 with the architecture and materials of the house and existing landscaping features.

Plantings also must be chosen carefully, as the goal is to provide year-round screening consistency. One requirement to consider, in addition, is that some plantings 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 penalize their 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.

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.

Table 4.4-7 – Air handling units improvement

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.

Table 4.4-8 – Control systems improvement strategies

Units mounted too close to the wall or surrounded by shrubs, or multiple units located too closely 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 homeowner to consider is the noise impact of an exterior condenser unit. Although technology has improved and newer units are quieter than once, the 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 approve building codes or ordinances that defines the pre-requisites to be met in order to avoid visual and noisy impact of exterior HVAC equipment.

4.4.3 DHW Systems improvement

A set of energy 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 too high compared to the values required;
- check the possibility to turn off all the pumps at night or in the hours of non-use of the plant;
- replace the existing DHW generation system with a heat pump water heater (see paragraph 4.2.3)
- check the thermal insulation of the distribution pipes;
- check if there is the 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 of energy and resources waste.

Actions leading to management improvement 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

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).

Table 4.4-9 – Operation and maintenance improvement strategies

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

Table 4.4-10 – List of possible retrofit actions for HVAC systems and the approximate energy savings

follows (Table 4.4-9):

- correct setting of control devices (e.g., reduction of the hours of operation, appropriately matching the needs, or precise setting of occupied spaces' temperature);
- disabling components which are unnecessarily consuming energy;
- implementation of control procedures and consumption monitoring;
- implementation of maintenance procedures;
- implementation of information strategies and incentives amongst users.

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.

The actions of operation and maintenance improvement often do not require physical investments but only dissemination of good practice and labour investments, 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 high energy performance of the building and its facilities.

Among the physical actions, those on plants are cost-effective because the inefficiencies are widespread and the obsolescence of components and systems requires a continuous technological and functional renewal.

The retrofit actions of the building envelope generally are 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 savings 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 by the overall result that is achieved.

The right approach to assess the potential for energy saving is to use computational 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 refer to the data of Table 4.4-10. The figures are for reference only. Actual energy savings will depend on different conditions and applications.

4.5 Simulation tools

Energy performance simulation programs are powerful tools to study energy performance and thermal comfort. Today, numerous tools are available and they differ in many ways; in their thermodynamic models, their graphical user interfaces, their purpose of use, their life-cycle applicability, and their ability to exchange data with other software applications.

At present, the most widespread methods to evaluate building energy performance rely on simplified steady-state calculations based on average reference data. Such methods are quite obsolete and inaccurate, as they do not properly account for the complexity of phenomena impacting energy performance (thermal inertia, temporal fluctuations, peaks and dips of boundary conditions) and prove to be particularly inadequate in the case of tropical climates and cooling-dominated buildings. In these scenarios, characterized by dynamic paths affecting building thermal behavior and energy performance, designers need more accurate, hourly-based methods. These calculation methods, which take into consideration the actual building's thermal response (heat absorption and release induced by the variation of outdoor conditions at different times of the day) are implemented in the so called dynamic state simulation tools.

Today, 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 absolutely reliable (actually, as for DOE2 and EnergyPlus, developed by the Lawrence Berkeley Laboratory, they are the engine of most commercial products). Generally speaking the user should be aware about the required steps to run properly the simulation, hereafter listed:

- creation of a geometric virtual model;
- description of thermo-physical properties of the building envelope, such as thickness of the walls, conductivity, density, specific heat, emissivity, infiltration rate and optical properties of glazed surfaces;
- setting up the operational schedules of the building in terms of internal gains, ventilation patterns, human behaviour and HVAC systems set point;
- definition of the outdoor climate data relative to the study location.

However, according to the features and complexity of buildings, several simplifications have to be introduced; these represent uncertainties to take into account in the interpretation of the results. For example, buildings are often characterized by complex geometries that are often overlooked by modelling tools. These simplifications can unintentionally lead to underestimate thermal bridging effects, whose magnitude may not be negligible. The accurate representation of all discrete spaces comprising the building, including zones such as ceiling voids, shafts, staircase etc., also affects the amount of thermal mass in the building and thus its thermal performance.

Once the geometrical model is ready, the description of the properties of the building envelope, which include all the thermo-physical features of the technological components, is required. In this regard, the knowledge of the technical and constructive solutions adopted, such as the thickness of the wall (e.g. the bricks texture), the roof, ceilings and floor typology, and all the elements which allow to describe the stratigraphy of the building's components, are pivotal to obtain reliable results. However, the collection of these data can very often be difficult, and several assumptions must be made. In addition, the difficulty to assess the correct air change rate of interior spaces and the air leakage through windows' frames or chimneys, add further errors to the final result.

After the envelope characterization, the operation of thermal zones (related to the building function and the users' behaviour) must be set. The function of buildings may range from private/residential to public such as museums, libraries, schools and universities. However, this variety requires to record this information in situ with interviews and questionnaires submitted to the occupants, or to assume reference values from Standards. For this reason, the parameters related to user behaviour are one of the main sources of uncertainties. Moreover, it should be noted that the temperature set point and the human behaviour are typical uncertain variables even in modern building.

Finally, since some errors can also be due to the numerical model that may not adequately capture certain physical phenomena, the following further limitations mentioned in the Standard[1] should be mentioned:

- the thermo-physical properties of the materials are time independent (i.e. phenomena like degradation along the time is not considered);
- the various surfaces of the room or zone elements are isothermal (i.e. the walls are considered homogeneous);
- the heat conduction through the room/zone elements is assumed to be one-dimensional (i.e. thermal bridges cannot be considered in the overall simulation);

1 *International Organization for Standardization (ISO). Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads -- Part 2: Explanation and justification of ISO 52016-1 and ISO 52017-1, ISO/TR 52016-2:2017 2017.*

- the air temperature is uniform throughout the room or zone (i.e. the air stratification in big volumes are not take into account).

In such respect, energy simulation tools can be adopted, since the early stage of design, in order to ensure the compliance with regulatory requirements and to guide the optimization of the design choices, through the comparisons of different alternatives.

Of course, the user must be aware that such tools require considerable experience and skill to obtain reliable data. The correct use of tools alone is insufficient; the tool user/analyst/modeller also needs to have the proper knowledge and sensibility to apply them in the right manner.

4.6 Building Energy Codes - Energy Performance Certificates and Green Building Rating Systems

Building energy codes are the key tools for governments to mandate the construction and maintenance of low-energy buildings. One of the main objectives is to set out minimum requirements for energy efficient design principles and construction processes. Building energy codes specify the construction, performance and consumption of new buildings as well as additions, alterations and renovations of existing buildings.

Implementation of these codes can sometimes take place on a voluntary basis however, they are mostly written in mandatory, enforceable language to describe the cost-effective energy saving measures and significantly reduce overall built environment energy consumption[1]. However, current coverage of building energy codes is far from universal, and where they are implemented, the codes are typically not aligned with meeting a net zero goal by 2050.

According to recent report of IEA[2], as of 2019, less than 75 (about 38%) countries have or are developing a mandatory or voluntary building energy code, and around 45% of those countries' building codes cover just part of the buildings sector as shown in figure 4.6-1. Eighteen of the countries have adopted their codes since 2015. The current extent of national and sub-national building energy codes worldwide shows that Sub-Saharan Africa and South and Central America have the least coverage of mandatory codes.

As an inherent part of building energy code, building energy certificates evaluate the performance of a building and encourage higher performance. Progress in implementing energy certification programmes gained speed in several countries during last few years. As shown in figure 4.6-2, roughly 85 countries had building energy certifications in 2019: 40 had mandatory building energy certification policies; 20 had widespread voluntary certification policies or programmes; and the remainder had only a handful of voluntary projects.

For example. in the European Union, energy certification is mandatory when a building is sold or rented. Nevertheless, building energy certifications still fall short of promoting major change in the buildings market, as they are typically voluntary or cover only a small portion of buildings. They are, however, an important tool to better understand the characteristics and energy performance of the building stock, both for mapping energy renovations and for energy planning purposes.

Focusing on Africa[2], Morocco and Tunisia have mandatory building codes in place that cover the entire buildings sector. Ghana and Nigeria have codes that cover part of the sector, Egypt and South Africa have voluntary codes, Botswana, Burundi, Cameroon, Cote D'Ivoire, Ghana, the Gambia, Kenya, Senegal, Tanzania and Uganda are developing building code standards. Building energy code upgrades are under way in South Africa to incorporate climate zone differentiation.

Rwanda's Green Building Minimum Compliance System became applicable to non-residential buildings in 2019. The remaining 38 countries in Africa are reported to yet implement building energy codes.

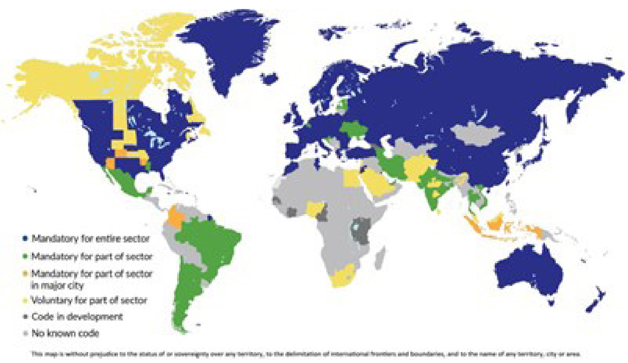


Fig. 4.6-1 – Building energy codes by jurisdiction (IEA, 2020)

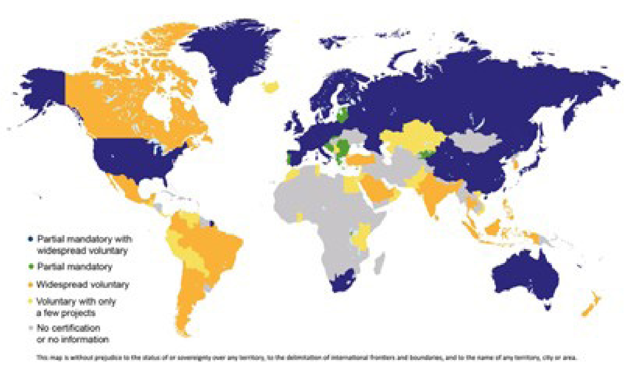


Fig. 4.6-1 – Building energy codes by jurisdiction (IEA, 2020)

1 T. Gaum, J. Laubscher, Building Energy Codes: Reviewing the Status of Implementation Strategies in the Global South, IJBES 9(1)/2022, 39-53.

2 Green Business Gazette, African countries urged to formulate energy codes for the building sector to reduce emissions, 2021.

4.6.1 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 comparably expensive procedures. EPCs are obtained rather fast, in comparison. Here, a visual inspection and energy survey is undertaken, mainly focussing on specific consumers and building feature, 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 of local (climatic) conditions.

Buildings that are achieving highest ratings, i.e., platinum, 5 star, exceptional etc. are typically better performing than even 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.

4.6.1.1 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 performances 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 Building Energy Efficiency Standard was set up in California with Title 24 in the year 1978, on voluntary basis.

EPCs are 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 not a federal law similar to that of the EU. The federal states are responsible to set standards and regulations.

In South Africa, EPCs are used earlier to evaluate public buildings only and currently from 2020 are compulsory for offices, entertainment facilities, educational institution buildings, and places of public assembly such as sporting facilities and community centres.

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. The country took a step forward in late 2018, developing its first national model building energy code for residential buildings.

In Brazil the National Program of Energy Efficiency in Buildings launched in 2010 the Brazilian energy Labelling Schemes for Residential (RTQ-R) and for Commercial buildings (RTQ-C), a voluntary standard.

The main types of building energy codes in use around the world are[3]:

- Prescriptive codes: These set performance requirements for specific building components.

3 *C40- How to set energy efficiency standards for new buildings.*

- Performance-based codes: These set a maximum level of energy consumption or intensity for the whole building, and can allow trade-offs (for example, less insulation but more efficient windows).

- Outcome-based codes: These require a specified performance to be achieved and verified over a period of at least 12 months (these are less common).

4.6.1.2 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 energy performance evaluation of buildings, but at the same time also take into consideration resource efficiency, the overall environmental impact of a building as well as its life cycle. GBRSs require an integrated design process to create projects that are environmentally responsible and resource-efficient throughout a building's life-cycle: from siting to design, construction, operation, maintenance, renovation, and demolition. A few of these programs are single-attribute, focusing solely on water or energy, while others are multi-attribute addressing emissions, toxicity, and overall environmental performance in addition to water and energy.

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 for 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 Life 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 buildings' environmental performance. The assessment of 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 (at retail or lending).

GBRSs typically comprise of a number of rating schemes that are tailored for 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 the 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 condition in the countries they have been developed for. This includes for instance legal, regulatory, social, cultural and climatic conditions that all must be addressed by a GBRS. Hence, the rating schemes are not necessarily and automatically uniformly applicable around the world, but require a careful revision and adaptation for the countries they are newly introduced at.

The main criticism about some GBRS is that many fully glazed buildings, recognised as mostly energy wasteful both in embedded energy and in operation, often reach the maximum sustainability rating: this is obtained by using most expensive envelope components and HVAC systems and by compensating the inefficient envelope with renewable energy, thus used for powering energy waste. Studies have shown that no significant difference in energy consumption between non-certified buildings and certified buildings was found[4]. Which is not what one should expect from green buildings.

Another, related, criticism derives from the fact that green building certification is being more and more fashionable and is going to have a very strong impact on building's marketing, stimulating greenwash in place of real greening.

4 *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*

Building Rating or Certification System	Type of Standard or Certification	Managing Organization	Issues / Areas of Focus
Building Research Establishment Environmental Assessment Method (BREEAM) UK	Green building rating and certification system through on-site independent third-party verification for: • New Construction • In-Use • Refurbishment & Fit Out • Communities • Infrastructure	BRE Global	Performance in: • Energy • Health & Well-being • Transport • Water • Materials • Waste • Land Use & Ecology • Management • Pollution No prerequisites for In-Use
Leadership in Energy and Environmental Design (LEED) USA	Green building rating and certification system through independent third-party verification for: • New Construction (NC) • Existing Buildings, Operations & Maintenance (EB O&M) • Commercial Interiors (CI) • Core & Shell (CS) • Schools (SCH) • Retail • Healthcare (HC) • Residential • Cities and Communities	U.S. Green Building Council	Performance in: • Sustainable Sites • Water Efficiency • Integrative Process • Location & Transporation • Energy & Atmosphere • Materials & Resources • Indoor Environmental Quality • Innovation • Regional Priority
Green Globes USA	Green building guidance and assessment program for: • Existing buildings • New construction	Green Building Initiative in the U.S. BOMA Canada	Environmental assessment areas to earn credits in: • Energy • Indoor Environment • Site • Water Efficiency • Materials • Project Management No prerequisites
Living Building Challenge USA	Performance-based standard, and certification program for: • Landscape and infrastructure projects • Partial renovations and complete building renewals • New building construction • Neighborhood, campus and community design	International Living Future Institute	Performance areas include: • Place • Water • Energy • Materials • Health & Happiness • Equity • Beauty All areas are requirements

Passive House Institute US	Performance based passive building standard • Third-party RESNET approved quality assurance/quality control • Earns U.S. DOE Zero Energy Ready Home status • Includes HERS rating	Passive House Institute US	Any type of building. New focus areas include: • air tightness requirements • source energy limit • space conditioning criteria • net zero energy
WELL Building Standard USA	Performance based standard and certification program for: • New and Existing Buildings • New and Existing Interiors • Core and Shell Retail • Retail • Education Facilities • Restaurant • Commercial Kitchen • Multifamily Residential	Administered by the International WELL Building Institute™ (IWBI)	Measures attributes of buildings that impact occupant health by looking at ten factors: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, Community, and Innovation.
BCA Green Mark Scheme Singapore	Benchmarking scheme that aims to achieve a sustainable built environment by incorporating best practices in environmental design and construction, and the adoption of green building technologies.	Building and Construction Authority (BCA)	Rates buildings according to five key criteria: • Energy efficiency • Water efficiency • Environmental protection • Indoor environmental quality, and • Other green and innovative features that contribute to better building performance.
Beam Hong Kong	Comprehensive standard and supporting process covering all building types, including mixed use complexes, both new and existing to assess, improve, certify, and label the environmental performance of buildings	Business Environment Council	Performance and assessment in: • Site aspects • Material aspects • Water use • Energy use • Indoor environmental quality • Innovations and additions
CASBEE Japan	Building assessment tools for • Pre-design • New Construction • Existing Building and • Renovation	JSBC (Japan Sustainable Building Consortium) and its affiliated sub-committees	Assessment areas include: • Energy efficiency • Resource efficiency • Local environment, and • Indoor environment
EDGE	A universal standard and a certification system for residential and commercial structures.	International Finance Corporation (IFC), a member of the World Bank Group	Assessment areas include: • Energy • Water • Materials

Green Star SA South Africa	Green building rating system for: • Office • Retail • Multi-unit residential	Green Building Council of South Africa administers program Independent assessors to assess and score projects	Categories assessed in: • Management • Indoor Environmental Quality • Energy • Transport • Water • Materials • Land Use & Ecology • Emissions • Innovation
Pearl Rating System for Estidama UAE	Green building rating system for: • Community • Buildings • Villas • Temporary Villas and Buildings	Abu Dhabi Urban Planning Council	Assessment of performance in: • Integrated Development Process • Natural Systems • Livable Communities • Precious Water • Resourceful Energy • Stewarding Materials • Innovating Practice
HQE (Haute Qualité Environmental, High Environmental Quality) France	Green building rating system for: • Non-residential building • Residential buildings • Detached houses	HQE Association	Assessment areas include: • Energy • Environment • Health • Comfort.
Green Rating for Integrated Habitat Assessment (GRIHA) India	Green building rating system for all kind of buildings: • Commercial, institutional, and residential buildings	Ministry of New and Renewable Energy, Government of India (MNRE)	Assessment through 34 criteria categorized under four categories: • Site selection and site planning • Building planning and construction • Building operation and maintenance • Innovation
Greenmark Scheme Singapore	Green building rating system for: • New buildings • Rental • Existing buildings • Schools • Office interior • Restaurants • Districts and infrastructure	Government of Singapore	Pre-assessment and assessment areas include: • Water • energy • environmental impact • indoor environmental quality

Green Building Index (GBI) Malaysia	Green building rating system for: • Residential buildings • Non-residential buildings	Government of Malaysia	Assessment areas include: • energy efficiency • indoor environment quality • sustainable site planning and management • materials and resources • water efficiency • innovation
GREENSHIP Indonesia	Green building rating system for: • Residential buildings	Green Building Council of Indonesia	Assessment areas include: • sustainable site planning & management • energy efficiency

Table 4.6-1 – Most commonly used GBRSs [6,7,8,9]

6 *S. Vierra, Green Building Standards and Certification Systems, 2022. https://www.wbdg.org/resources/green-building-standards-and-certification-systems*
7 *www.bca.gov.sg*
8 *www.greenbuildingindex.org*
9 *http://www.gbcindonesia.org*

05 | DESIGN AT COMMUNITY SCALE

5.1 Energy and the urban metabolism

An effective metaphor sometimes used is the city as a living system, and as such provided with its own metabolism[1]. The inputs of a city – energy, goods, food and water –are metabolised and transformed, by means of technological and biological systems, into inorganic and organic waste, greenhouse gases plus some goods and food: the city's outputs (Fig. 5.1-1).

The direct impact of cities' life on climate change is mainly due to the CO_2 production deriving from the combustion of fossil fuels[2], i.e. from their energy system; other GHG sources are nitrous oxides deriving from duel combustion and F-gases due to leakage of air conditioning and refrigeration systems. But the direct impact is not the only one. We know that cities have one more impact, indirect, on global warming, the one due to the emissions embodied in the flow of materials and food entering them. It is an impact that in most cases is far higher than the direct one, as shown in a study[3] carried out for the C40 cities (network of the world's megacities committed to addressing climate change): in average, 85% of GHG emissions caused by these cities are embodied in goods and services imported from elsewhere (including electricity) and only 15% produced within their borders.

Even if in settlements other than mega and big cities the unbalance balance between the emissions produced directly within their borders and those embodied in the goods and in the food imported is generally less extreme, however the embodied emissions issue is a very critical one and should never be overlooked.

Mainly because of these embodied emissions cities are responsible for 60-80% of global greenhouse gas emissions[4], a contribution whose extent is explained also by the fact that they consume 75% of the natural resources entering the economic circuit[5] and 67% of all the food produced in the world[6].

Thus, for minimising emissions a prerequisite must be fulfilled: minimisation of fossil fuels and materials inputs; prerequisite that can be satisfied by maximising renewable energy use, energy efficiency and recycling and reuse of water and materials.

This implies the abandonment of the present linear metabolism, based on the approach "Make-Use-Dispose", that has characterised the urban development since the beginning of the industrial revolution.

Limiting the analysis to the direct emissions due to the local energy consumption, the energy system of a city can be considered as a thermodynamic system in which high grade, i.e. low entropy energy is transformed into low grade energy, i.e. high entropy. 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. As any thermodynamic system, urban energy system can be more or less efficient, i.e. can require more or less high grade energy to perform its tasks, thus releasing more or less low entropy waste. The present urban thermodynamic system is very inefficient, because inefficient is the way it metabolises the low entropy input, and for this reason we waste a very large amount of high grade energy that is contained in fossil fuels – as well as in solar radiation, in wind, in water heads, in biomass.

5.1.1 Designing a low energy development

To design a low energy settlement means, first of all, to maximise its thermodynamic efficiency, i.e. to minimise the amount of high grade, low entropy, energy that is used or, as it is more commonly said, the amount of primary energy consumed. Only after this has been done, it is conceivable that a settlement runs mainly on renewable energy sources.

In low energy urban design, thus, the main aim is to

1 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

2 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.

3 The Future of Urban Consumption in a 1.5°C World - C40 Cities - Headline Report, C40, Arup and University of Leeds, June 2019

4 Ellen MacArthur Foundation (2017), Cities in the Circular Economy: An Initial Exploration - https://www.ellenmacarthurfoundation.org/publications/cities-in-the-circular-economy-an-initial-exploration

5 Ellen MacArthur Foundation (2017), Cities in the Circular Economy: An Initial Exploration - https://www.ellenmacarthurfoundation.org/publications/cities-in-the-circular-economy-an-initial-exploration

6 Cities and Circular Economy for Food, Ellen MacArthur Foundation 2019

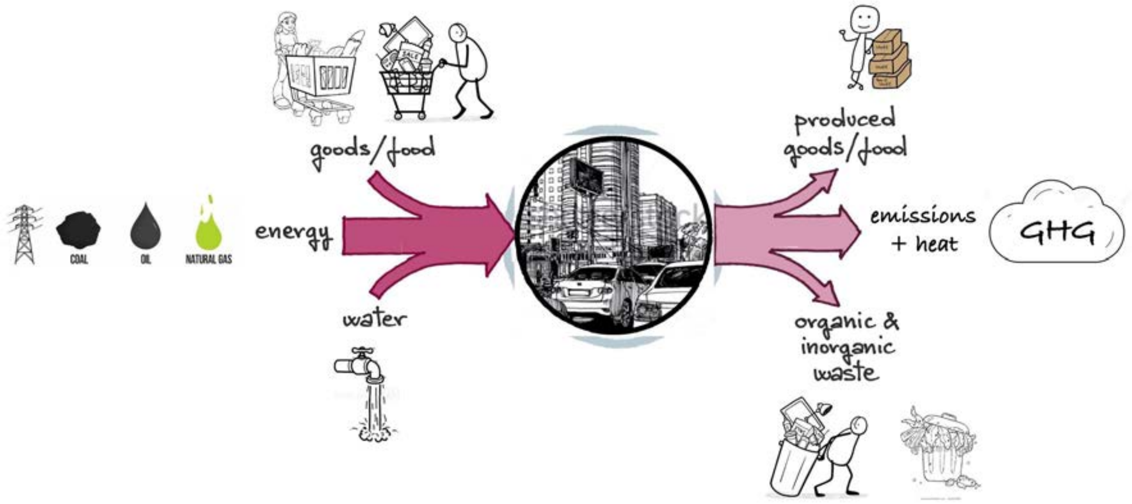


Fig. 5.1-1 – Urban metabolism

minimise primary energy consumption, that presently is due for more than two thirds to residential, commercial and transport sectors. The fulfilment of this aim involves several combined 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 in consideration, involving water, wastes and mobility, i.e.:

- minimise primary water consumption and exploit energy potential of sewage water;
- minimise the volume of waste generated and going to disposal, and use the energy content of wastes;
- minimise transport need and optimise transport systems;
- minimise the primary energy consumption of transport means;
- maximise the share of renewable energy 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 to furthermore maximise the proportion of clean and renewable energy 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 strong 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 strongly increased. This the first action should be linked to the rearrangement of the city functions in such a way that they are as much as possible close one another, so reducing the need for motorised transport or, at least, reducing travel distances. This leads to an urban planning aiming to land mixed use.

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 different time pattern of use, smoothing power peaks.

5.1.1.2 Minimise energy demand of buildings

Buildings design, after urban design, has the second major impact on long-term energy consumption and new buildings should therefore meet the best energy performance.

Envelopes for low energy buildings

For minimising buildings energy demand, crucial are appropriate orientation and facades design aiming to maximise solar gains and minimise heat losses in climates where winters are cold. At the same time, during the hot season in these climates and during almost the whole year in hot climates, orientation and facades design should aim to the minimisation of both heat and solar gains through the envelope. The issue of comfort in hot seasons/climates is a critical one, as in the recent years space cooling has begun to create concern for its fast growth all over the world and the consequent energy consumption.

Appropriate building shape and orientation, internal layout, the position of openings and sun shielding can enhance ventilation in mid seasons and reduce the need for air conditioning in the hottest periods (see chapters 3 and 4). Naturally, the implementation of most of these rules 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 energy demand has been minimized, with appropriate urban and buildings 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 renewable energy sources

As the energy consumption is minimised with appropriate technological systems, renewable energy can have a significant role in the energy balance of an urban settlement. Many are the technologies available and already 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 applied more and more frequently.

Many are now the biomass CHP plants all over Europe.

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.

Sterling engine is used in smaller (down to 10 kW) biomass fuelled CHP units that are being developed for multifamily housing. Recently, small scale, single house or apartment scale biomass CHP systems have been developed and marketed[7].

Biomass CHP systems could be adapted to hot climate areas, by using the waste heat for cooling.

Popularity of biofuels is growing, mainly in cars as a substitute or as integration of gasoline or diesel oil; more recently, also small internal combustion CHP units running on biofuels are becoming available. There is a growing concern, however, about the environmental impact and the competition with food production of energy plantations, if these are the origin of biofuels.

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[8] (see paragraph 6.2).

Photovoltaic systems, in a low energy consumption settlement, are best used when integrated in the buildings envelopes. PV systems, being competitive with fossil fuels for electricity production, are the main actors of the energy system of a low energy urban settlement, providing electricity also for cooling, coupled with heat pumps.

Wind energy

Wind power is not available everywhere, but in coastal areas is often significant enough to make cost effective the installation of wind turbines. Also hills ridges are suitable locations. Offshore wind farms are becoming an attractive options, due to the technological improvements and the lowering of costs; besides being capable of harvesting higher speed winds, these plants have the advantage to reduce the problem of the visual impact, which often prevents or slows down the development of wind power.

Not only large wind turbines are to take into consideration, because small wind generators, either horizontal or vertical axis, are an option (see paragraph 6.3). Even if their cost-effectiveness is lower than for the large ones, in the perspective of raising fossil fuel costs and in windy contexts, they could give a contribution to the renewable energy input of the settlement.

Mini hydro power

Mini-hydro potential is still largely unexploited especially in developing countries, including the one deriving from the water supply; this water often is collected in springs or basins up in the mountains and delivered at 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: a more or less

7 *R. Padinger, S. Aigenbauer, C. Schmidl, Best practise report on decentralized biomass fired CHP plants and status of biomass fired small- and micro scale CHP technologies, IEA Bioenergy: Task 32, February 2019 - https://www.ieabioenergy.com/wp-content/uploads/2019/05/T32_CHP_Report_01_2019.pdf*

8 *IEA Task 25, Solar Assisted Air Conditioning of Buildings, http://www.iea-shc-task25.org/*

Super capacitors	10
Lithium-ion batteries	14
Lead-acid batteries	23
Pumped water	28
Compressed air	36
Compressed hydrogen	68

Table 5.1-1 – Energy storage transfer losses [%]

large and well insulated tank containing water, or ice. Also phase change materials, capable of storing more heat per unit volume than water, can be used.

Less easy is to store electricity. The most common technology is the battery. Well established means for storing electricity are also pumped hydro and compressed air, used by energy utilities.

Other technologies, however, are proposed, such as supercapacitors, superconductive coils and flyweels[9]. Hydrogen is another storage medium, using electricity for producing it from water (hydrolysis) and then recovering part of this electricity by using the gas for supplying a fuel cell. This system is by far the less efficient for electricity storage[10] (Table 5.1-1) but, with pumped water, is suitable for seasonal storage, necessary to counterbalance the difference between the PV production in summer and in winter, especially considering that space heating, where needed, will be provided by heat pumps.

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 give a significant contribution to the city's energy balance.

An alternative to the incineration of wastes is their gasification, producing syngas. Such gas can be used both to supply a CHP unit and to be distributed for cooking use.

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 to keep windows closed, impairing natural ventilation.

The way a neighbourhood is conceived has an indirect strong impact on the GHG emissions due to motorised transport. This is because building and neighbourhood design is also connected with mobility, in many ways. The main connection is related to the 5 minutes' walk strategy (Figure 5.1-2), which is based on the idea that all the places a citizen needs to reach with high frequency are within a maximum 5-10 minutes' walk from home (the best is 5 minutes, according to sustainable urban planning literature; Paris, instead, is implementing the 15 minutes city approach). These places are the ones related to education, work, knowledge exchange, shopping, recreation, community engagement, health, public transport, exercise, and nutrition. This is the so-called mixed land use approach, opposite to the one based on the spatial separation of urban main functions (work, living, leisure) that has been driving 20th century urban development. The implementation of this approach has a strong impact on buildings design, as they should provide room for a variety of functions, i.e. they should reflect the mixed use philosophy by, for example, having the shops or small worshops at ground floor, offices at the first floor and apartments in the upper floors.

The mixed use strategy reduces so much the need for a car, that most citizens will give up theirs, and will move walking or riding a bicycle – and using car sharing services when occasionally the car is actually needed. In this vision, vehicles are electric, powered with renewable energy.

The connection between neighbourhoods' design and GHG emissions is further reinforced by the fact that making the car ownership useless in most cases, the number of cars would significantly be reduced, reducing accordingly the amount of embodied emissions, as the cars would not be built. Buildings and mobility will be more intertwined with the growth of electric cars, as their battery can be used as an electricity storage for the individual building or as distributed storage for the grid.

5.1.2.1 Mitigated environment paths

An important issue is to give planning priority to pedestrians and cyclists. The aim is to maximise 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 comfort of outdoor spaces, by mitigating environmental conditions. Trees are the most obvious answer to provide shade in summer. Arcades sheltering from rain, wind and

9 *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*

10 *U. Bossel, Physics and Economy of Energy Storage, First International Renewable Energy Storage Conference (IRES I), Gelsenkirchen, October, 30th/31st 2006*

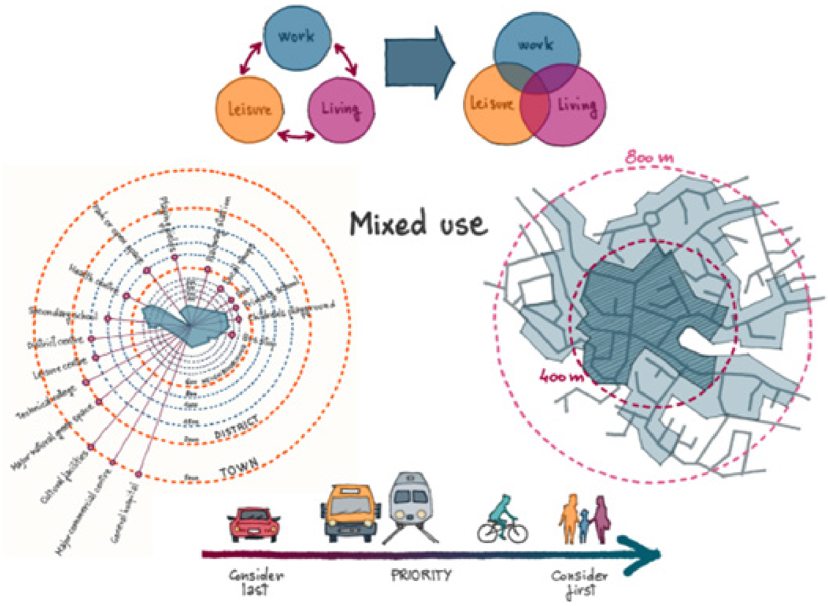


Fig. 5.1-2 – Five minutes' walk strategy

5.2 Water and sanitation

Water is essential for the environment, food security and sustainable development. All the known civilizations have flourished with water source and it 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, being the two most important urban services, have wide ranging impact 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 in water supply, to pump, treat and distribute water. With a growing population, the demand for water has been rising simultaneously, requiring more and more energy.

Despite the technological advancements, the global scenario still remains grim, as large amount of the inhabitants of the world do not have access to safe water and adequate sanitation.

In most urban areas, the population is increasing rapidly and the issue of supplying adequate water to meet societal needs and to ensure equity in access to water is one of the most urgent and significant challenges faced by the policy-makers.

As consequence of rapid population growth, combined with industrialisation, urbanisation, agricultural intensification 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 damages, both because they lead to 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.

This problem deserves 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 refers to 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 activity of 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 know in the hydrological cycle, hence is a primary source of water for us.

Rivers, lakes and ground water are all secondary sources of water. In present times, 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, accessed by wells or boreholes.

5.2.2 Importance of water conservation

The increased demand and resources depletion make water conservation essential to have an efficient water management system as well as strategies for efficient water reuse.

To that end the three following issues have to be considered: rainwater harvesting, water recycling and water conservation. In practice, and as 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 should be implemented. Water efficiency measures include also reduction in losses and in overall water use.

The recommended measures for water reuse and water conservation can be summarized as follows:

- reduce the potable water use for non-potable applications;
- install dual plumbing lines for the use of treated waste water for flushing applications. The treated water, which meets the local pollution control board standards can also be used for lawn watering;

- harvest rainwater;
- use rainwater harvested from the rooftop, 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 fast as possible to a drainage point, either by storm-water drainage or a sewer. If drainage is faced with a more sustainable attitude, it is possible to benefit from on-site infiltrations. This system permits to slow down the accumulation and flow of water into the drainage points 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 it by a natural system, before discharging it to a watercourse.

Drainage can be slowed down using swales, soak-ways, holding ponds and by having more pervious surfaces.

Pervious surfaces needs to 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 material 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 the 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%. In case the site hydrogeology does not allow the run-off factor to be 0.6, measures are to be taken to allow the collection of run-off into soak pits or collection pits so that the net run-off from the site is not more than 60%. The run-off coefficient for different type of surface are shown in the Table 5.2-1.

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 dike etc. should be constructed to carry the polluted water directly to municipal drains.

5.2.4 Building design strategies for reducing water consumption

Communities and buildings design and management can give an important contribution to water conservation.

The recommended guidelines for an 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

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

Table 5.2-1 – Run-off coefficient for various surfaces Source: UNEP, Eco-housing Guidelines for Tropical Regions, 2006

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;

- adopt planting of native species and trees with minimal water requirement;

- use mulches and compost for improving moisture retention in soil;

- encourage rainwater harvesting and storage/recharge for capturing good quality water.

Efficient toilets and devices for other uses

Several devices are available for water conservation in building. As examples the following innovations can be mentioned:

• ultra low-flow flush toilets (flow rate of 3 litres per flush);

• water-efficient urinals and waterless urinals;

• faucet aerators;

• low-flow showerheads (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 showerheads.

The potential of water conservation can be easily understood taking into account 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 faced was that the old bowls of WCs - western commodes - did not flush the contents properly with 6.2 litres of water per flush; however, now the design of the bowl has been modified and it has been elongated to facilitate the 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[1].

It has to be stressed that benefits of adopting the mentioned efficient 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

With respect to the physical alternatives to fulfil sustainable management of freshwater, there are two solutions:

• finding alternate 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 given to the first option and only limited attention has been given 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 environmental problems often caused by conventional large-scale projects using centralised approaches.

Rainwater harvesting in buildings has been practiced for more than 4000 years and, in its broadest sense, is a technology used for collecting and storing rainwater for human use from rooftops, 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 provided at mouth of drain pipe prevent leaves and debris from entering the system. If stored water is to be used for drinking, a sand filter should also be provided.

Underground masonry/reinforced cement or concrete tanks, or over ground PVC tanks could 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 rooftops is free of mineral pollutants like fluoride and calcium salt but is likely to be contaminated by air and surface pollutants. All these contaminations can be prevented largely by flushing off the first 10-20 minutes of rainfall. Water quality improves over time during storage in tank as impurities settle in the

1 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.

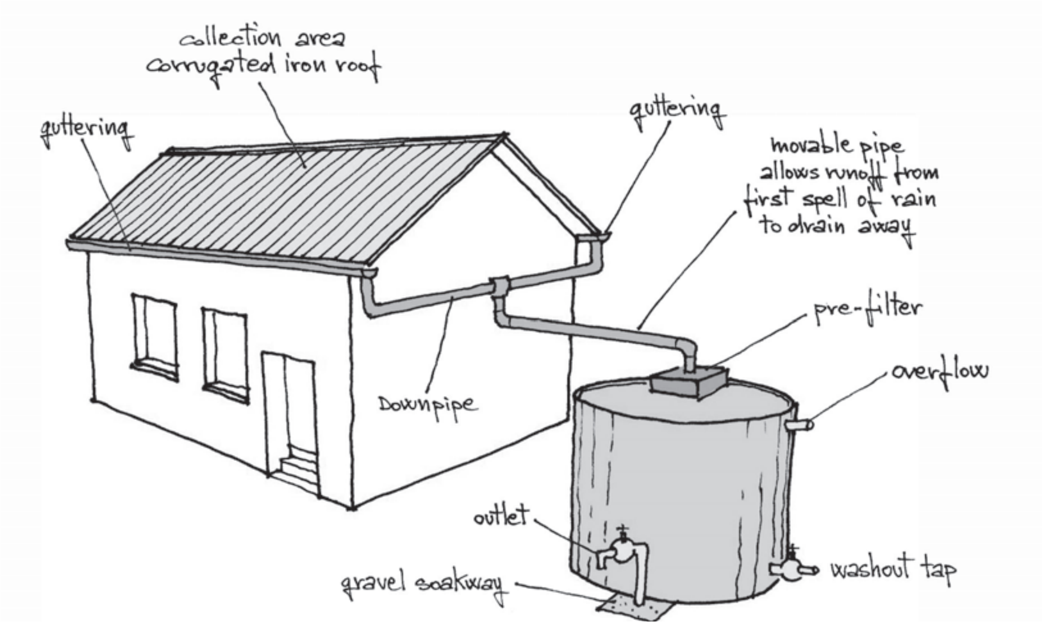


Fig. 5.2-1 – Rainwater harvesting system

tank if water is not disturbed. Even pathogenic organisms gradually die out due to storage. Additionally, biological contamination can be removed by other means.

5.2.5.1 Sizing the rainwater storage tank

The monthly rainwater amount that can be collected can be calculated according to equation:

$$W_{ry} = A_c \times e \times h_N \times \eta \qquad (5.2\text{-}1)$$

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).;

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.

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

Table 5.2-2 – Yield coefficients

The value of 0.8 can be used in absence of more precise information.

The monthly water requirement in the household is defined according to the equation:

$$Wwr = [(P_d \times n_p + W_i \times A_w) \times N] + (W_m \times n_m) + (W_c \times n_c)$$
(5.2-2)

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];

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) Class F (high consumption)	 60 100	 l/ wash l/ wash
Average consumption for private use	**Consumption**	**Unit of measure**
Washing cars (each car)	300	l/wash
Watering the garden	2	l/m²day
Watering orchard	0.17	l/m²day
Average consumption for public use	**Consumption**	**Unit of measure**
Watering:		
terraces	2	l/m² day
roads with pavement or asphalt pavement	1	l/m² day
roads with paved floor	1.5	l/m² day
gardens and flower beds	2	l/m² day

Table 5.2-3 – Determination of annual process water requirements for people and for irrigation

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:

$$Vn = Minimum\ of\ (Ws\ or\ Wd) \times 1.2 \qquad (5.2\text{-}3)$$

where:

V_n = storage tank volume [l];

W_s = water surplus = excluding months where < 0 [l];

W_d = water deficit = excluding months where > 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 as 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-

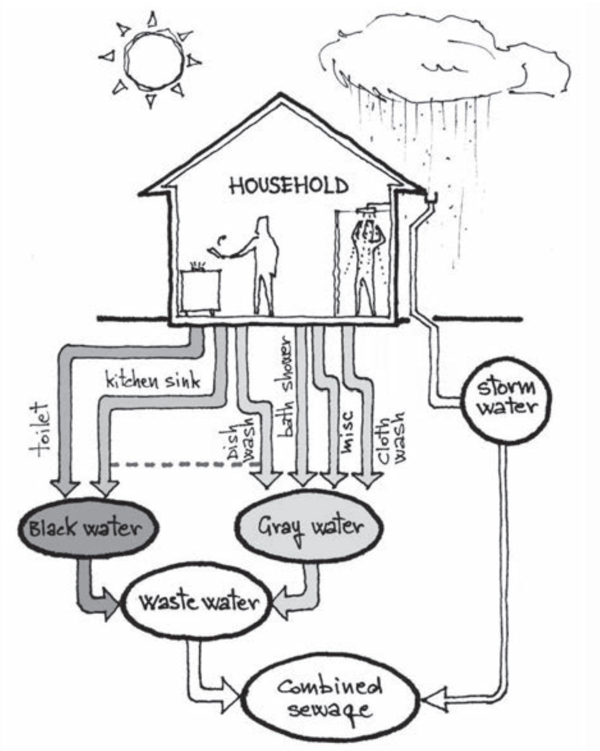


Fig. 5.2-2 – Sources of household wastewater

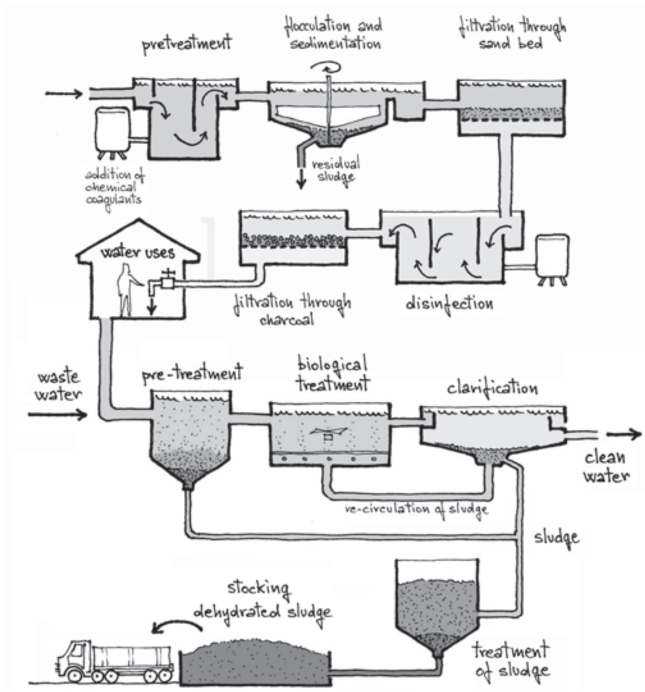


Fig. 5.2-3 – Drinking water treatments (up) and waste water treatments (down) as parts of the water management system

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 also should be removed. Pathogenic and faecal indicator microorganisms need to be reduced to acceptable levels, to ensure that this 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 produces 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.

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.

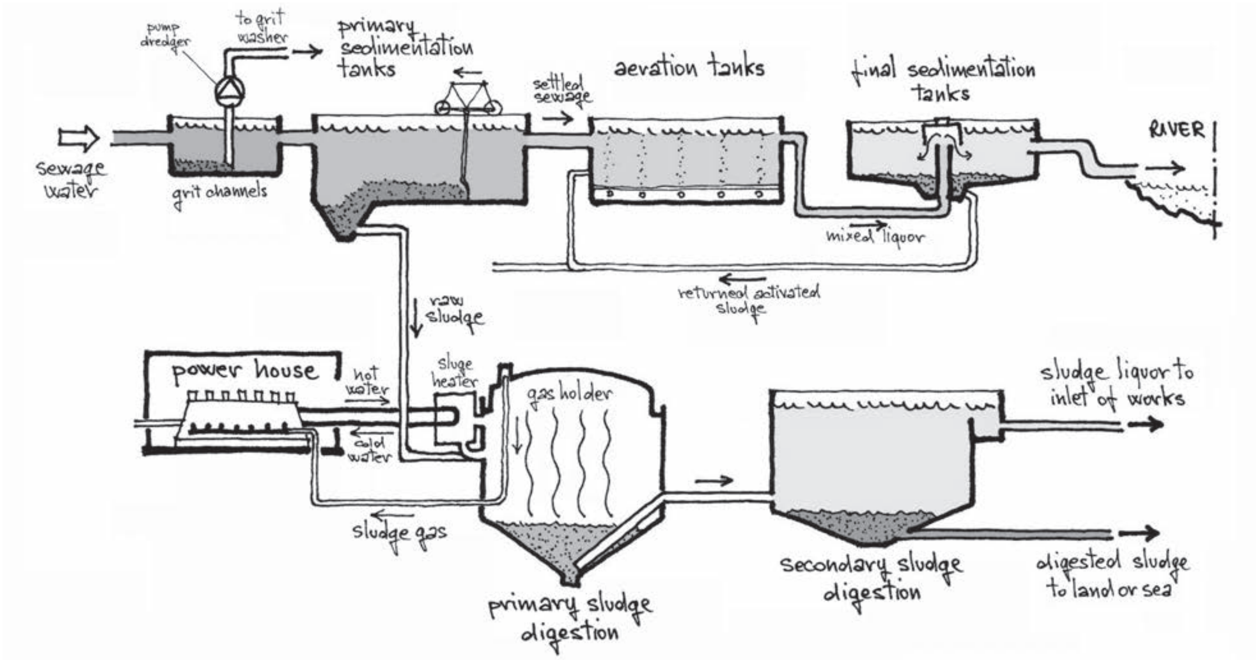


Fig. 5.2-4 – Biogas production from sewage water at neighbourhood level

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.

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 carrier for the future and there are examples that demonstrate that it could be use also 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), as shown in 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.

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 6000 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.

It is also recognised the 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 on 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.

Fig. 5.2-5 – Digesters construction stages - Sources: 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[2]

Gryaab receives approximately 4,000 litres of water per second. It is cleansed from nitrogen, phosphorus and organic matter, which if released into the sea would lead to eutrophication and oxygen depletion.

The facility also receives fat and food waste from restaurants, schools, and food producers in the region.

Every year Gryaab produces more than 70 GWh of biogas, which is sold to Göteborg Energi and upgraded to 95–98% methane. Göteborg Energi compresses the biogas and sells it as vehicle fuel. Gryaab produces enough biogas in a year to drive a car 2500 times around the globe.

Each year, approximately 55,000 tonnes of sludge are produced at Gryaab. The treated sludge contains nutrients and mulch – what is needed for crops to grow. Some of the decayed sludge is composted and used as construction soil. About half of the sludge is hygienised and used as fertiliser, replacing artificial fertiliser.

2 https://smartcitysweden.com/best-practice/220/gryaab-works-for-a-cleaner-ocean/

5.2.7 Water cycle: main criticisms and solutions

In many cities of the world sewerage systems are not available or not managed correctly.

One century ago the same picture characterized a large part of today's developed countries cities.

At that time, even when a sewerage system was available, wastewater was directly disposed in rivers, lakes or in the sea. After, slowly, water treatment started to be implemented, but with the open cycle approach: no energy was recovered with biogas plants nor cleared water was reused. It is like this still now in most developed countries cities.

In most developing countries cities and towns there is to start from scratch, and this condition can be used as a chance for applying since the beginning the closed water cycle approach and the exploitation of the energy potential of wastewater, giving an answer to both the energy and water shortage (cleared, non potable water can satisfy many urban and peri-urban uses).

About waste water management, the guidelines that

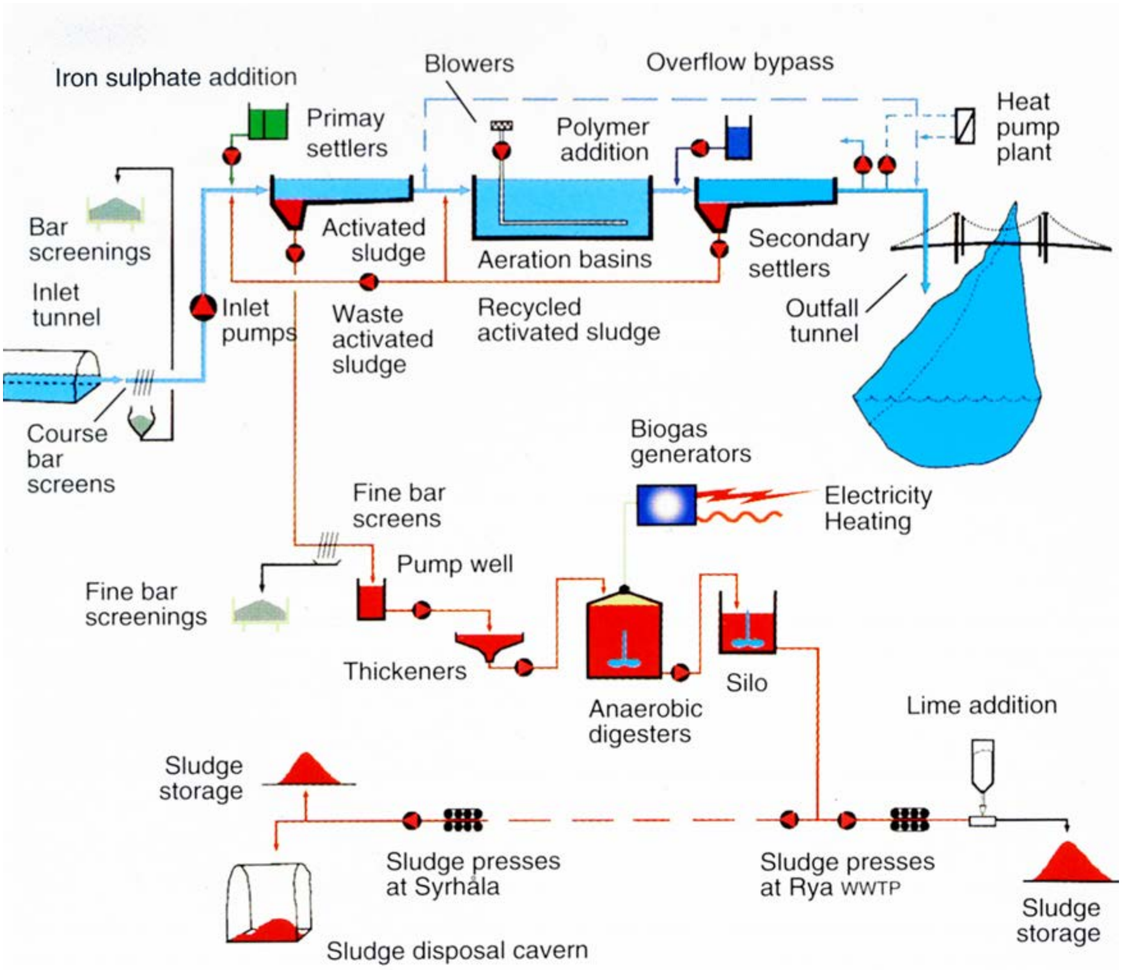


Fig. 5.2-6 – Functional scheme of the plant

could be followed 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 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.

5.3 Solid waste management

Today cities have to face many urgent and interrelated problems. Climate change, other global environmental effects, local pollution, population increase, energy and matter depletion, water and waste cycles.

In this framework 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 the framework of the urban metabolism theory, urban waste cannot be "simply" considered as a quantity of matter to be disposed (in developing cities, it has to be faced first of all as a sanitary problem).

As consequence, material and energy recovering from waste should be promoted as much as possible on the basis of the local peculiarities, features and attitudes and properly integrating available technologies.

5.3.1 Data about waste production

In general, data collected are described by basic indicators related to waste generation per capita, waste composition and main practices for waste management. These data can be highly variable depending on many factors (i.e. economic and social conditions, habits, type of territory etc.).

About the amount of waste per capita it is possible to argue that per capita waste produced in cities is linked to the average income[1], as shown in figure 5.3-1.

1 *S. Kaza et al., More Growth, Less Garbage, World Bank Group, 2021*

5.3.2 Solid waste characterization

Regarding the waste composition, waste generated in cities of 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 low income countries the organic fraction is generally higher than in high income cities[2], above 50% in the average.

5.3.2.1 Heating values, humidity, main elements and contaminants

The moisture content and the hating value[3] are the main elements to be considered in order to plan how the waste can be effectively treated.

Also the analysis of contaminants and precursors of pollutant emissions has to be accomplished in order to prevent dangerous effects during and after the management.

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 it is inversely proportional from the moisture content.

5.3.3 Integrated management systems

Urban wastes disposal is a sanitary problem and represents one of the most important issues of the management of metropolitan area.

Further 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.

Wastes represent one of the most important outputs of urban metabolism but, by means of internal recycling processes, they can also become a significant input if considered in the framework of an integrated waste management system that should include:

- waste separation and collection;
- materials recovery;
- energy recovery;
- final disposal.

2 *Nanda, S., Berruti, F. Municipal solid waste management and landfilling technologies: a review. Environ Chem Lett 19, 1433–1456 (2021). https://doi.org/10.1007/s10311-020-01100-y*

3 *LHV means low heating value while HHV means high heating value.*

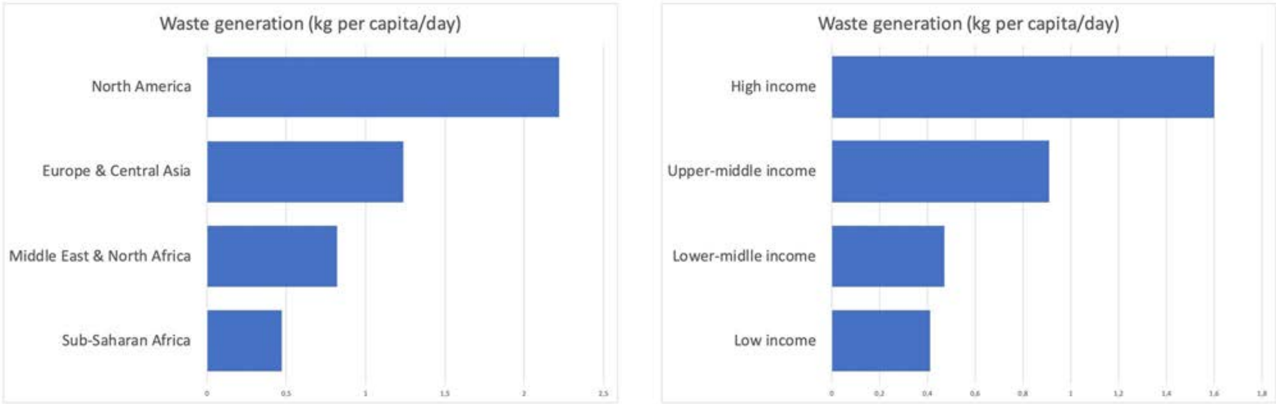


Figure 5.3-1 – Average per capita waste generation according to the geopolitical area and income.

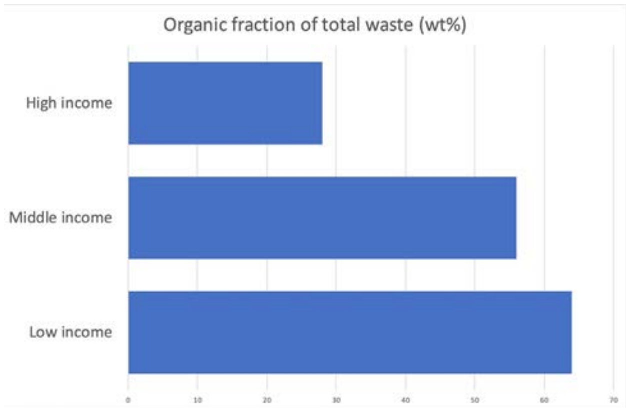


Fig. 5.3-2 – Organic percentage in urban waste according to income.

Apart rational and general schemes of management, also site-specific factors should be considered for, as follows:

- composition of the waste: this would impact on handling and transportation options as well as on options for recycling, reusing, recovering energy or incineration;
- accessibility to waste collection points;
- cost of storage and transport;
- social attitudes to waste collection services such as willingness to segregate waste to assist recycling; willingness to pay for waste management services; opposition to define sites for waste treatment and disposal facilities.

A correct 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 effectively implement collection and separate collection of waste. This approach is the consequence of the shift from the linear to the circular urban metabolism. In a sustainable city waste is minimized because input flow of materials is minimised, through the minimisation of packaging, the enhancement of repairing, reusing, lending and exchanging products, the implementation of deposit return scheme (DRS), etc. In other words, implementing the principles of circular economy[4], as they are conceived by the European Commission, as one of the pillars of the European Green Deal[5].

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 are also taken into account.

5.3.4 Waste to matter and waste to energy

Despite the wide debate of the last years, often the recovery of material and energy are still considered as antagonistic practices, while they are both essential elements of the integrated waste management system and they have to be balanced in different way depending on the context. Unfortunately, also well-developed cities are still concentrated in defining how much urban waste has to be recycled and how much has to be incinerated, instead of taking action for facing the problem in order to improve cities urban metabolism, and in taking into account standards of source separation without considering enough how the standards are reached and the related economic and environmental effects.

Environmental benefits due to waste to energy and matter recovery can vary depending on the stage of development of the considered city and on the local performance of the energy generation system and of the industrial sector. As example, this can imply that the higher GHGs reduction due to waste to energy is reached in cities with a fossil and not efficient power system.

4 Circular Economy Action Plan (2020), European Commission
5 The European Green Deal, European Commission, Brussels, 11.12.2019 COM(2019) 640 final

5.3.5 Available and applicable technologies

As consequence of the solid waste characteristics (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 considerations can be drawn, namely:

- since the problem related to un-collected waste and spontaneous disposal is still very serious, waste collection should be practiced properly;
- recycling needs to be pushed by the residents themselves or with the assistance of voluntary agencies; generally speaking, the more accessible recycling centres are available, the more waste per capita is delivered;
- for the biodegradable fraction of 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 an effective use of the outputs (i.e. request of compost);
- thermal-chemical technologies can be attempted only after ensuring their suitability based on waste composition (in case of low LHV they result not suitable) and taking into account economic aspects and difficulties in managing the plants in a correct and safe way;
- landfill disposal should be reduced not only for the mentioned environmental problems, but also because of the rising costs of construction and operation;
- further landfills should have all the needed 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 seem still difficult to be overcome;
- the solution to waste management is not merely technical, but also organisational. There is a great need to move away from the disposal-centric approach and towards the 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 to be evaluated in order to select a proper treatments are described.

5.3.5.1 Thermo-chemical treatments

Thermo-chemical treatments represent first of all a fundamental part of an integrated waste management systems and after that a way to produce 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 waste can be processed by thermo-chemical treatment equipped with energy recovery.

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	

Table 5.3-1 – Requirements for energy recovery from wastes

After the previewed pre-treatments, wastes could be treated by different thermal processes to be converted in heat and power. The most popular is the thermal treatment of combustion (incineration), but, especially for small and medium sizes, also pyrolysis and gasification are applicable.

Incineration involves burning the wastes at high temperatures. It could be done with energy recovery or without energy recovery. In modern incinerators, hazardous and recyclable materials are removed, prior to combustion. It is considered useful for destroying pathogens and toxins at high temperatures, especially from clinical wastes. It is also attractive in countries having a shortage of land. A main concern in incineration is the emission of harmful pollutants, including also dioxins and furans. Nowadays suitable technologies for abating dangerous pollutants are available and accessible all over the world. Of course, the involved personnel should be trained about the correct management of the plant.

Technologies for pyrolysis and gasification of urban wastes are also available at commercial scale in this field.

Technical-economic feasibility of pyrolysis and gasification is possible if these thermal treatments are coupled with integrated waste management systems of small regions (20-80 kt/year).

If compared with combustion, pyrolysis and gasification could bring benefits such as smaller space occupation, more acceptability, less additives, less (and more inert) slag, fuels available for storage, transportation and different uses (also gas turbine combined cycle or co-combustion). Despite the small number of commercial applications, energy and mass balance of existing plants can confirm performances nearly comparable to combustion plants.

5.3.5.2 Mechanical Biological Treatment (MBT)

These are a flexible mix of mechanical and biological treatment methods, used to recover all type of resources from a mixed waste stream. The recovered materials could then be recycled. The mechanical part is similar to the MRF (Materials Recovery Facility[6]) and the biological treatment normally consists of anaerobic digestion or composting. The process also may produce a fuel from the waste, termed 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 greenhouse gases reduction and renewable energies uses. 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 the reduction of the dependence on natural gas, which over the long run may result in a monetary profit.

Composting

When anaerobic digestion is not feasible, wet organic waste can be treated by composting. It 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

Considering 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 end diseases.

Further, despite waste management has an important role as source of energy and materials and as motivation for new net employment, many barriers can be met toward the implementation of a new necessary urban policy: a not well determined institutional framework, insufficient financial resources, uncertainness related to the available data, lack of skill and specialists capable of putting in action policies, lack of information in the citizens, resistance to change, effects difficult to be predicted.

5.3.7 Basic guidelines

Although it is certain that waste management should be planned by solutions that are strictly dependent on the local characteristics, the following guidelines should be followed in order to overcome many of the previous mentioned problems:

- provide facilities for collection of segregated waste;
- identify facilities for 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 safe environment in the surrounding areas. Sanitary landfills need to be designed and people need to be trained in managing and maintaining it (a common mistake is to provide the infrastructure, but neglect the managerial aspects);
- establish an efficient waste reduction, recycling, and reuse (3R) program;
- avoid or reduce toxic and hazardous materials. Recycle items such as ballasts, mercury-based lighting products, used oil, unusable batteries, electronic devices, etc.

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6 *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 in 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. 6.1.4), where the interstices between the cells let the light through, or where the thin films are deposited in such a way as to result 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) that 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.

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 to deliver 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).

The space occupied by the inverter varies depending on the power, and it ranges from devices with the size of a briefcase, for a few kW, to larger devices, approximately as 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, between the generator and the inverter is interposed a storage system, a battery, for storing the electric energy when production exceeds consumption and make it available when consumption exceeds production. When systems are grid

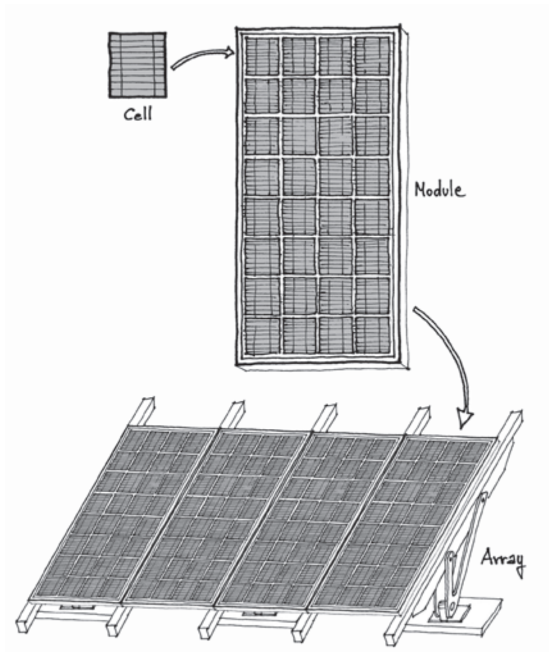


Fig. 6.1-1 – Cells combine in modules or panels, panels combine to form an array


6.1-2 – PV on flat roof


Fig. 6.1-3 – PV on pitched roof (Photo credit (left): USFWS Pacific Southwest Region -http://www.flickr.com/)

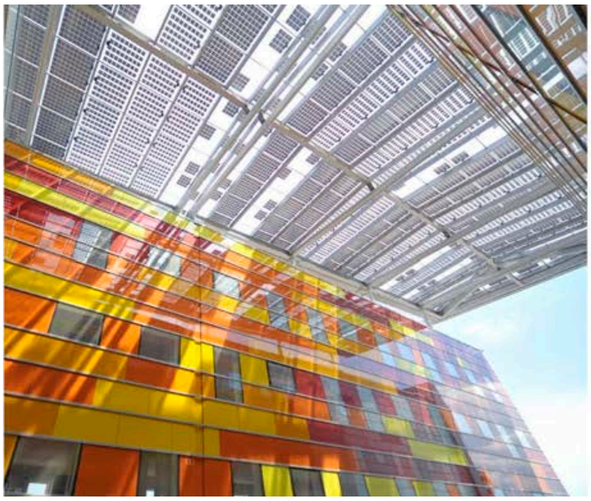



Fig. 6.1-4 – Left: TGV Railway station Perpignan (France), Architecture: Arep (Photo credit Laurent Lacombe - http://upload.wikimedia.org/wikipedia/commons/c/cf/Projet_BIPV_-_Gare_TGV_de_Perpignan.jpg); right:

connected, instead, the energy produced is fed into the grid totally or for the portion that is not directly used on site. During periods of little or no sunlight, is the grid itself to integrate 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:

$$E_{PV} = PR \times P_{PV} \times S \quad (6.1\text{-}1)$$

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].

The productivity of a photovoltaic system is highly dependent on the climatic context in which it is located. The amount of electricity production, in fact, is directly proportional to the availability of solar radiation and, at a much lesser 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 the heat loss. At the latitudes of African countries those are near the equator, the optimum tilt angle is 0° (horizontal), but up to 15° there is not any significant production decrease. Hence the fact that, opposite 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 in the south or north facade, since they would remain in the shade for half a year.

As indicative figure, in Africa a 1 kW_p well designed photovoltaic system can produce annually between 1100 and 1900 kWh electricity, 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 collectors surface of about 7.5 m^2.

Architectural integration of photovoltaic systems

Architectural integration represents a privileged sector 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 opportunities, 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, the possibility to use the energy produced on site according to the logic of distributed generation.

In order to obtain the best performance of a photovoltaic system, integrated or not in the building envelope, a careful planning is necessary. The modules must be located in such a way to intercept the maximum possible solar radiation, avoiding shadowing produced by trees, surrounding buildings or parts of the building itself. Ventilation of modules, leaving a gap between their bottom surface and the roof or other building component on which they are mounted, is an important prerequisite to avoid lower performances than expected.

When mounted on a roof, care must be taken not only to leave a ventilated gap, but also to increase the roof insulation, to avoid that a significant heat flow due to the panels' relatively high temperature reaches the indoor environment.

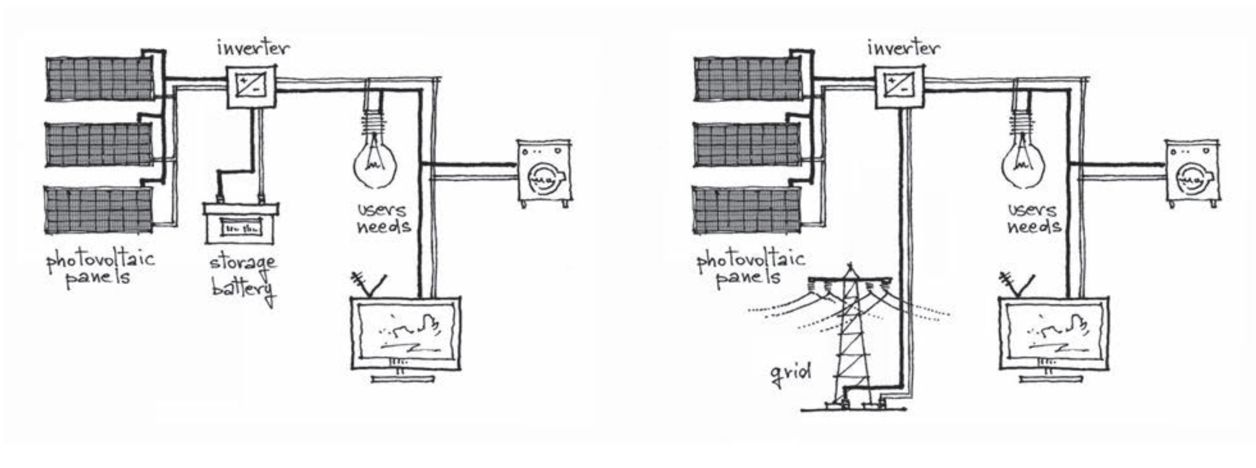


Fig. 6.1-5 – Stand alone (left) and grid connected (right) PV systems

6.2 Solar Thermal

Solar thermal systems directly convert solar radiation into heat. Their use is compatible with all the applications that require thermal energy at relatively low temperature, such as for example the production of hot water and summer air conditioning.

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.

The flat solar collectors are conceptually very simple: an absorbing plate, integrated with the pipes for the heat transfer fluid, is placed into a box insulated in the back and along the sides. The absorber plate surface exposed to solar radiation is normally black, painted or "selective" (a treatment that allows to improve the performances thanks to the low emissivity in the far infrared). A transparent cover, located frontally to the plate, reduces the convective losses and, mainly, the radiative ones in the far infrared (greenhouse effect).

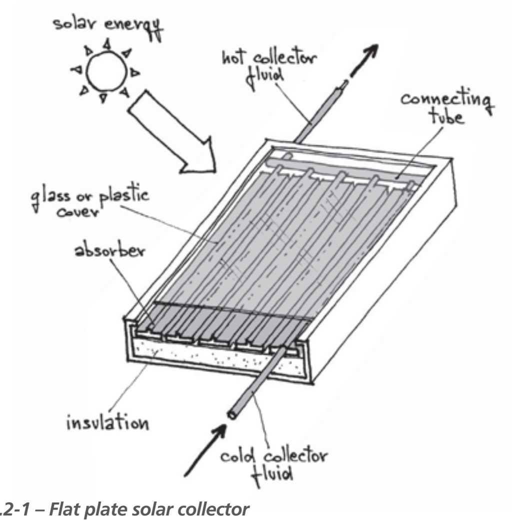


Fig. 6.2-1 – Flat plate solar collector

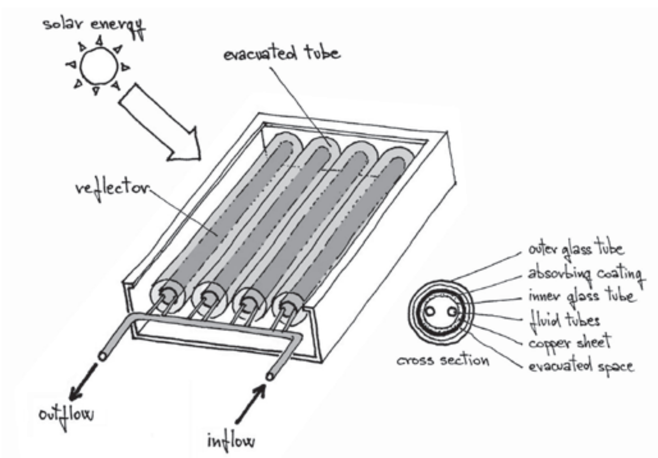


Fig. 6.2-2 – Evacuated solar collector (model Sydney)

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 represented by the unglazed collectors, or plastic absorbers, which are 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 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, and on the mean external air temperature: for low temperatures, i.e. up to 50-60 °C and in tropical climate the evacuated collector's better performance 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 in to 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 general, in Africa the countries near to equator, the best performance is obtained when the collector is horizontal, as for PV panels but, to avoid the

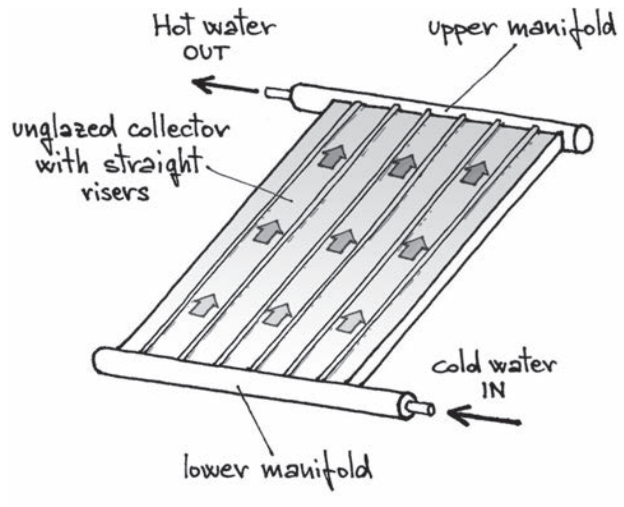


Fig. 6.2-3 – Unglazed solar collector

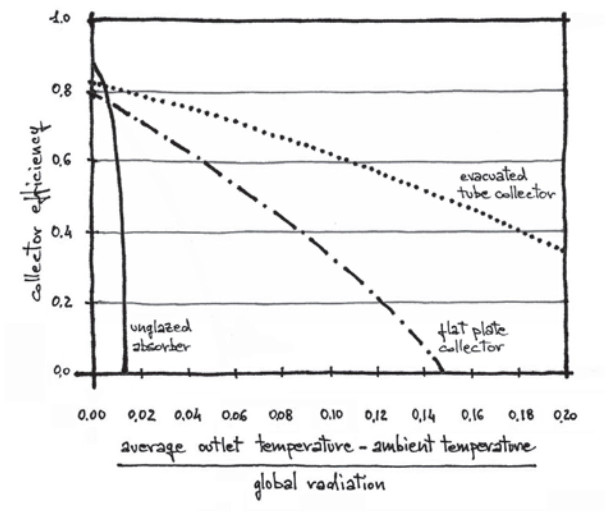


Fig. 6.2-4 – Efficiency of flat plate and evacuated collectors

stagnation of air bubbles and dust accumulation, it is necessary to give them a little inclination.

The efficiency of a solar collector (Fig. 6.2-4) is function of the incident solar radiation and the temperature difference between the fluid and 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 overcast sky and during night do not provide hot water. To reduce the inconvenience a storage tank is used, to store excess heat when sun is shining. The heat stored is used when solar radiation is low or by night.

In cold and temperate climates, because of the low air temperature, in 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 is delivered to the user according to its needs.

In Africa, except in climate BWk and BSk climates, freezing cannot take place, and the heat exchanger could not be necessary (Fig. 6.2-5). However, to prevent limestone deposit or corrosion damaging the collector, the closed loop with heat exchanger (without any anti-freeze liquid) is recommended. The fluid circulates in the collectors loop either by gravity (thermosyphon principle) or by an electric pump that is activated by a control unit when 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 by 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.

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

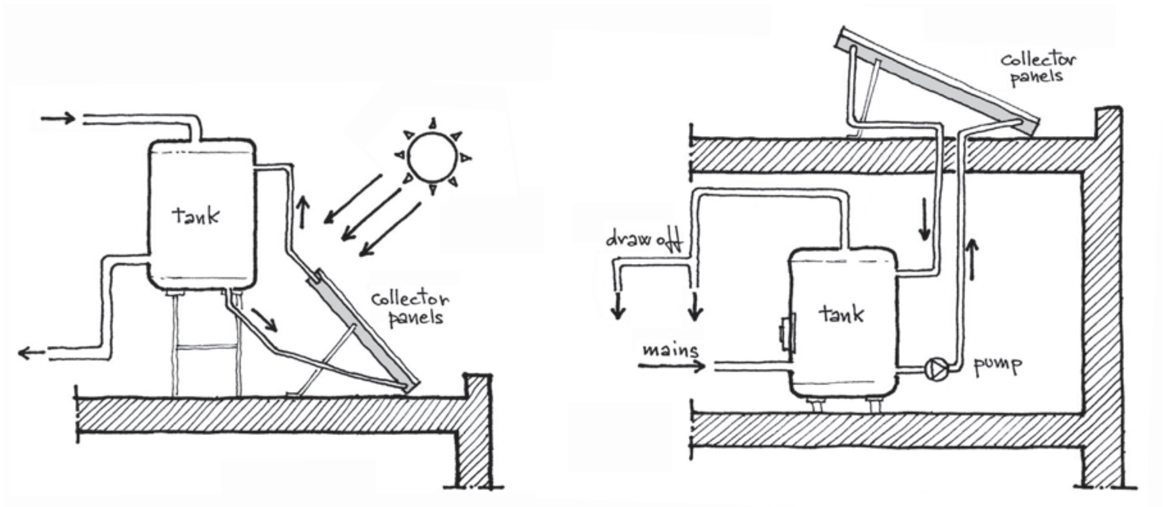


Fig. 6.2-5 – Natural (left) and pump assisted (right) circulation solar system

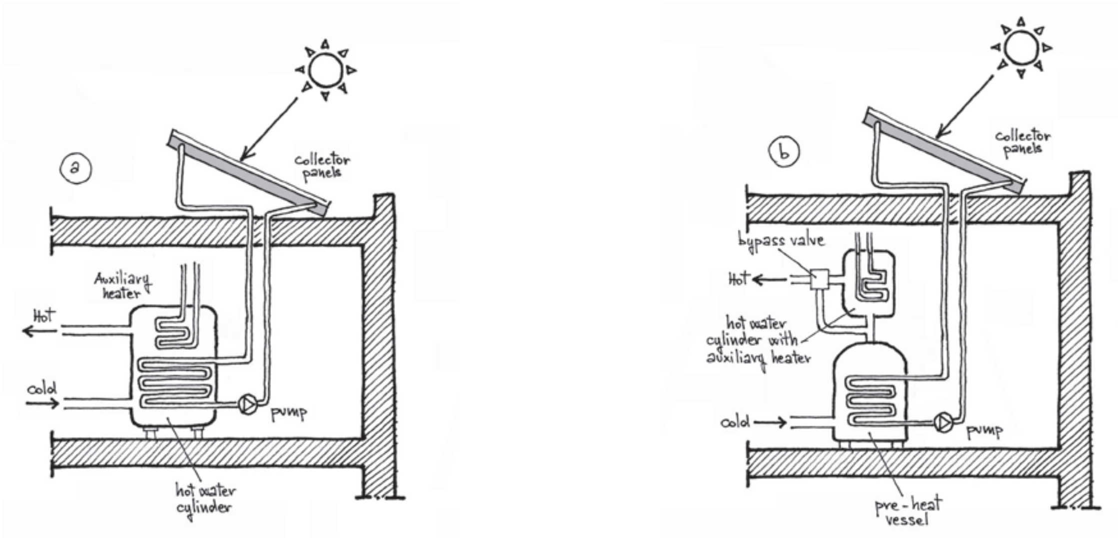


Fig. 6.2-6 – Pumped solar water heating systems (a) with single storage vessel (b) with separate pre-heat vessel

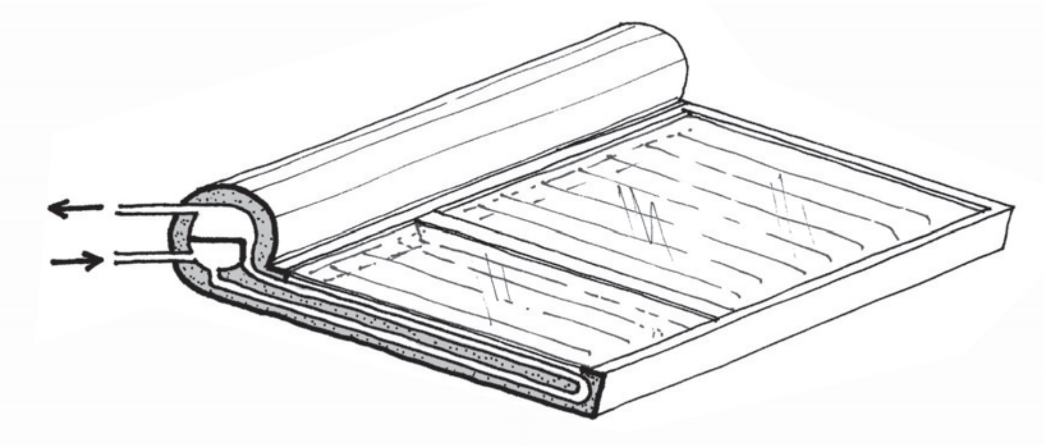


Fig. 6.2-7 – Single family, integrated storage solar DHW system

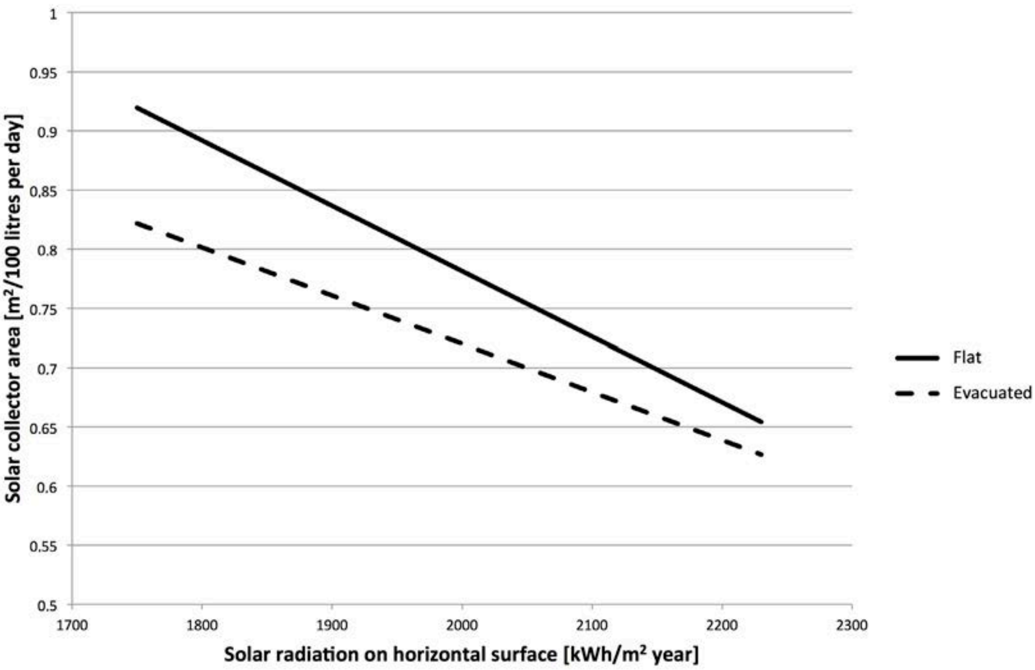


Fig. 6.2-8 –Collector area needed for 100 litres/day hot water production as a function of annual solar radiation incident on horizontal surface, for flat plate and evacuated collector. Hot water temperature = 40 °C; Solar fraction = 0.7.

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 guess about the collector area needed in Africa, the graph in figure 6.2-8 can be used. The graph gives the collector area needed to produce 100 liters/day of hot water at 40 °C, with an annual solar fraction[1] of 0.7, as a function of the annual solar radiation incident on horizontal surface (see Appendix 4 for data). The area needed for different hot water production is obtained is linearly proportional.

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

Solar Cooling system with absorption chiller is out of the experimental stage since several years. The heart of the system is an absorption chiller that generates chilled water being 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.

1 *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.*

6.2.3.2 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).

The external warm, moist air enters the lower part of a slowly rotating desiccant wheel, packed with silica gel (or some other absorbent or adsorbent) between two wire meshes. Inlet air is dehumidified and heated (moisture condensation 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. A 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 also for solar desiccant cooling the ratio of the surface of the solar collectors to that of the space to be conditioned ranges between 0.1 and 0.3.

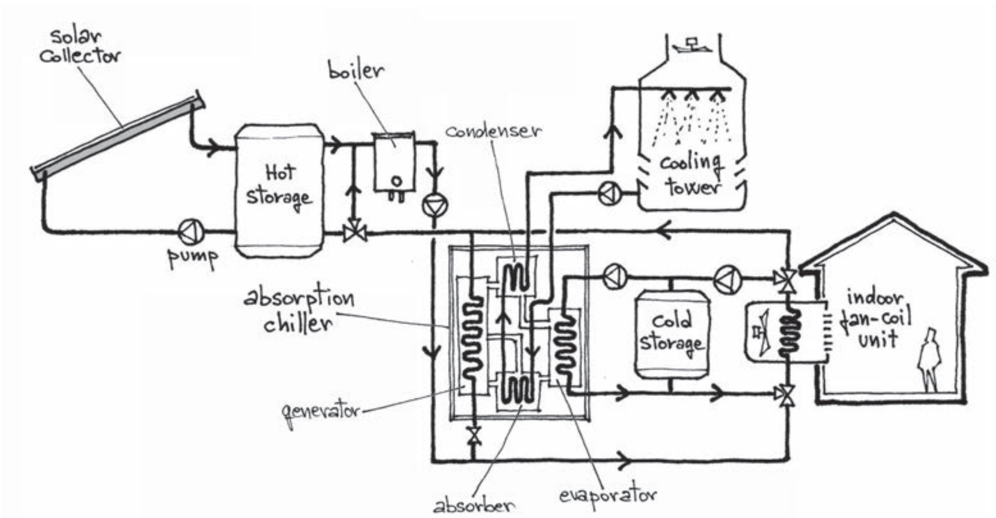


Fig. 6.2-9 – Solar powered air conditioning system

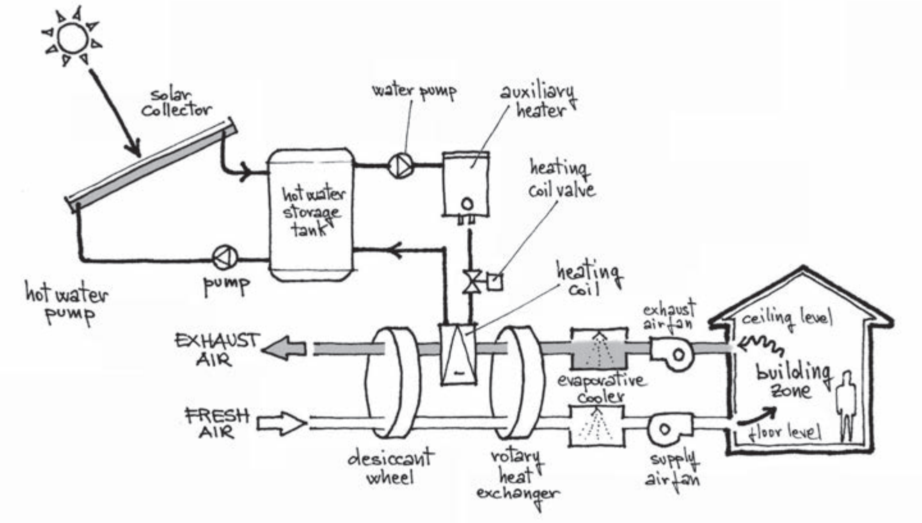


Fig. 6.2-10 – Main components of a solar-powered desiccant cooling system

6.3 Wind energy

Small wind energy system in the agricultural, industrial and urban context represents a technology being explored and that 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 the most diverse uses: residential buildings, hotels, commercial or manufacturing activities. The produced energy 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 (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 in case of high wind.

Vertical axis wind turbines do not need any 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 the building 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, above the roof strong turbulences can occur, which is unfavorable to horizontal axis devices because of extra stress to turbine blades and lower energy production (these problems are far less critical in vertical axis turbines). To overcome this problem, the wind turbine hub should be 1.4-1.5 times higher than the construction. 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 meters from the user, in order to have a noise level equal to that of background.

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 cost, higher than the average.

To evaluate the electric power that a horizontal axis wind turbine can produce the following formula can be used (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].

Since the power is function of the cube of wind speed, it is not possible to evaluate the mean power obtainable by a given device simply using the mean wind speed. The energy production depends on the wind speed distribution (wind duration curve, figure 9.4-4).

An example can highlight better the importance of the wind duration curve. Let's take two extremes for a wind turbine whose diameter is 5 m:

a) for all the time wind speed is constant and equal to 8 m/s;

b) for half the time wind speed is 16 m/s and for the other half is zero.

In both cases the average wind speed in the period is 8 m/s. From the graph of figure 3 it can be derive that in case a) the mean power produced is 2 kW and in case b) is 15.5/2 = 7.75 kW.

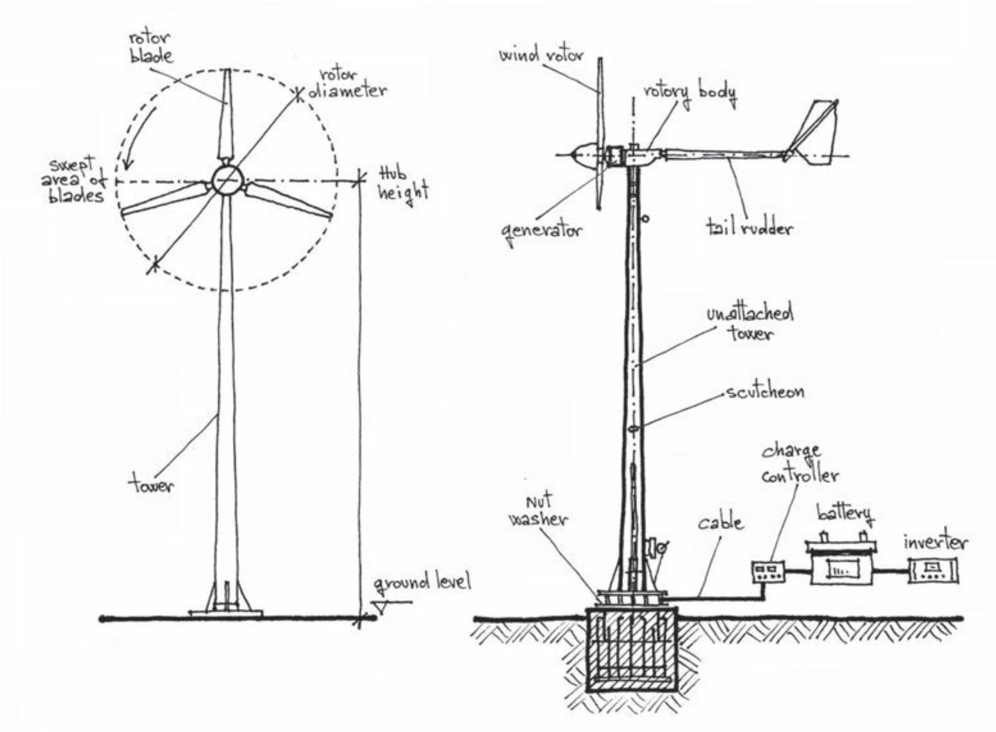


Fig. 6.3-1 – Horizontal axis wind turbine

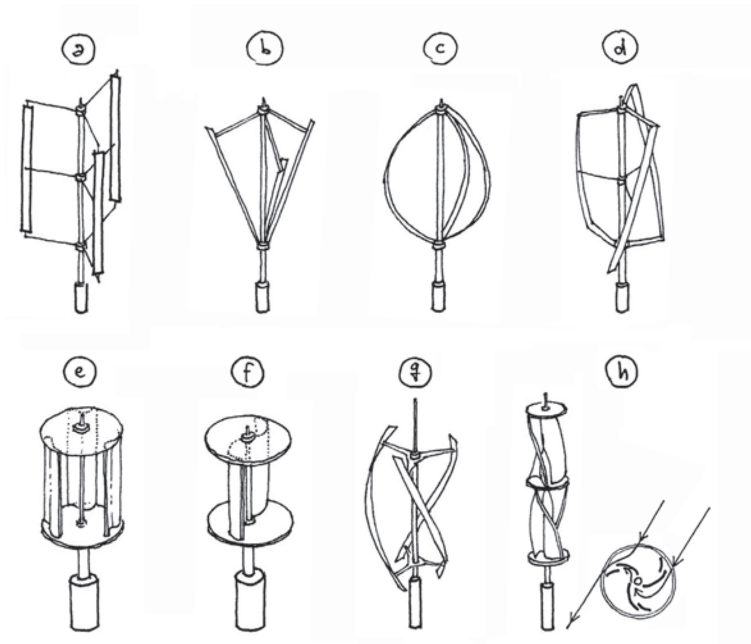


Fig. 6.3-2 – Vertical axis wind turbines. (a), (b), (c) Darreius type; (d) Gorlov type; (e) Squirrel cage Darreius; (f) Savonius type; (g) and (h): innovative turbines design

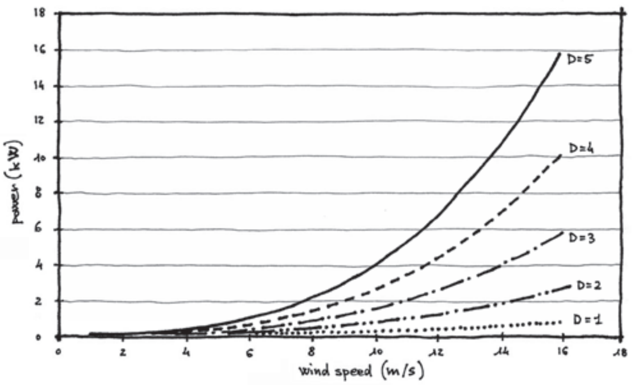


Fig. 6.3-3 – Electric power produced by a horizontal axis wind turbine (α = 0,15); D = diameter [m]

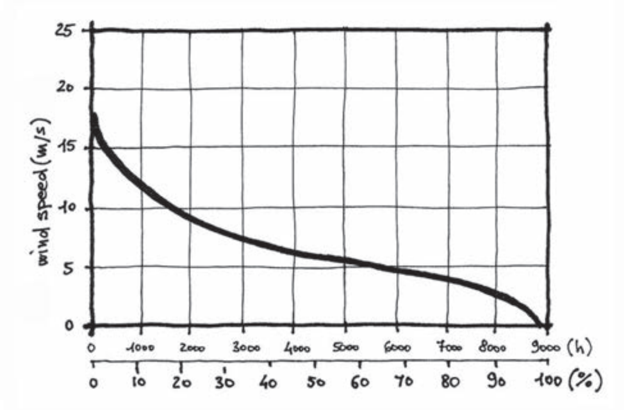


Fig. 6.3-4 – Duration curve

6.4 Biomass

Accordin to IEA[1], the traditional use of biomass dominates residential energy demand in sub-Saharan Africa today, with more than 80% of the population relying on it. Three-stone fires and other traditional stoves that burn wood, charcoal and other forms of biomass typically have very low efficiencies, ranging from 10% to 25%. The large amounts of these fuels needed to meet basic cooking needs with such stoves means that they account for more than 95% of total residential energy use in sub-Saharan Africa, resulting in average per capita consumption 16% higher than the average for emerging economies worldwide, even though average residential electricity use is eight-times lower than the average in the emerging market and developing economies.

6.4.1 Biomass cookstoves

Indoor biomass cooking smoke is associated with a number of diseases, including acute respiratory illnesses and even cancer, with women and young children affected disproportionately. It is estimated that smoke from cooking fuels accounts for nearly 2 million deaths annually[2], 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[3]. The number of premature deaths is highest in southeast Asia and sub-Saharan Africa[1]. 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[4].

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[3]. 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 and 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 reach up to 2 tons per family[2]. 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).

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. This is due to the fact that biomass use for cooking contributes in most cases to deforestation, therefore CO_2 emitted by biomass combustion is not reabsorbed by new trees or bushes. Other products of incomplete combustion and climate forcers 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[5]. While some of this reduction might not be counted toward CO_2 reduction because it derives from

1 *Africa Energy Outlook 2022, IEA*

2 *WHO (World Health Organization) and UNDP (United Nations Development Programme). The Energy Access Situation in Developing Countries. New York: United Nations Development Programme, 2009*

3 *IEA, World Energy Outlook 2010 - www.worldenergyoutlook.org.*

4 *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*

5 *The World Bank, Household Cookstoves, Environment, Health, and Climate Change, 2011*

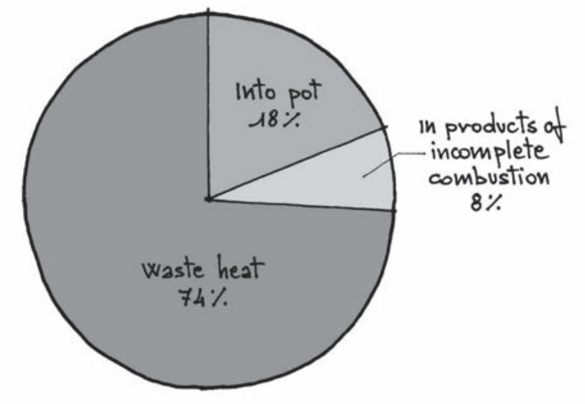


Fig. 6.4-1 - Energy flows in a typical wood-fired cooking stove

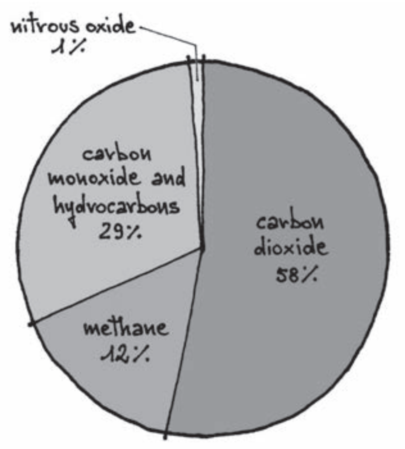


Fig. 6.4-2 - Greenhouse gas emissions from a typical biomass cookstove

sustainable biomass, a substantial fraction could come from the biomass resources contributing to resource depletion.

6.4.1.1Improved stoves

Many improved stoves models have been developed in the world – with and without chimney – varying in complexity depending on purpose, frequency of use, volume of pot required, and investment cost. Among the most popular in Africa are the Maedaleo and the Jiko stoves. They do not solve the problem of the smoke, but reduce fuel consumption up to 50%, compared to a three stone fire.

The simple Maendaleo 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%[6].

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%[7]

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

6 *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*
7 *B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995*

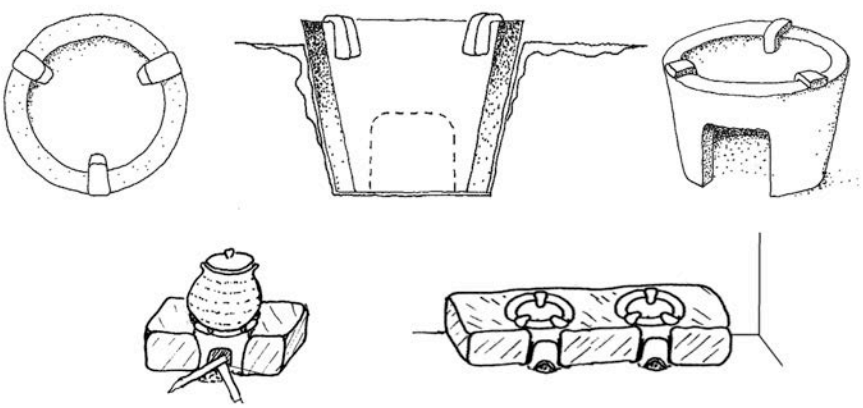


Fig. 6.4-3 - Maendaleo Stove (Adapted from: B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995)

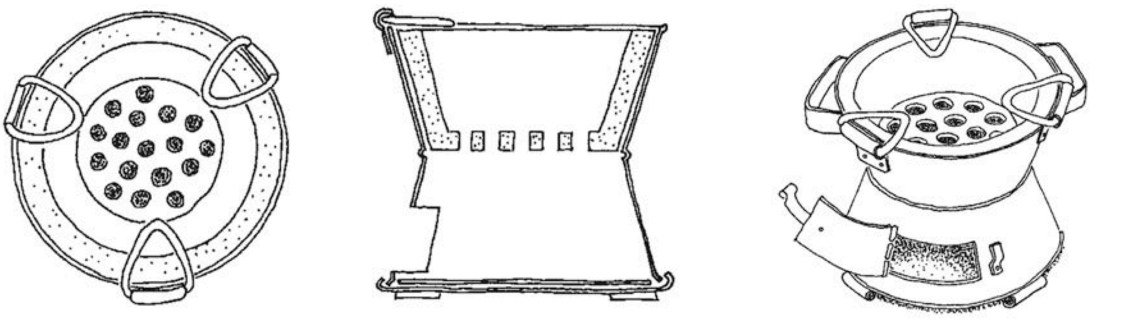


Fig. 6.4-4 - Kenya Ceramic Jiko (Source: B. Westhoff, D. Germann, Stove Images, Brandes & Apsel Verlag, 1995)

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 above 50% compared to three stone fire. A type of fixed rocket stove is shown in figure 6.4-6.

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, normally self-contained, that provide higher efficiency and low pollution, due to the use of a refractory liner in the combustion chamber allowing very

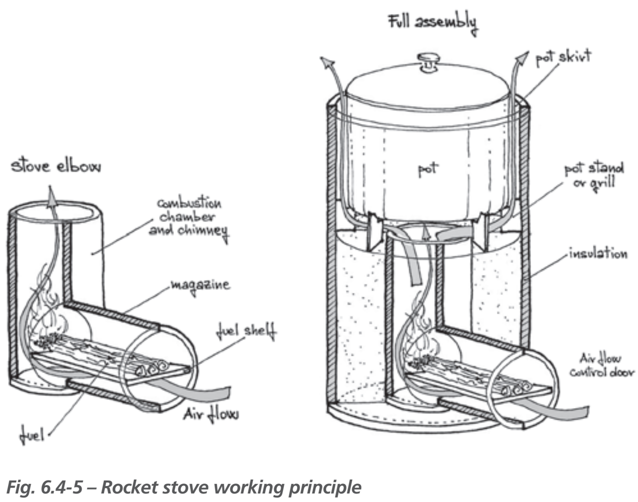


Fig. 6.4-5 – Rocket stove working principle

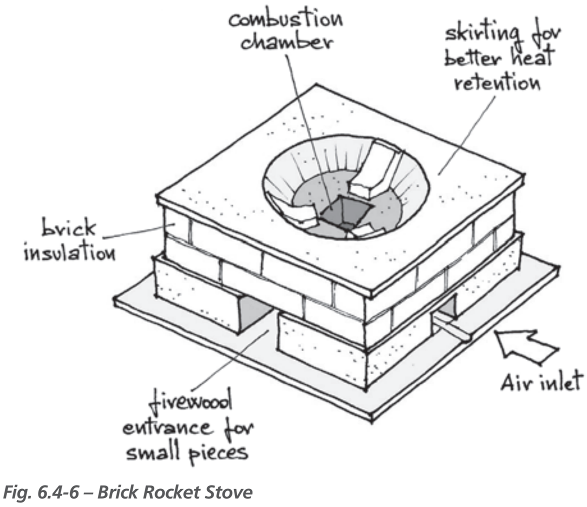


Fig. 6.4-6 – Brick Rocket Stove

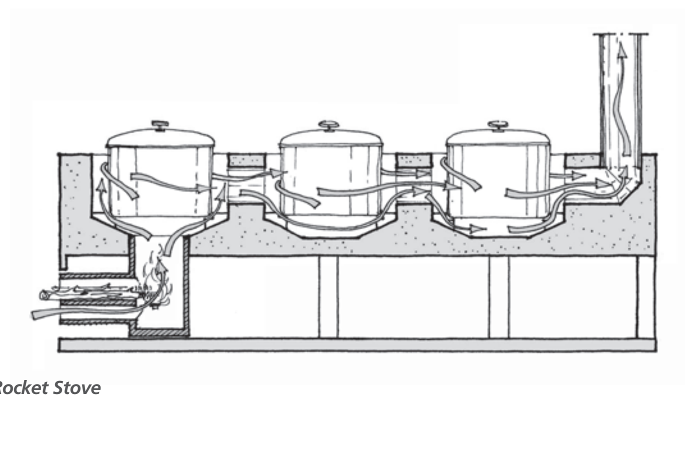


Fig. 6.4-7 - Three pot Lorena mud Rocket Stove

high flame temperature. They were developed for developed countries market.

Kitchen typically integrates cooker and an oven, heated by the hot air and smoke flow (Fig. 6.4-8). Hot water production is also an option of this kind of device.

In some cases the stove have 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 optimized 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.

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.

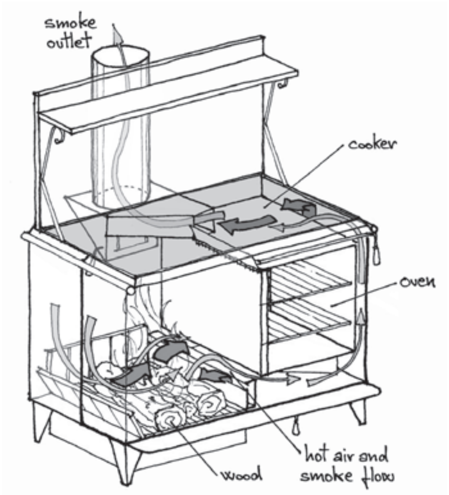


Figure 6.4-8 – Kitchen stove

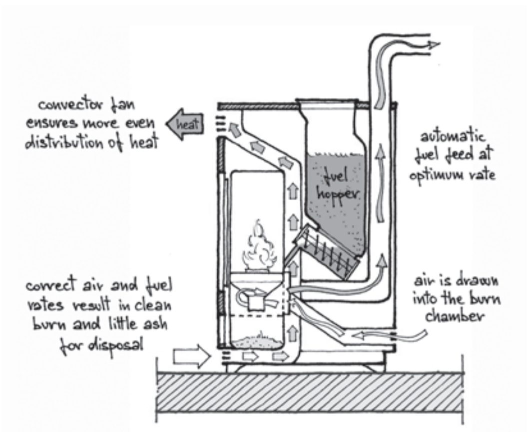


Fig. 6.4-10 – Heating wood stove with automatic fuel and combustion control

6.4.1.4 Pellet/briquette heating stove

Heating wood 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

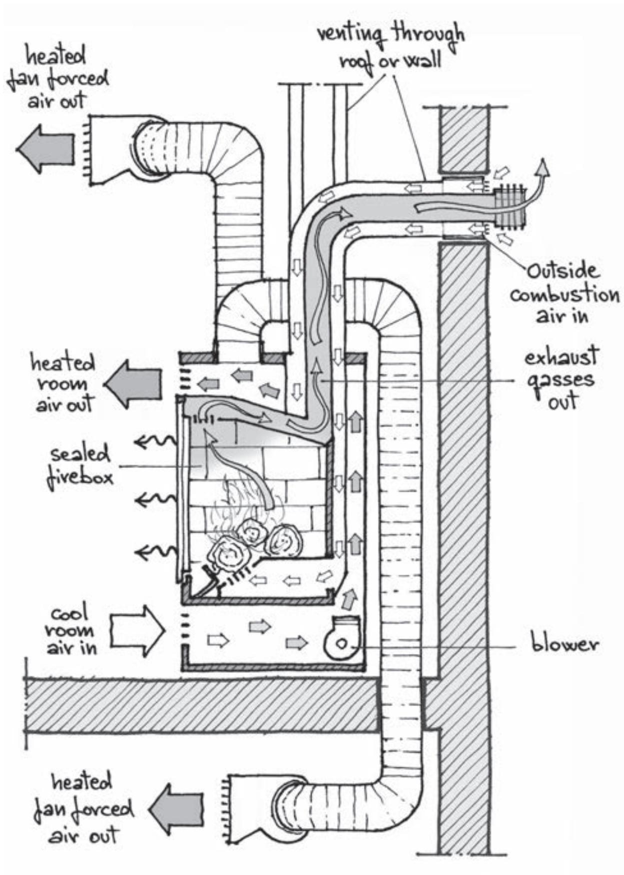


Fig. 6.4-9 – Fireplace heating system with forced-ventilation

an overall efficiency close to 90% and typically provide a thermal power between few kilowatts to 30-35 kW.

Problems related to environmental pollution due to the smoke produced by fireplaces and wood burning heating stoves must be carefully taken in account, also if automatic fuel and combustion control systems can assure an optimal burning in all operating conditions, significantly reducing airborne particulate.

6.4.2 Beyond simple biomass burning

Biomass represents a promising source, alternative to fossil fuels, for many reasons: availability, different typologies, programmability and storage, technological maturity, new researches in the field of small cogeneration,

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

Table 6.4-1 – Biomass classification according to the supply sector

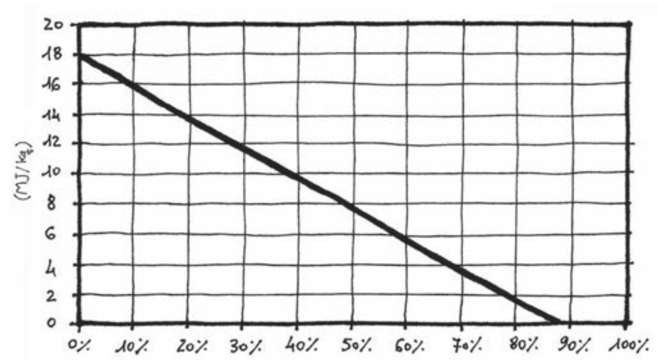


Fig. 6.4-11 - LHV of biomass versus humidity content

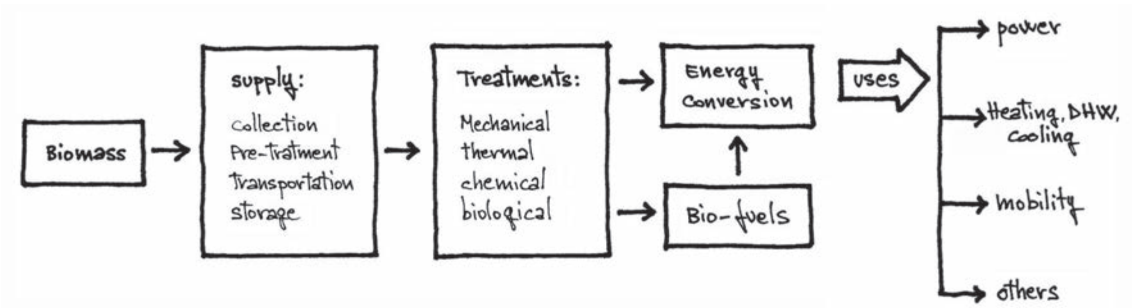


Fig. 6.4-12 – Biomass to energy processes

bio-methane distribution and second-generation biofuels production.

In fact different technologies are available today depending on the type of biomass to be processed, the final energies to be satisfied and on the economic conditions.

6.4.2.1 Biomass characterization

Processable biomass includes plants (trees, agricultural plants, bush, grass, algae, etc.), agricultural residues (crop and agro-processing), and wastes (organic fraction 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).

Unlike other renewable sources, for analysing 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 a capital importance.

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%

Table 6.4-2 – Moisture content for selected biomass resources (source: European Biomass Industry Association)

Heating values, humidity, density and contaminants

As well as for urban waste (see also section 6.3), also for biomass the moisture content (Table 6.4-2) and the heating value (Table 6.4-3) are the main elements to be considered in order to plan how waste can be effectively treated. Also the analysis of contaminants and pollutants has to be accomplished in order to prevent environmental hazards due to emissions during and after the management. These data can be highly variable depending on the type of the biomass and on the pre-treatment and storage mode.

6.4.2.2 Available and applicable technologies for transforming biomass into energy

Generally speaking, thermochemical processes are applied when the humid content and the ratio C/N (Carbon/Nitrogen) are quite high, otherwise biochemical processes are applied. In most of the cases mechanical and other conditioning treatments are scheduled between collection and the following steps of the chain.

Depending on the properties biomass can be used in many applications for energy conversion, from the small stove to the big cogeneration plants.

Thermochemical treatments

Biomass can be treated in different biochemical or thermal treatments to be converted into heat and power. The most common is the thermal treatment of combustion, but, especially for small and medium sizes, also pyrolysis and gasification are applicable.

Small scale

Potential small scale uses of biomass in Africa include

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

Table 6.4-3 – Some characteristics of biomass fuels compared to oil and coal (source: European Biomass Industry Association)

stoves, water heaters and gasification systems.

Design of gasifiers depends on type and quantity of fuel used and whether gasifier is portable or stationary. Gas producers are classified according to how the air blast is introduced in the fuel column. The most commonly built 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, suitable for using a variety of biomass and they have been developed in many countries.

The suitability of a particular type depends on the application and type of biomass. For use in internal combustion engines, downdraft gasifier is the most suitable. Updraft and crossdraft gasifiers are suitable for thermal applications.

In downdraft gasifier, air is introduced into downward flowing packed bed or solid fuels and the gas is drawn off at the bottom (Fig. 6.4-13a). A 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 act as counter-current to fuel flow. The gas is drawn at higher position. The updraft gasifier achieves the highest efficiency as the hot gas passes through fuel bed and leaves the gasifier at low temperature. The sensible heat given by gas is used to preheat and dry fuel. Disadvantages of updraft gas producer are the excessive amount of tar in 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 for operation to low ash fuels such as wood, charcoal and coke. The relatively higher temperature in 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. Crossdraft gasifier operates well on dry air blast and dry fuel.

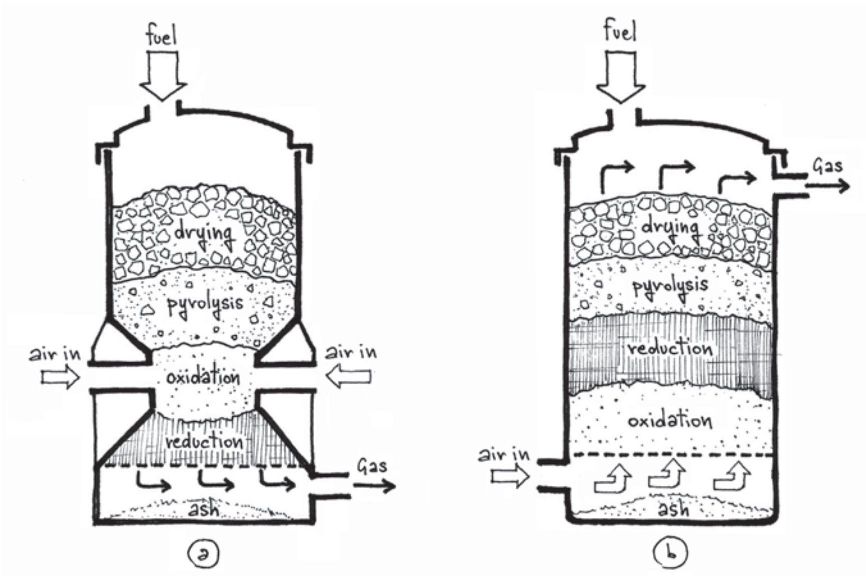


Fig. 6.4-13 – Sketch of downdraft (a) and updraft (b) gasifiers

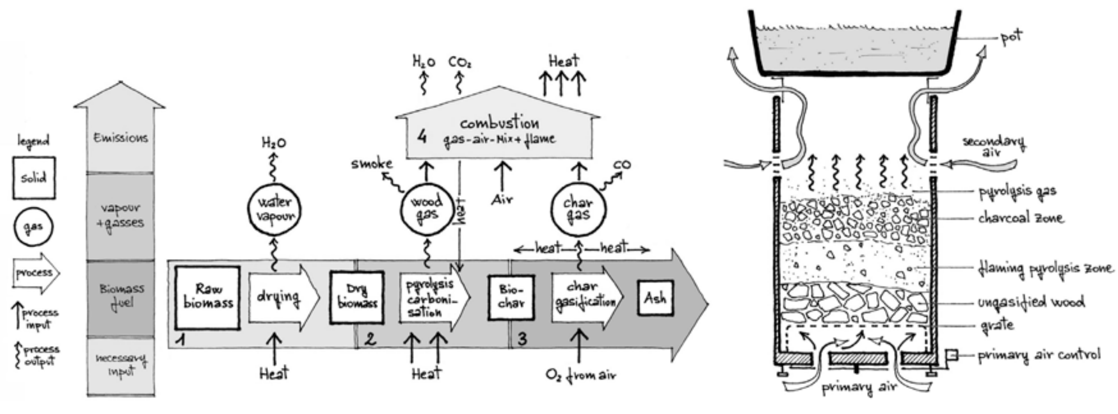


Fig. 6.4-14 – Micro-gasifier or wood-gas-stove working principle

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[8]:

1. as biomass is heated, it evaporates excess moisture and it's surface temperature in- creases,

2. at elevated temperatures, biomass pyrolysis into combustible vapours and a solid, known as char,

3. red hot char can be converted to ash if sufficient oxygen is available,

4. 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 which 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[11]:

- 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

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%[9] and a fuel saving ranging from 30 to 50%[10], compared with the three-stone open fire.

Medium-large scale

In general, technologies suitable for 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 by a suitable depuration line for abating dust, ash and other pollutants emitted.

8 *C. Roth, Micro Gasification: Cooking with gas from biomass, GIZ HERA, 2011*

9 *T. B. Reeda, E. Anselmo and K. Kircherc, Testing & Modeling the Wood-Gas Turbo Stove,*

10 *S. Carter, S. Shackley, Biochar Stoves: an innovation studies perspective, UK Biochar Research Centre (UKBRC), School of GeoSciences, University of Edinburgh, 2011*

Further, also storage and final disposal of ash and dust are taken into account in plants design.

Stirling engines, Organic Rankine Cycles (ORC) and steam-driven twin screw expanders represent other smart and efficient technology in order to produce power or to cogenerate power and heat (to be converted in 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 kind of biomass in absence of oxygen (anaerobic digestion). This process takes place in the digester (Fig. 6.4-15).

Anaerobic digestion is the process of conversion of 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 produces 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 strongly 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 process stability due to its high buffering capacity and its high content of trace elements. In order to increase the gas yield most of the biogas plants are operated today by co-fermentation of manure together with non-agricultural organic wastes, harvesting residues and energy crops.

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.

Considering waste water management output, on the basis of available experiences in EU and of technical literature, a value of 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[11].

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 a separated gasholder, which can be simply a large plastic inflatable container (Fig. 6.4-16).

The production of a household biogas digester only partially substitute other sources of energy as shown in Tables 6.4-5 and 6.4-6, but significant savings of fuelwood for cooking can derive.

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 of tropical regions biomass and bio-fuels can contribute to meet 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

11 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

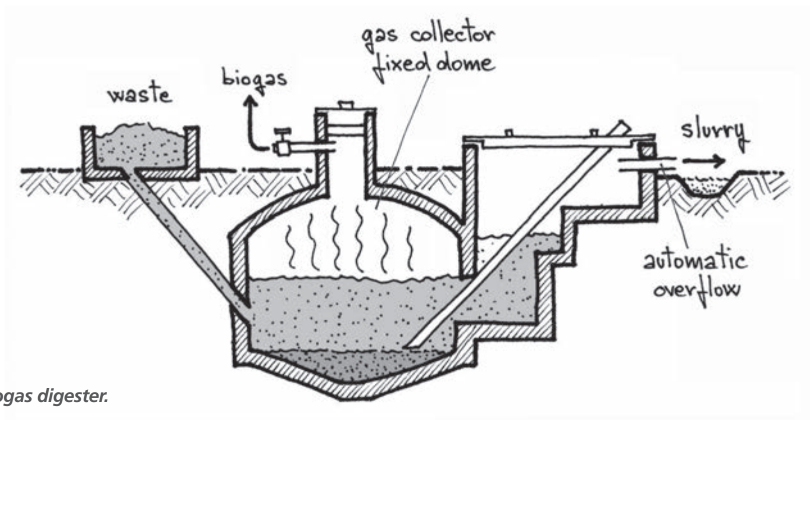


Fig. 6.4-15 - Scheme of a biogas digester.

Substrate	m³ 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

Table 6.4-4 - Biogas yield from different substrates (Adapted from: F. Cotana and D. Giraldi, Renewable energy for agricultural companies: a biogas micro-chp project)

	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 6.4-5 – Biogas consumption of selected appliances

	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

Table 6.4-6 – Biogas consumption of some applications

used for a variety of purposes such as cooking, drying, heating water, generating steam, etc.

The producer gas 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 future sustainable communities characterized by high energy efficiency, biomass, in particular if by-products are adopted, could be an important part of the energy system. Even if the supply of biomass could be a problem due to logistical problems regarding biomass transportation, this aspect has not to be considered as an insurmountable obstacle.

Indeed, the use of local biomass should be preferred, reducing this issue, which however 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.

The possibility of improving biomass production through specialised cultivations (i.e. energy crops, short rotation forestry etc.) should be carefully assessed; deep researches have to be carried out in order to evaluate all the effects of any modification. This is a key point for guarding biodiversity and local agricultural traditions.

Despite the debate about food and no 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 will be used more sustainably and productively and if residues and wastes will be used it is possible to produce bio-energy, feed a growing population and conserve the environment at the same time.

Fig. 6.4-16 – Above xground plastic inflatable gasholder

6.5 Hydropower

Hydropower is energy from water sources such as the ocean, rivers and waterfalls. "Mini- hydro" means which 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 to be considered for providing clean electricity generation. The key advantages of small hydro are[1]:

• high efficiency (70 - 90%);

• high capacity factor[2] (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;

• it is a 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 effect 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.

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:

$$P = \eta \rho g Q H \qquad (6.5\text{-}1)$$

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 in the range 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:

$$\text{Energy} = P \times CF \times 8760 \quad [\text{Wh/year}] \qquad (6.5\text{-}2)$$

6.5.2 Types of turbine

Turbines can be categorized mainly in 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.

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.

1 Mini-Hydro Power, 2010, http://w3.tm.tue.nl/fileadmin/tm/TDO/Indonesie/Hydro_Power.pdf

2 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}

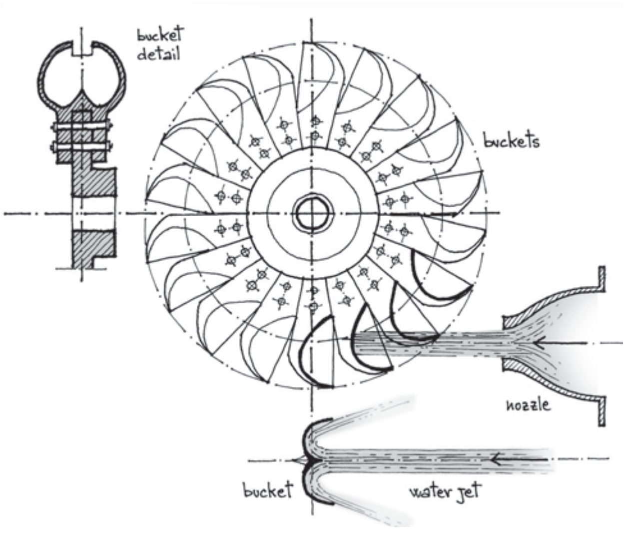


Fig. 6.5-1 – Pelton wheel

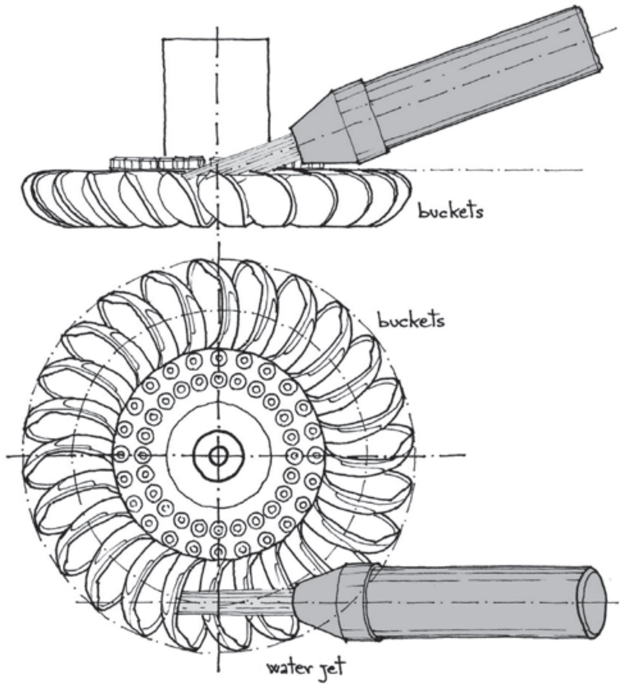


Fig. 6.5-2 – Turgo turbine

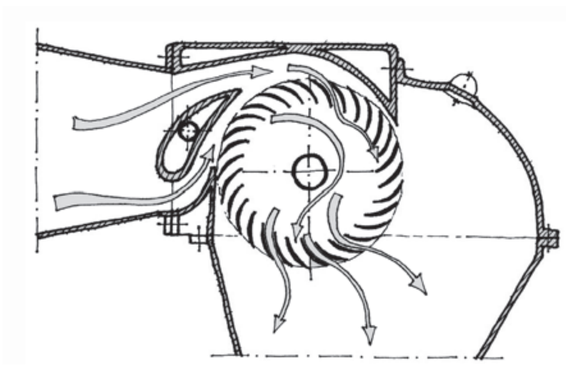


Fig. 6.5-3 – Crossflow turbine

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.

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.6.5-3) 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 into the runner (Fig.6.5-5). 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. 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 wide range of flows.

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

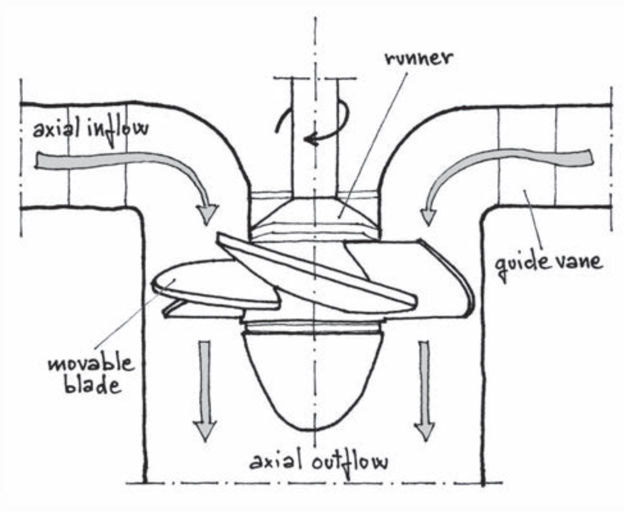


Fig. 6.5-4 – Propeller type turbine

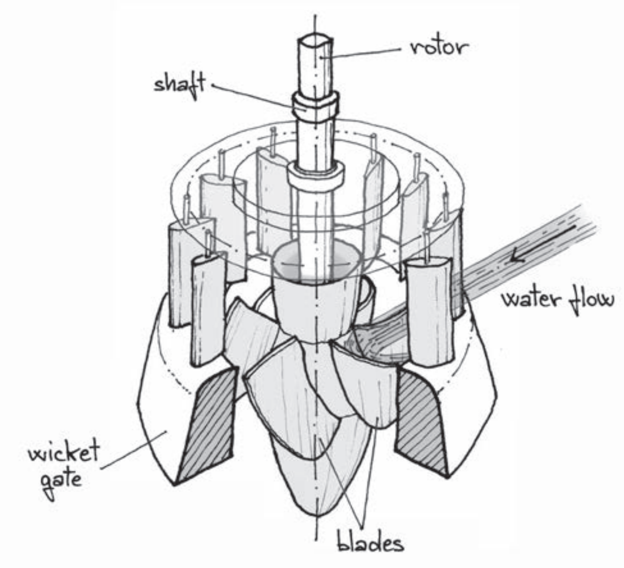


Fig. 6.5-5 – Kaplan turbine

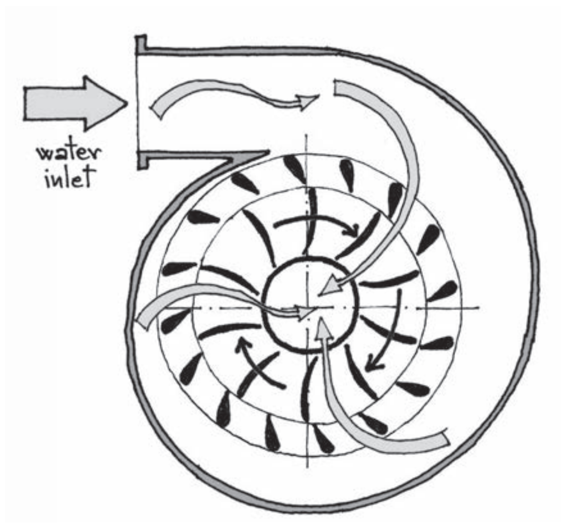


Fig. 6.5-6 – Francis Turbine

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.

Archimedean screws for hydropower (Fig.6.5-8) 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 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[3].

3 *Renewables First, http://www.renewablesfirst.co.uk/hydro-learning-centre/archimedean-screw/*

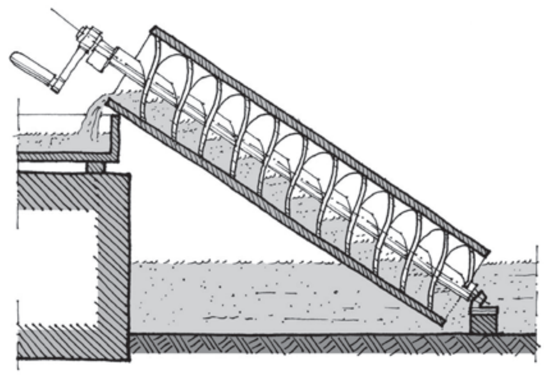


Fig. 6.5-7 – Archimedean screw used as a pump to lift water

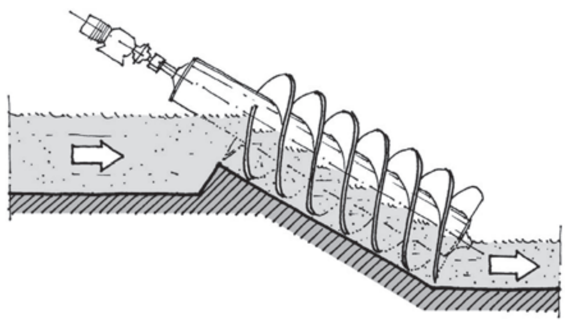


Fig. 6.5-8 - Archimedean screw used as a turbine

6.5.3 Turbines operating regions

Each type of turbine works at best within defined operating regions, in terms of head and flow rate, as shown in the subsequent figure.

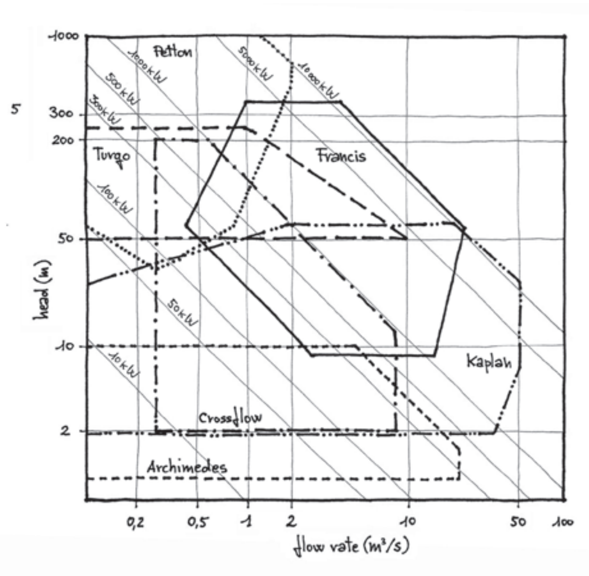


Fig. 6.5-9 – Operating regions of different types of turbines

07 | NET ZERO ENERGY BUILDINGS AND COMMUNITIES

7.1 Net Zero Energy Buildings

According to IPCC, to have in 2050 only a 1.5°C rise of earth surface temperature compared to the preindustrial value, by that time the net amount of GHG emissions flow in the atmosphere must be zero. It is a tremendous challenge that must be faced in all energy consuming sectors. In the building sector, taking into account the existing stock, whose energy consumption can be reduced only to certain extent, it is necessary to act vigorously on new constructions, also because a very fast growth is going on in emerging and developing countries. In this context, the only answer consistent with emissions reduction target is to start to move towards zero energy buildings. This is going to occur in the EU where, according to a Directive[1] on Energy performance of Buildings[2], member States shall ensure that as of 2021, all new buildings must be nearly zero-energy buildings (NZEB).

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 covered 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 demand 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 with renewable sources, not only heating, cooling, hot water and lighting.

Actually, 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 the choice between RE supply on-site or off-site (EU Directive favours on-site) and, if the on-site option is chosen, there needs to be specified if on-site means within the building footprint or it includes the building's pertaining area.

Also for RE produced off-site there are two options: 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 far away wind or solar park).

Whatever the definition, a zero-energy building represents a tremendous change, at technical, economical and cultural level. Technical because imposes a new way to design and construct buildings; economical because imposes to look at the operation cost, not only to investment; cultural because it is unavoidable that the language of architecture has to change.

1 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.

2 Directive 2010/31/EU of The European Parliament And Of The Council of 19 May 2010 on the energy performance of buildings (recast).

The design process is already subject to analysis and revision as 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 play their role.

The zero energy goal challenges also the concept of flexibility in the use of a building: a modification of the internal layout, of spaces' functions involves a shift from the equilibrium production-consumption of energy of the original project. If functions and the way the building is used are changed, it is necessary to redesign the entire system, or at least, to adapt it.

In zero energy buildings' occupants behaviour becomes a crucial factor; a relationship between occupant and building is tied up, stronger than in the recent past, and closer to that of more far away times, when the only available energy was the renewable one. In this relationship a crucial role have the electric and electronic appliances, for both 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 interact with it, injecting or withdrawing energy.

The grid and the building have, in general, different needs, and a dialog have to take place for finding a reasonable equilibrium. It is not a problem regarding only electric engineers; buildings must be designed and operated in a way to take into account this issue since the beginning.

With a zero-energy building, unless the energy source is biomass, and the technology used the 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 facades or "nearby". Thus, there is a physical, spatial limit for the production of renewable energy (the available area for the collection of solar energy), obliging to a maximum consumption limit. This limit, in turn, has a very strong impact on urban planning, especially 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 are becoming more and more important in the characterisation of zero energy buildings. For zero energy buildings, embodied energy is the only one to be consumed. Embodied energy will have to be balanced in the building's lifespan. Materials' choice, thus, will become an extremely critical factor, and a new expertise will have to be included into 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 gives an overview of relevant terminology addressing the energy use in buildings and the connection between buildings and energy grids.

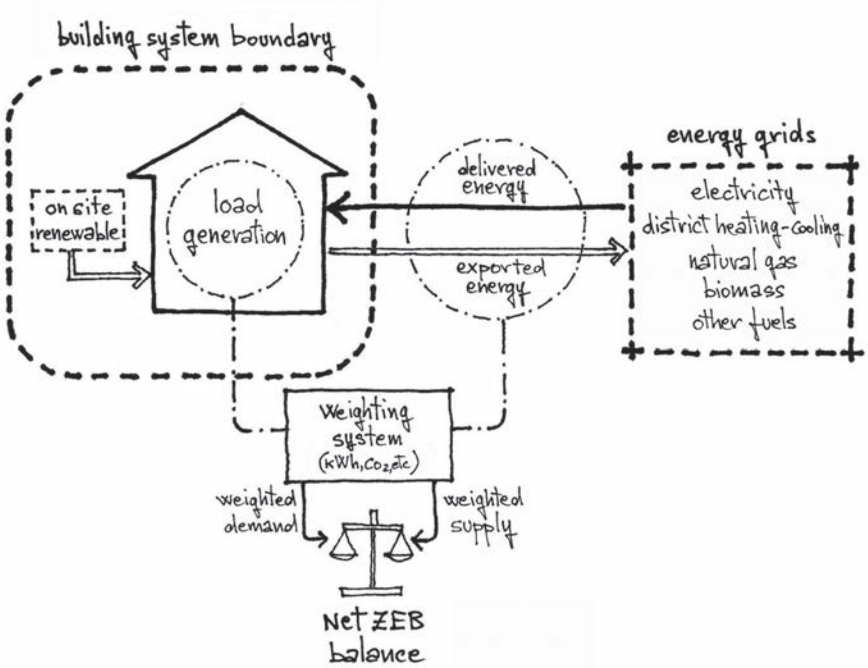


Fig. 7.1-1 – Sketch of the connection between buildings and energy grids showing the relevant terminology (Adapted from: K. Voss, I. Sartori, E. Lollini, Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions, REHVA Journal – December 2012)

The definitions of the terms are:

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^2y]. 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^2y].
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 : $\lvert\text{weighted supply}\rvert - \lvert\text{weighted demand}\rvert = 0$ 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.

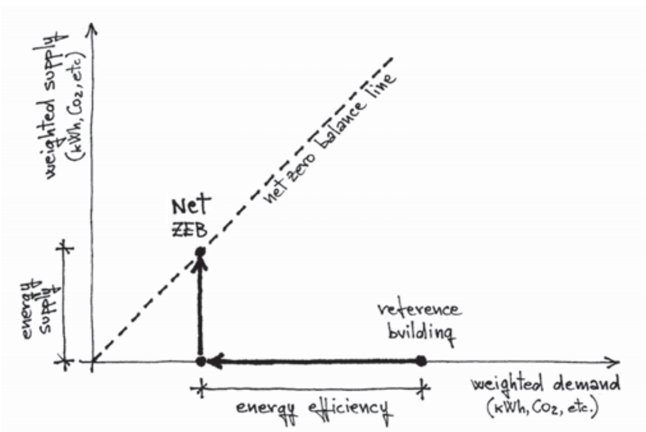


Fig. 7.1- 2 – Graph representing the net ZEB balance concept (Adapted from: K. Voss, I. Sartori, E. Lollini, Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions, REHVA Journal – December 2012)

The physical boundary identifies the building (as opposed to a cluster 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 up to the meters (or delivery points). The physical boundary is also useful to identify 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 the balance between building's energy consumption and renewable energy production, on yearly basis. There is also to consider the problem of the load matching, i.e. of the time coincidence demand-supply. 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 to have a non negligible 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[3]:

$$f_i = \min\left(1, \frac{\text{electricity production from renewable energy source}}{\text{electricity consumption}}\right) \times 100\ [\%]$$

(7.1-1)

i = time interval (hour, day, month)

It is noted that diminishing the time interval (yearly, monthly, daily, hourly), the index becomes smaller, down to values lower than 30% when the hourly time interval is chosen.

There is also to consider another type of coincidence, 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 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 not only minimises the load match index, but also supplies to or absorbs energy from the grid at the time it 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 the thermal one, already used for both heating and cooling. Or the storage 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 case of gas, the fossil primary energy consumed can be balanced with a surplus production of 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 weather forecast, grid's needs, instantaneous kWh cost, etc., minimising as much as possible the supply-demand mismatch.

Building design (and construction and operation), then, requires that a 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 following the zero-energy building is the zero-energy district, prelude of the zero energy city.

3 *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*

7.1.3 Zero energy buildings in Africa: early experiences

If design and construction of a zero-energy residential building is a challenge, requiring high level integrated design, even bigger is the challenge with commercial buildings, due to the greater complexity of their architecture and mechanical systems. Also 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 have been built only since few years. The main reason lies in the fact that the way a residential building is used is confined between not too large extremes; it 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 wider.

In chapter 8 the most significant case studies built in Africa are reported.

7.2 Net Zero Energy Communities

According to UN[1], a very fast process of urbanisation is taking place, especially in developing countries, with a world population expected to reach 9 billion people 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.

Just in settlements, on the other hand, is mostly concentrated the world final energy consumption (for heating and cooling of buildings, for lighting, for electric and electronic appliances, for transport), accounting for more than 70% of the total. Thus, more than two thirds of 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, the need arise for very strong actions for curbing the fossil energy consumption trend in cities, where most of the energy is consumed. It is necessary, in other words, to develop a new urban design approach based on a new urban energy system, to avoid the catastrophic effects of global warming on one side, and to cope with the unavoidable constant increase of oil cost on the other.

By combining in appropriate way, according to the local climate and resources, the technical and technological means today available, it is possible to design the energy system of a settlement reaching the aim of zero CO_2 emissions. The energy system must be conceived since the beginning 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 a linear, fossil fuel based, energy economy, but a circular, renewable sources based, energy economy.

1 *United Nations, Urban and rural areas 2003, New York, 2004*

08 | CASE STUDIES

CASE STUDY 01	CENTRE OF EXCELLENCE FOR PAEDIATRIC SURGERY
Location	Entebbe, Uganda
Latitude	0.0512° N
Longitude	32.4637° E
Type of climate	Tropical
Type of building	Hospital
Date of construction	2013-2020
Owner	Emergency
Design team members	Renzo Piano Building Workshop, Studio TAMassociati

The building

The new medical center, completed in 2020, was Designed by Renzo Piano Building Workshop (RPBW) and Studio TAMassociati for the Italian NGO EMERGENCY and mainly aimed at providing free treatment to children with surgical needs from all over Africa.

Thanks to the large areas dedicated to teaching, the hospital acts also as regional training center for health professionals. It represents a meeting point between the knowledge of the EMERGENCY personnel and the young Africans who will therefore have access, in their own continent, to top quality specialized training, without having to resort to costly study periods in foreign countries.

The hospital complex, consisting of 4 main buildings and some ancillary structures, is an effective example of how the principles of sustainable architecture can be applied in a work of great value, not only architecturally but also socially.

Following the promoter and designers' intentions, the architectural style of the complex appears very discreet and essential, but at the same time combines ingenuity and ambition, with the aim to communicate a sense of protection, spaciousness and hope.

View of the complex
© Archivio Emergency, ph. Will Boase

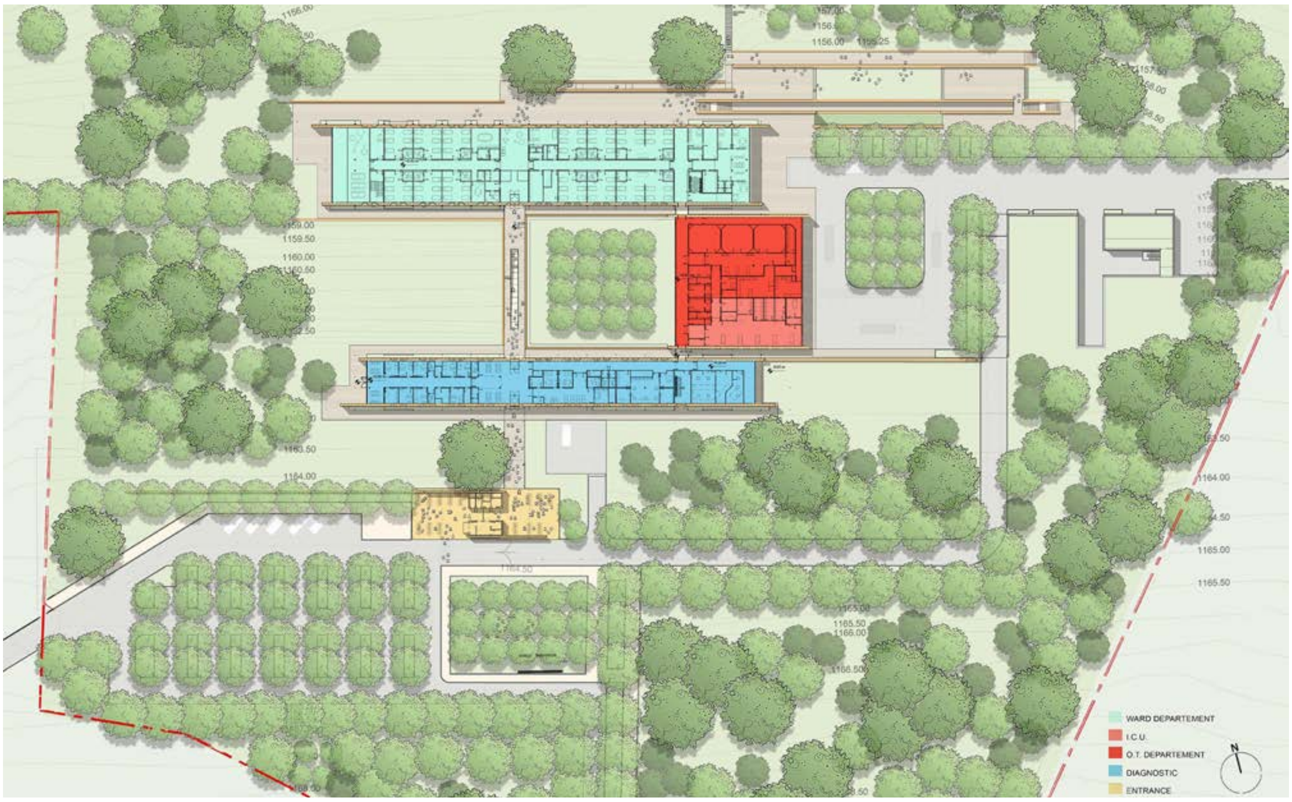
The Location

The area, located north of Entebbe near Wakiso District, about 35 km south-west of Kampala, follows the natural course of the land to the shores of Lake Victoria. In this context, three buildings, oriented along the east-west axis, are arranged in parallel, with the fourth building enclosing the east side of the inner courtyard with a large garden, which is the focal point of the project. Considerable spaces are dedicated to play areas, both outside and inside the hospital. Play is intended as a healing factor, a fundamental element on the road to recovery, a way of making the children's stay in hospital as relaxing and cheerful as possible. The hospital itself is designed as a place that amazes, thanks to ever-changing glimpses and openings. A way of making the facilities welcoming and friendly, to calm the fears of the young patients.

A technical installations area, physically separated from the hospital to minimize noise, houses the energy production and distribution technical systems.

The entrance and reception area are located in the smallest building, a single-story structure that also contains access control and accreditation activities. All other buildings have two floors: the ground floor and the basement. The south wing of the complex houses clinics, diagnostics and services for outpatients; the ground floor of the north area includes inpatient wards, recreation rooms and spaces dedicated to children's play and recreation, as well as classrooms for training health care personnel, offices and a cafeteria, located in the basement.

Finally, the fourth building houses the intensive care unit, three operating rooms and, on the floor



Ground floor planimetry
© RPBW

Cross section
© RPBW

Ward Department West front
© Archivio Emergency, ph Will Boase

Rammed earth facade
© Archivio Emergency

below, the pharmacy and services for medical, paramedical and support staff.

Energy Concept

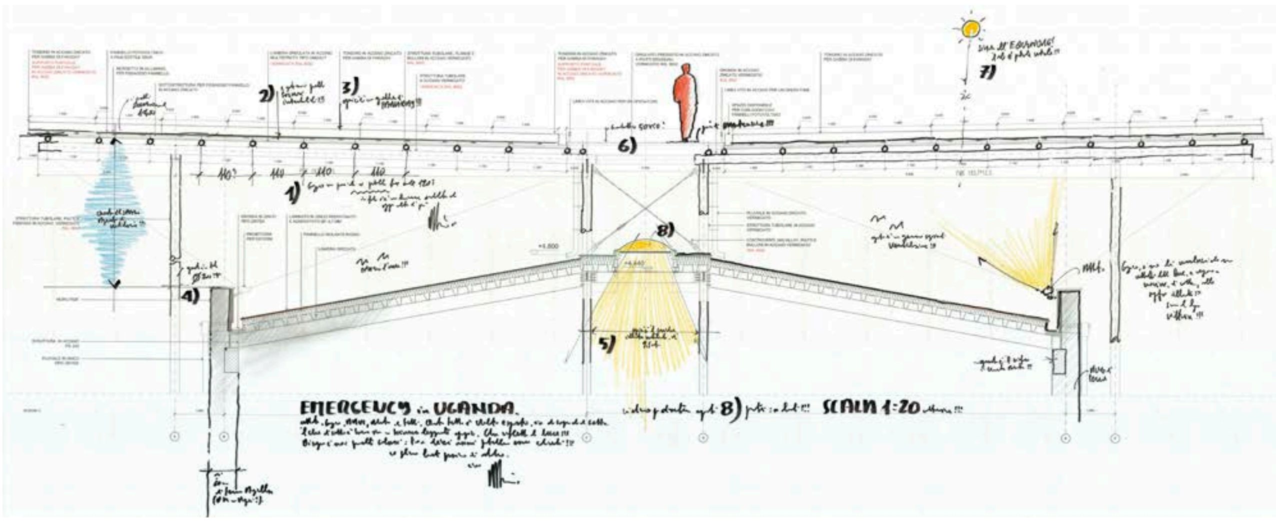
Climate responsiveness, sustainability and energy efficiency were taken as the key principles of the project. The main orientation of the buildings reduces the areas exposed to the east and west, presenting the main fronts to the north and south, where the sun passes higher and is easier to shade. The roofs, which in hot climates often causes overheating problems, are designed to shade the buildings as well as all the uncovered walkways, and at the same time produce solar electricity for the hospital. Roofing canopies are made from a suspended trellis structure supporting 3,000 square meters of photovoltaic modules (around 300 kW_p). This system can ensure that the hospital has an autonomous electricity supply during the day, but is also connected to the main grid, to provide energy to the surrounding community at times when self-consumption is low.

The air-conditioning systems, with ground water heat pumps, have been designed to ensure maximum comfort with minimum consumption of resources, always keeping the needs of emergency and operating rooms in the foreground.

Natural lighting

Light represents one of the prevailing elements of the project, supporting natural solutions wherever possible. The inpatient ward and the outpatient department will be lit with large windows looking out onto the surrounding greenery, with the in-between spaces using natural overhead illumination.

The large roofing canopies, the windows embedded into the thick walls and venetian blind shading systems filter sunlight and protect the interior spaces from overheating.



Design's sketch
© RPBW

Photovoltaic roof
© RPBW

Natural ventilation

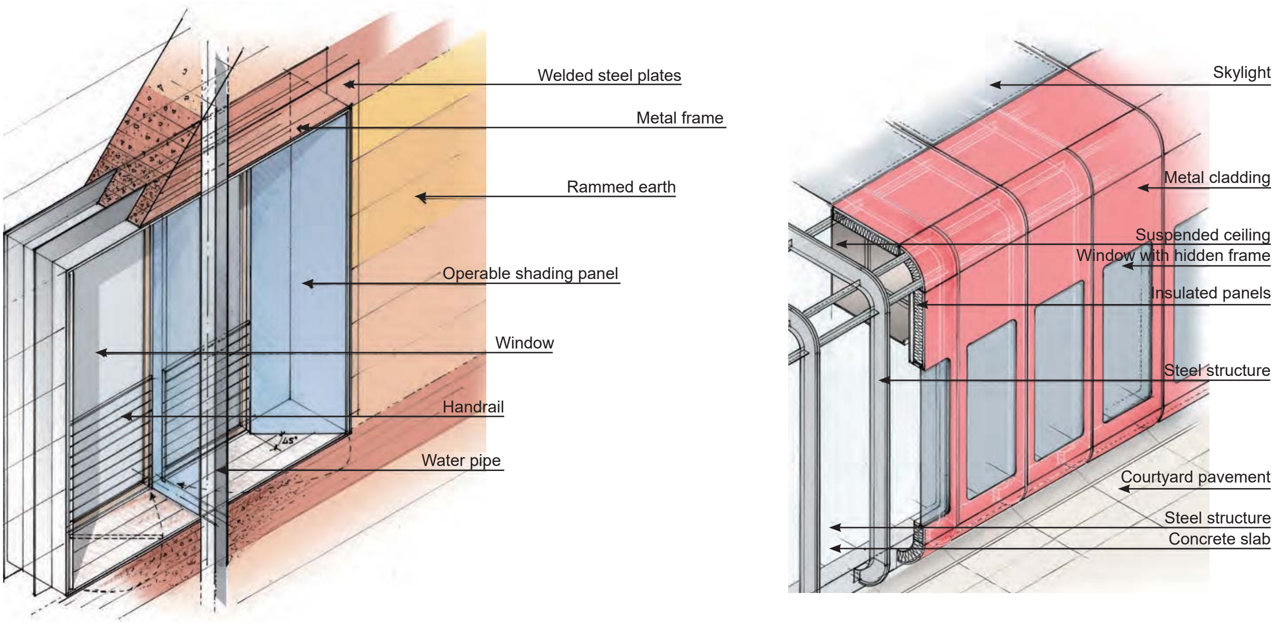
Openings between rooms and corridors and between them and the outside allow for natural ventilation of interior spaces. An automatic BMS optimizes the internal energy consumption, along with the use of low-energy devices, such as LED illumination.

Building materials

As is well known, one of the main features of sustainable architecture is the use of low environmental impact materials, possibly produced at a local scale. In this regard, the project involved adapting the RPBW's traditional working method in order to realize a vital structure with limited means, using local resources, both in terms of materials and manpower.

The most important example is represented by the external facades: walls are made of Terra Pisè, a local construction technique based on rammed earth. This material provides buildings thermal inertia and a good insulation, through a simple but functional installation, keeping temperatures and humidity constant all over the year. Rammed earth technique is an ancient building method involving a mixture of earth, sand, gravel, binding agents and a little water, compressed in wooden or metal frames or modules. The biggest benefit is that the material is available on site and there's no need for cement or highly specialized workers.

In this specific case, the outstanding aspect of using this construction technology was the integration into a modern, technological structure, combined with advanced building systems, such as steel trusses and pillars, building integrated photovoltaics, solar control systems and metal cladding.



Technical Axonometries
© RPBW

Construction stage
© Emergency NGO

CASE STUDY 02	CENTRE POUR LE BIEN-ÊTRE DES FEMMES
Location	Ouagadougou, Burkina Faso
Latitude	12.3714° N
Longitude	1.5197° W
Type of climate	Hot semi-arid
Type of building	Complex for collaboration
Date of construction	2005 - 2008
Owner	AIDOS
Design team members	FAREstudio

The building

The building, designed by FAREstudio, is based on the separation of the primary activities performed by the Centre pour le Bien-Être des Femmes (CBF) into two closely relatedvolumes: a Training Centre, dedicated to management and awareness-rising activities, and a Consultancy Centre, where medical visits, legal assistance and psychological counselling are provided to the community almost free of charge. Volumes with different rooms are independent from the umbrella roof structure, placed at the top of the platform and freely articulated around a series of shaded and ventilated patios that ensure privacy from the exterior. Such system manufactured with a lightweight waterproof PVC canopy, guaranteeing protection against rainfall and, above all, from direct sunshine.

The building actually, located in the middle of West Africa between the Sahara Desert [to the North] and the coastal rain forests [to the South], should face with different climate phenomena. For this reason, the canopy not only protects from the sun and rainwater, but also allows the collection of the latter for irrigation purposes.

The building raises on a platform above ground level and ensures internal hygienic/climatic conditions that are extraneous to local culture and building practices (protection against dust, mud and humidity).

Construction site
© FAREstudio

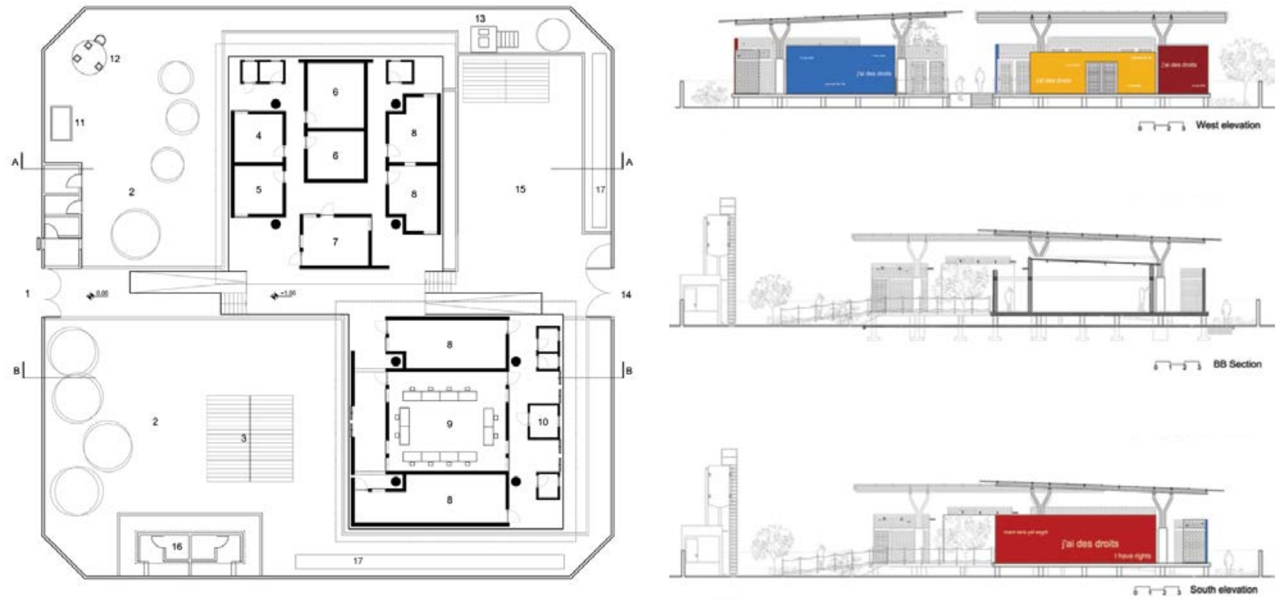
Bioclimatic approach

The climate as well as the local habit guided the overall design, more in detail the following strategies have been adopted:

- building orientation, as a strategy to reduce the effects of hot wind and take advantage of mutual over shading;
- upper shading, in order to protect heavy materials against direct exposure to sun and overheating;
- extensive use of operable windows and gaps between elements, in order to enhance natural ventilation;
- creation of transitional spaces, such as verandas or patios, aimed at providing various degrees of environmental wellbeing;
- combination of heavy and light materials in order to dose thermal insulation and natural ventilation;
- use of vegetation, in order to better regulate the overall microclimate.

Building materials

The building walls are constructed using BTC [Briques en Terre Comprimée], clay bricks made on site using a rough mixture of earth, sand and water stabilised with cement and compressed with an hydraulic press.



Planimetry, elevations and sections
© FAREstudio

Construction site
© FAREstudio

The making of these sun-baked bricks consumed no additional energy [transportation and/or cooking], limiting the environmental impact of the entire intervention.

The choice to use site-formed mud bricks was based on their temperature and humidity reduction characteristics, enhanced here by their protection against contact with water, perhaps the only serious limitation they pose.

The use of this technology represents the desire to introduce alternative and sustainable technologies within a context that is tied to standardised, though not always optimal building practices and the widespread importation of foreign materials.

The outside walls, devoid of any openings, are finished in brightly painted plaster. The local NGO's slogan, completes the decoration of the walls, turning the entire building into a large canvas that broadcasts the structure's social objectives in an informal manner.

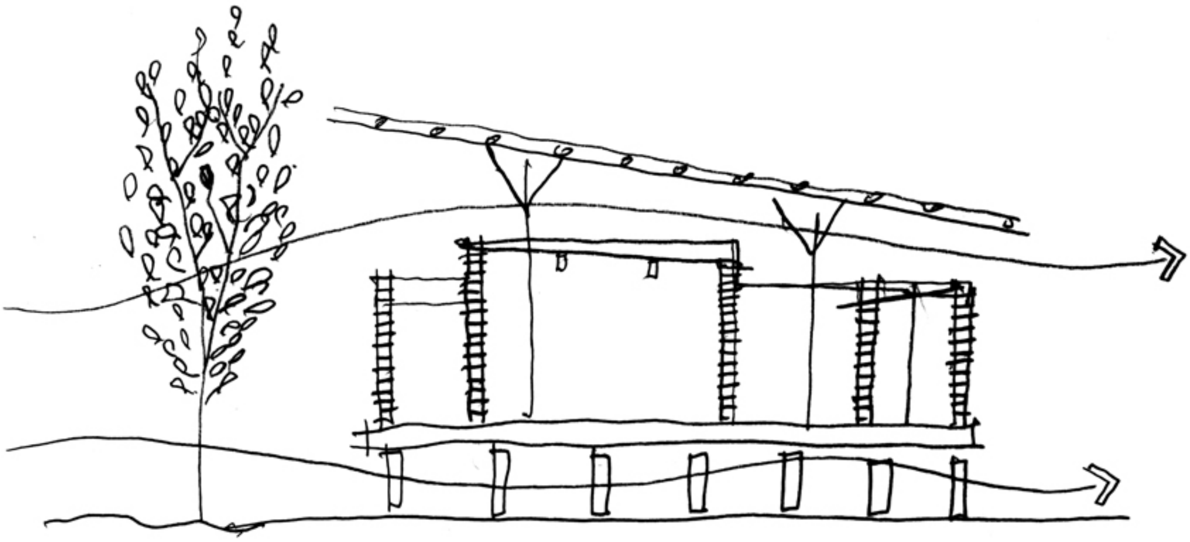
The buildings are covered by corrugated aluminium and translucent decking that allows natural light to filter into the interior, reducing the need for artificial illumination.

Natural ventilation

The space between the steel roof and the velarium and the open cavity beneath the platform, together with the exterior openings fitted with operable glass fins, all help to improve the natural ventilation of interior spaces and drastically reduce the need for mechanical air conditioning.

The exterior space, as the interior, is designed to be used as an open area by the entire community. It is a space of sharing and of information used to present the themes dealt with by the CBF.

Construction site
© FAREstudio



Ventilation concept's sketch
© FAREstudio

Indirect and informal communication is also favoured by the organisation of small events and public discussions.

The garden is a micro environment that surrounds the structure and takes advantage of the shade provided by the building and trees and the humidity produced by the plants.

A grass layer reduces the effects of erosion, while various species from Western and Sub-Saharan Africa have been planted with the twofold intention of creating shade and promoting the return of autochthonous vegetation.

Energy concept

Integrated systems for the regular control of energy consumption are accompanied by energy self-production: water is supplied by a newly drilled and dedicated well, and photovoltaic cells have been installed along the perimeter wall reducing the use of the power generator.

The elimination of mechanical air conditioning [limited to medical rooms in order to assure filtered air] is perhaps the project's most important achievement in terms of environmental sustainability.

These simple steps affect both personal behaviour and collective responsibility: the provision of an effective system is useless if users do not have a comprehensive understanding of the advantages of a proper maintenance of the whole system.

Construction site
© FAREstudio

Photovoltaic and water storage system
© FAREstudio

CASE STUDY 03	THE RIDGE
Location	Cape Town, South Africa
Latitude	33.9249° S
Longitude	18.4241° E
Type of climate	Mediterranean
Type of building	Office
Date of construction	October 2020
Owner	Deloitte
Design team members	Arup e studioMAS

The building

The new headquarters of Deloitte consulting company was designed by studio Arup and studio MAS to be an innovative response to the need of a low-energy building with the goal of reducing up to 82% of Co_2 emissions, which is particularly innovative when compared not only with the architectural African market, but also worldwide.

The building consists of four above-ground floors and three basement floors of 8,500 m² and has been awarded with the 6-star (World Leadership) Green Star for design and construction by the Green Building Council South Africa.

The goal of sustainability was achieved mainly avoiding a fully air-conditioned building, common to many commercial buildings in Africa, while aiming to human comfort through architectural and technological design that made different aspects interact, to reach the goal of low energy consumption.

Energy concept

The main guideline of the design project seems simple: use the ventilation and natural lighting offered by the climate, the geographic location, and the lot position, controlling, implementing, and maximizing them through the specificities of the architectural design (both in terms of plan and volume) and energy-efficient climate control systems that contribute only when necessary.

Indeed, this design strategy makes the most of the city's Mediterranean climate, which can provide

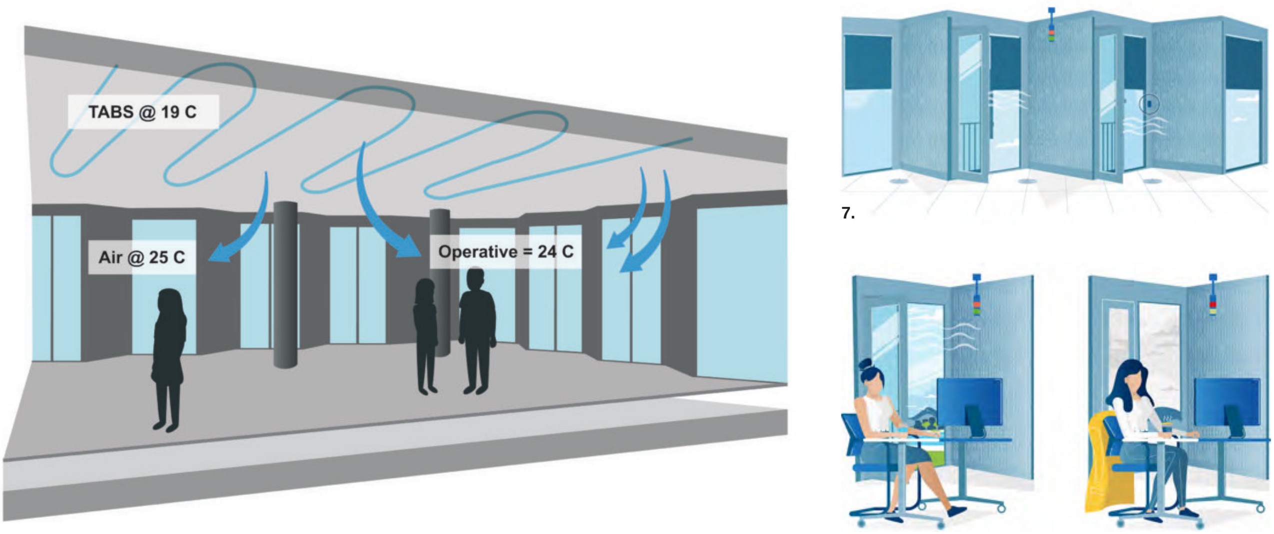
Exterior view
© Arup

natural ventilation most of the year, seeking to maximize the times when this occurs.

In this regard, the unfavourable conformation of the rectangular lot, which naturally seemed to offer the easier realization of a very deep and dark surface, moreover unfavourably oriented, difficult to manage without an excessive contribution of ventilation and artificial lighting, is overcome by the conception of a full-height central atrium flanked laterally by two four-story volumes that overlook it and take advantage of its natural lighting. In fact, the atrium was conceived as a huge chimney that lets fresh air flow inside from the façade's opening windows, through the office spaces and then conducts it outside through skylights.

Façade structure

The response to the unfavourable orientation for thermal and light control was the design of the distinctive "zig-zag" facade with the glazed elements facing North and South. This minimized the solar heat load by preventing solar radiation, coming from east and west, from entering the building. In this way, optimal daylight is maintained, as is the unobstructed view of Cape Town, without the need for exterior shading.



Heating and ventilation schemes
© Arup

Façade detail
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The wood façade includes locally sourced, solid, self-supporting CLT (cross-laminated timber) panels.

Also within the facade stratigraphy, plastic eco-bricks were used as void formers within the structure to reduce the carbon footprint.

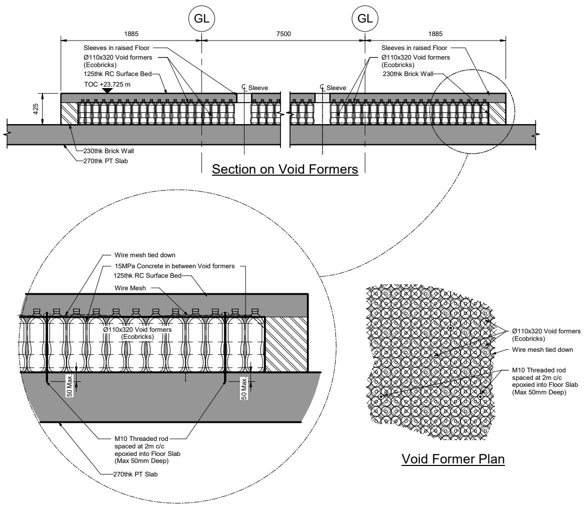
The top floor is acoustically and thermally separated from the atrium in order to prevent warm air from spilling into it, both as part of the fire-fighting strategy and to increase the effectiveness of natural ventilation at the lower levels.

Natural ventilation

The arrangement of levels around the atrium and the facade design allows the building's temperature to be controlled using only natural ventilation for 81% of the year, while for the remaining period, when weather conditions are not favourable for natural ventilation, air conditioning is required to regulate the temperature.

Manually operated windows on the exterior façade involve workers in the control of the building's temperature and let them find their own comfort zone; a green/red light system, controlled by the building management system (BMS), advises workers (for whom guidance has been drafted to influence their behaviour to associate comfort and efficient building performance) on the optimal window position based on the outside temperature and wind conditions. When the weather outside is not suitable for natural ventilation and the windows are closed, the BMS activates the mechanical air conditioning system. Users can also activate a perimeter integration system that provides half an hour of additional cooling. When windows are open, the mechanical ventilation system of that zone

Construction site
© Arup



Façade detail
© Arup

is automatically turned off by the BMS.

There are also energy-efficient climate control systems that use natural ventilation along with the building's TABS (thermally activated mass floors) structure, that uses hot chilled water for radiant floor heating/cooling.

The mechanical system is on the roof and air conditioning is provided by three heat pumps, one of which is a simultaneous heat pump, in order to provide both heating and cooling at the same time.

The photovoltaic system is also on the roof and produces 140 kW, corresponding to 30% of the building's peak electricity consumption.

In addition to energy modelling, thermal comfort analysis was also applied. This allowed Arup to demonstrate that the building's mixed-mode of operation with TABS, achieves thermal comfort throughout the year, and reached the highest threshold of ±0.5 of predicted average thermal comfort for more than 90% of the year.

This integrated design approach minimizes energy consumption, while supporting users' comfort.

Construction site
© Arup

Construction site
© Arup

CASE STUDY 04	GREEN CITY
Location	Ben Guerir, Marocco
Latitude	32.2359° N
Longitude	7.9538° W
Type of climate	Tropical
Type of building	Residential
Date of construction	Under construction
Owner	OCP Group
Design team members	Mohammed VI Polytechnic

The complex

Green City is a project aimed at the development of sustainable urban environments through the use of several techniques, technologies and devices based on passive architecture.

The Mohammed VI Polytechnic (UM6P) is the centre of Green City, located in Ben Guerir, Marocco, close to the city of Marrakesh. Compliant with the requirements of sustainable development and those of CO_2 emission control, it pays attention to responsible water management through a dual circuit involving drinking water separated from grey water recovered from washing machines, kitchens and toilets and which can still be used, rainwater storage and wastewater recycling, it uses waste recovery techniques through appropriate channels, as well as renewable and clean energy production such as wind, solar and biomass. Within this project, the construction of a complex of 100 villas for the university's researchers is characterised by four different building types with different surfaces, but sharing the same principles of bioclimatic architecture.

The case study is represented by the ZITOUNE house, which exemplifies the objective of using different passive systems and materials available locally and at very low cost in terms of production

Exterior view
© Mohammed VI Polytechnic

and installation, materials that are ratified from a thermophysical point of view through experimental verifications and reviews of technical literature.

The most evident feature is the creation of a space under the slab on the ground floor for the placement of a 500 m^3 bed of pebbles, 1 metre deep, connected to an air tower that emerges from the house and at the top of which is positioned a solar air collector to pre-heat it during the cold season and circulate it among the pebbles that will accumulate and then release, thanks to their inertia, inside the building. Similarly, this large chimney will serve to cool the air and provide fresh air during the hot night periods.

Natural ventilation

It is obvious here that some solutions from the Islamic building tradition of the Mediterranean countries, where the need to defend themselves from extreme temperatures and to make use of local resources, led to the use of the subsoil or natural cavities to exploit the thermal inertia of the ground and to the creation of 'wind towers' to trigger or enhance convective air motions for natural ventilation and cooling.

Construction site
© Mohammed VI Polytechnic

Construction site
© Mohammed VI Polytechnic

The creation of natural summer ventilation by means of a wind capture system that would appear to reduce the annual cooling load by 17%.

Building materials

The ZITOUNE house was built with blocks of local limestone rocks, called BOUSKOURA rocks, which contribute to the inertia of the envelope; processed on site and reduced to 40 cm thick blocks, they are an excellent example of a low-cost effective material that employs local labour, recovering traditional knowledge in a positive sustainable circular economy.

A 10-cm thick mixture of hemp and gypsum then protects the outer façades, forming the insulation, which is in turn protected by a 10-cm layer of porphyritic rock that prevents atmospheric agents from damaging the hemp.

Energy concept

The building's roof is composed of hollow core slabs, enclosing a 20 cm air space with a radiant barrier (an aluminium sheet on the upper side and a poluyan film on the lower), further painted with white mortar to reflect excessive solar radiation. To complete this synergy of passive techniques, sun-screens have been installed on the southern sides of the house, which are most affected by solar radiation, and some windows have been automated with differential circuits to ensure automatic night-time operation in summer and the relative heat exchange.

The choice of these natural limestone materials and hemp insulation would seem to guarantee reductions of 20-30% in annual thermal loads, when combined with the pebble bed system, as well as achieving a reduction of around 89% in CO_2 emissions.

Construction site
© Mohammed VI Polytechnic

Wind tower's elevations and section
© Mohammed VI Polytechnic

CASE STUDY 05	DANO SECONDARY SCHOOL
Location	Dano, Burkina Faso
Latitude	11.1464 °N
Longitude	-3.05784 °W
Type of climate	Tropical
Type of building	School
Date of construction	2006-2007
Owner	Dreyer Foundation, Munich
Design team members	Diébédo Francis Kéré, EGC (Entreprise Générale de Construction)

The building

Situated at the edge of o small town in Burkina Faso, the project comprises an L -shaped addition to on existing school complex.

The design incorporates locally available materials and sustainable features that respond to the specific constraints of climate.

Energy concept

This new building closes the southern angle of the compound and is oriented along east-west axis which reduces direct solar radiation onto the walls, which are themselves protected from the sun by o wave-like canopy.

The extension compromises three individual blocks housing classrooms, offices and o computer room. An oval Amphitheatre, open to the exterior, serves as a sitting area during breaks.

The ensemble is covered by a tilted, cantilevering roof structure whose undulating bays create a rhythm against the orthogonal enclosure below.

Exterior view
© Kerè Architecture Archive, ph. Erik-Jan Ouwerkerk

The lower channellings of these waves lead the rainwater away from the building.

Materials

Walls of locally available laterite (laminated with thin layers of cement to form 30 cm thick, load bearing partitions) sit on a granite stone bed.

Regularly spaced, tall window shutters are painted in bright colours that vary with the activity inside.

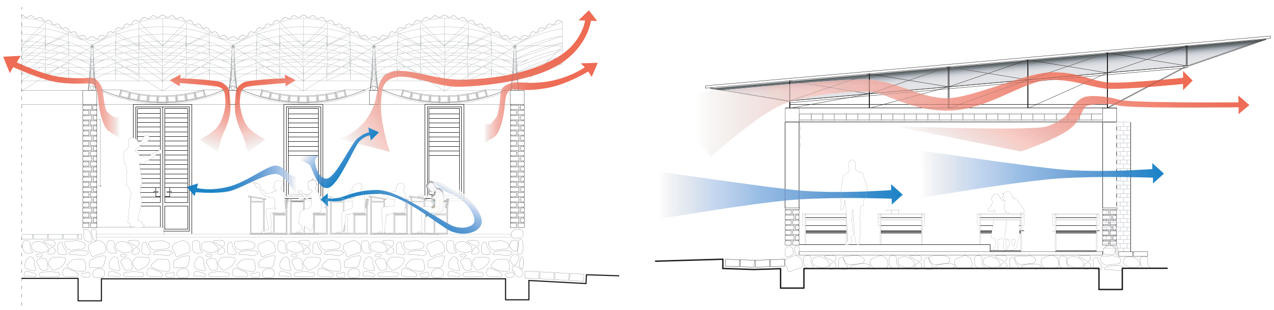
The ceiling consists of 3 m wide, modular elements assembled from 14 mm and 16 mm thick iron bars and welded together on site.

These are crooked and are stored in a longitudinal direction with an inclination created by concrete girders and the ring joist.

Natural ventilation

Slits in the ceiling allow hot air to exhaust through the roof, keeping the building naturally ventilated.

Comprised of cement stones hanging on the construction of thin, flat rolled steel, the bottom side of



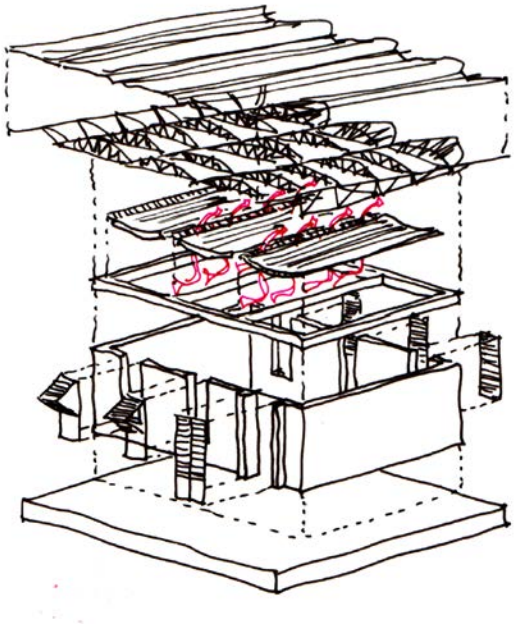
Climate diagrams
© Kerè Architecture

Façade detail
© Kerè Architecture

the ceiling is painted in reflective white to distribute light within the classrooms.

Together with the roof cladding made out of corrugated sheet, the roof's undulation gives the building its extraordinary appearance.

Throughout the construction process, local artisans were trained in new techniques, ensuring that building methods would stay within the community. This collateral process will turn into use either for the maintenance and for further construction sites.



Axonometry sketch
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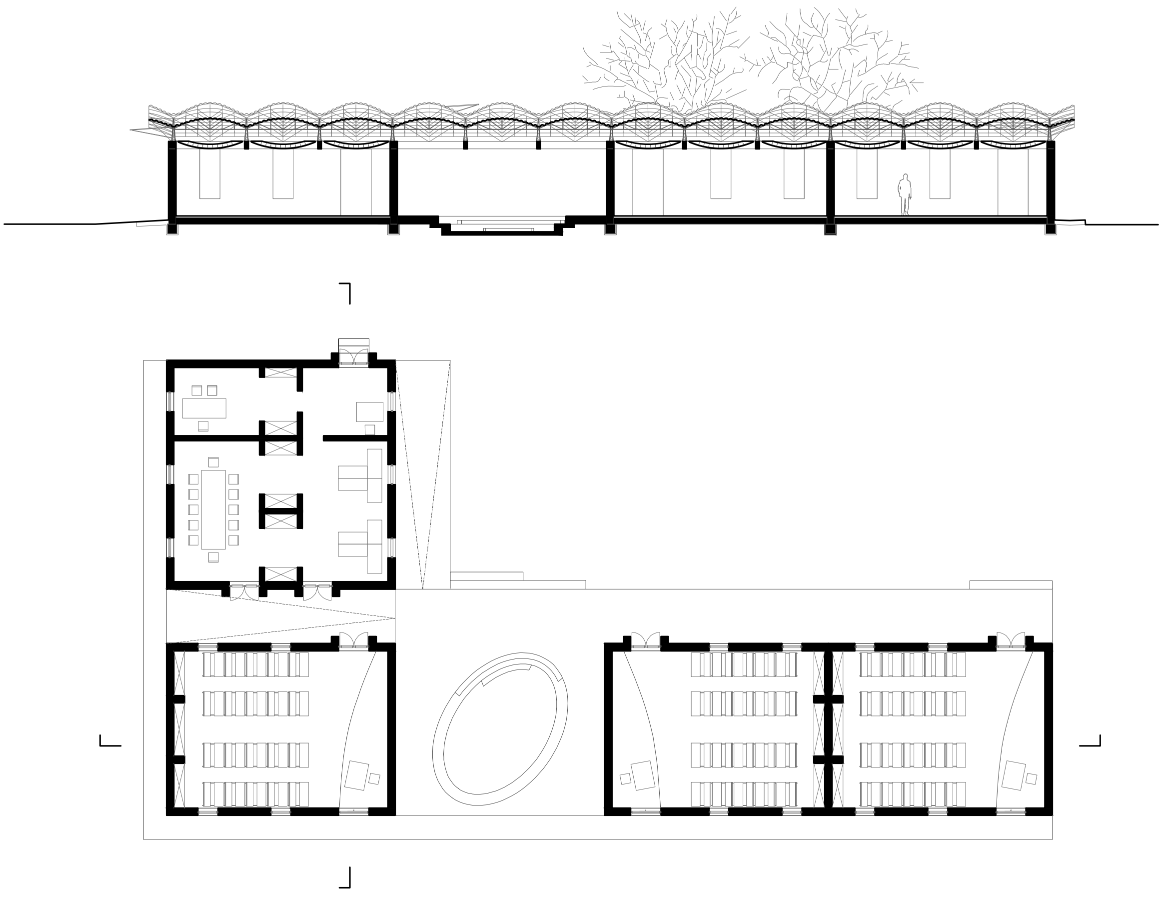


Planimetry and section
© Kerè Architecture

CASE STUDY 06	COCA-COLA EAST & WEST AND AFRICA BUSINESS UNIT HEAD OFFICE
Location	Nairobi, Kenya
Latitude	1.2921° S
Longitude	36.8219° E
Type of climate	Temperate
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

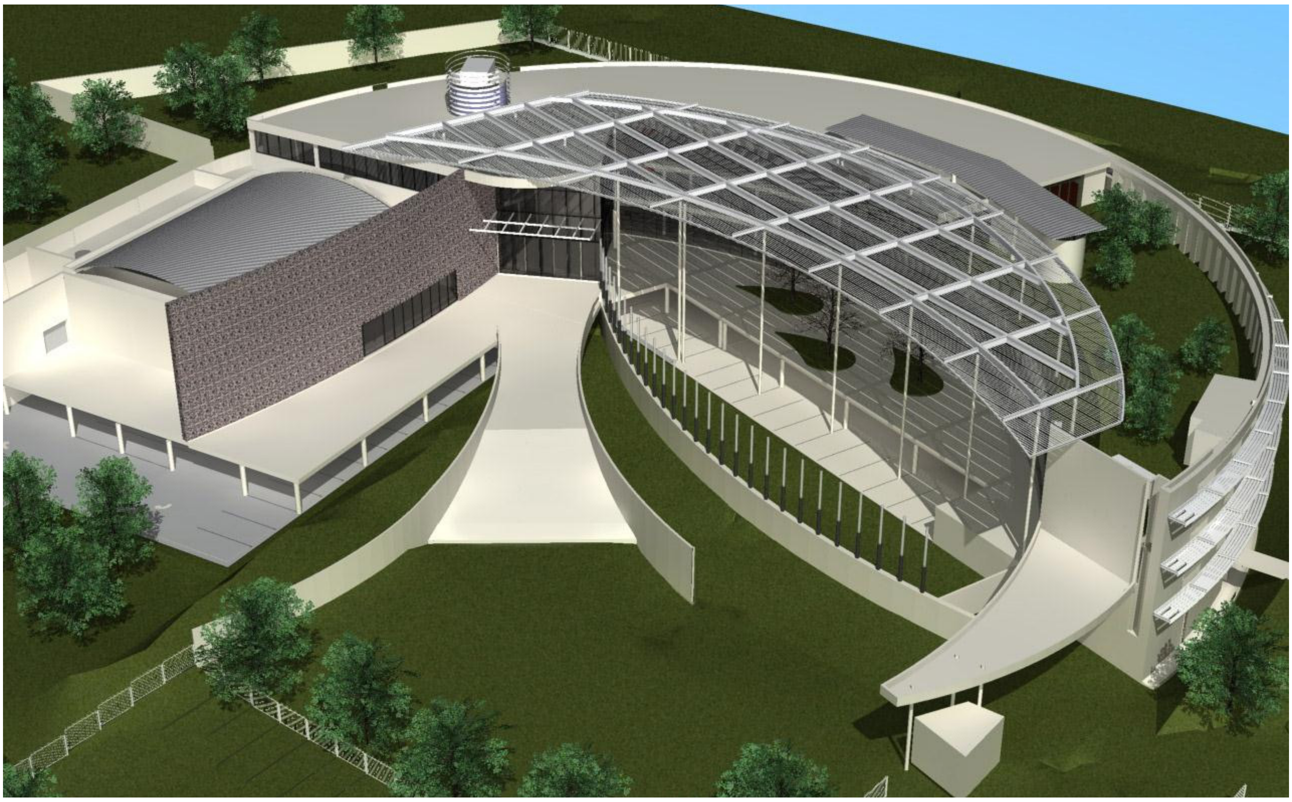
Coca-cola Headquarters Office in Nairobi is the business unit for the company's operations in 30 countries in Central, East and West Africa. It is located in the upper part of Nairobi city, in a site heavily constrained by road reserves and building lines. The floor area is about 12140 m^2 including 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.

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.



Exterior view render
© GAPP Architects

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.

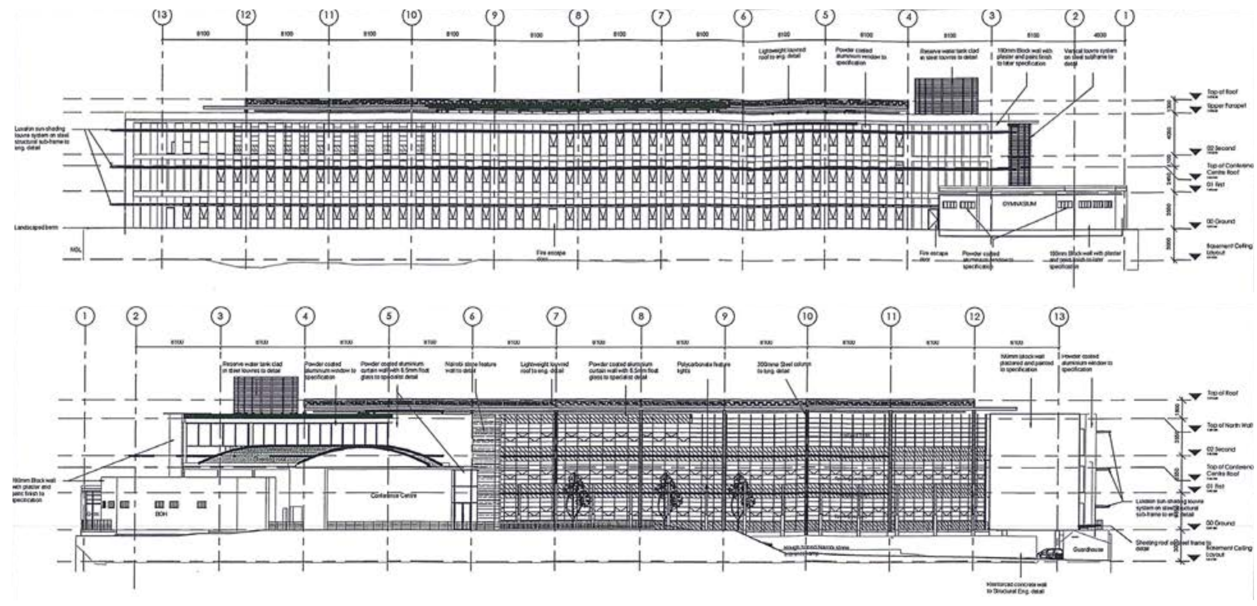
Natural ventilation

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.

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.

North Facade



North and South elevations

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.

Double hollow concrete blocks locally provided are the main materials used in the North facade.

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.

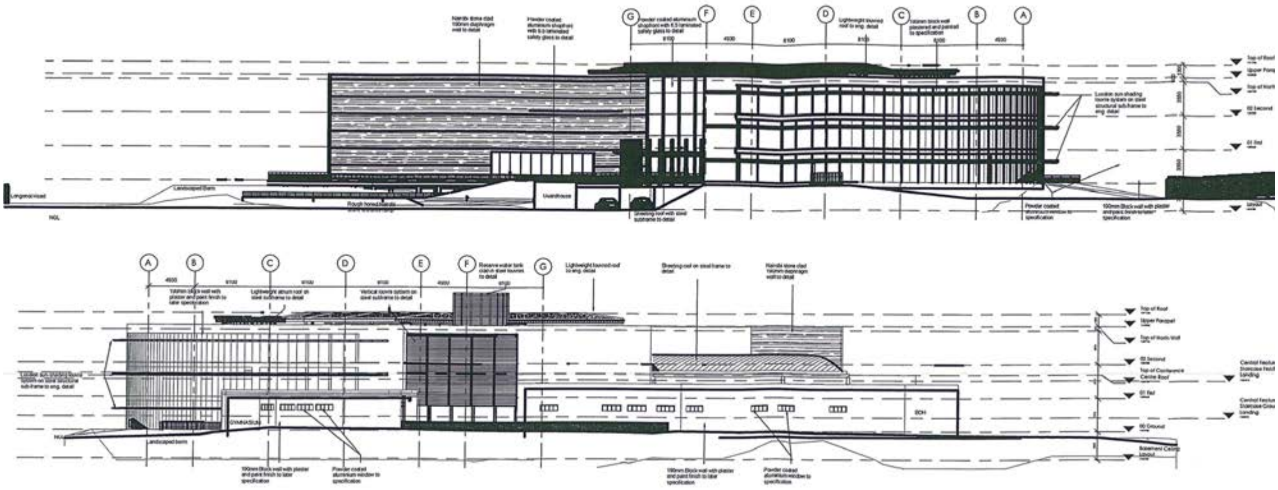
Paper and plastic waste is separated and sent to the local recycling enterprises.

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.

This building is a good example of passive building design adapted to the temperate climate in Nairobi, where the temperature is warm throughout the year but in the cold season can go down to temperatures below 15°C. 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.



East and West elevations
© GAPP Architects

Exterior views
© GAPP Architects

CASE STUDY 07	UMOJA HOUSE
Location	Dar es Salaam, Tanzania
Latitude	6.3690° S
Longitude	34.8888° E
Type of climate	Hot-Humid Climate
Type of building	School
Date of construction	2002
Owner	Foreign & commonwealth Office
Design team members	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.

Project's goals

The main project's goals were to create a secure building, to build to European standards in a country with an extremely aggressive climate and 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.

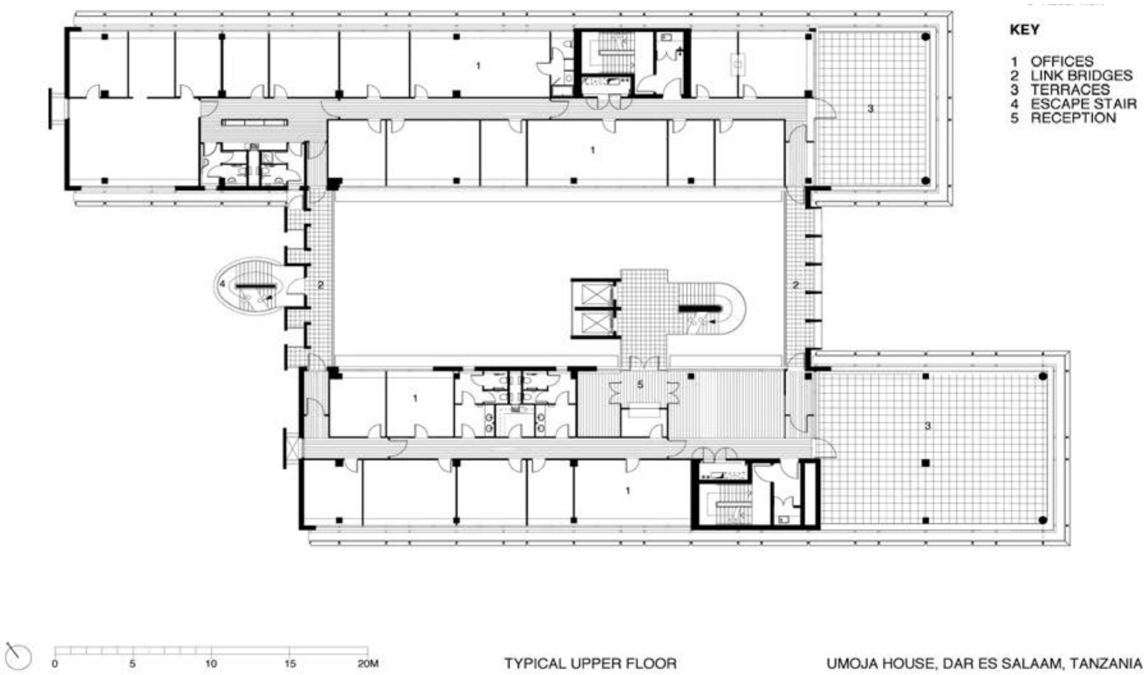
The building is positioned with respect to the movement of the sun. The longer facades have a north-south orientation while the shorter facades face east and west to avoid morning and evening sun.

Exterior view
© Building Design Partnership

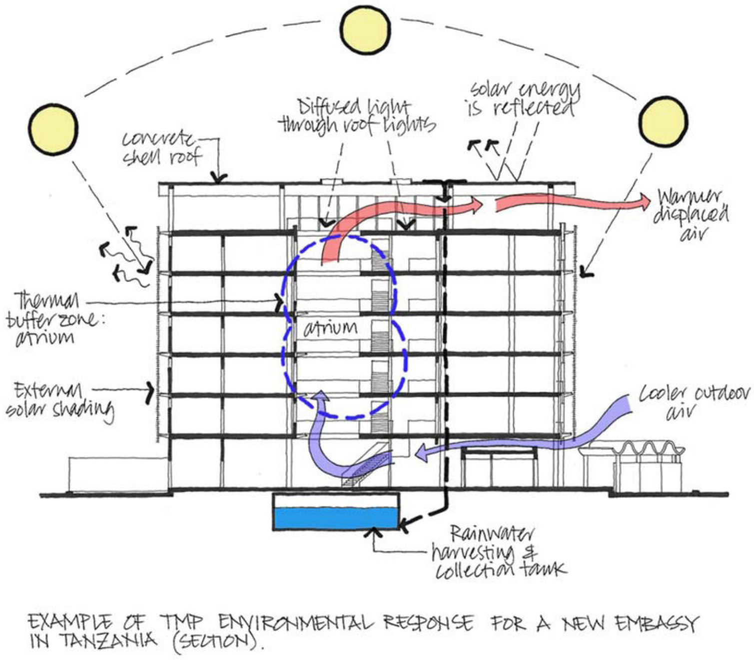
Facade's structure The facades are shaded to protect them from the effects of the sun and the increase of indoor temperatures. The building has two main wings with an open central bay linked with corridors and staircases. An open bay in the middle creates a courtyard that creates the stack effect in the building.

Sun shading 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

The building has a rainwater harvest system that collects water in the basement. This water is used



Typical upper floor planimetry
© Building Design Partnership



Climate design
© Building Design Partnership

Waste management

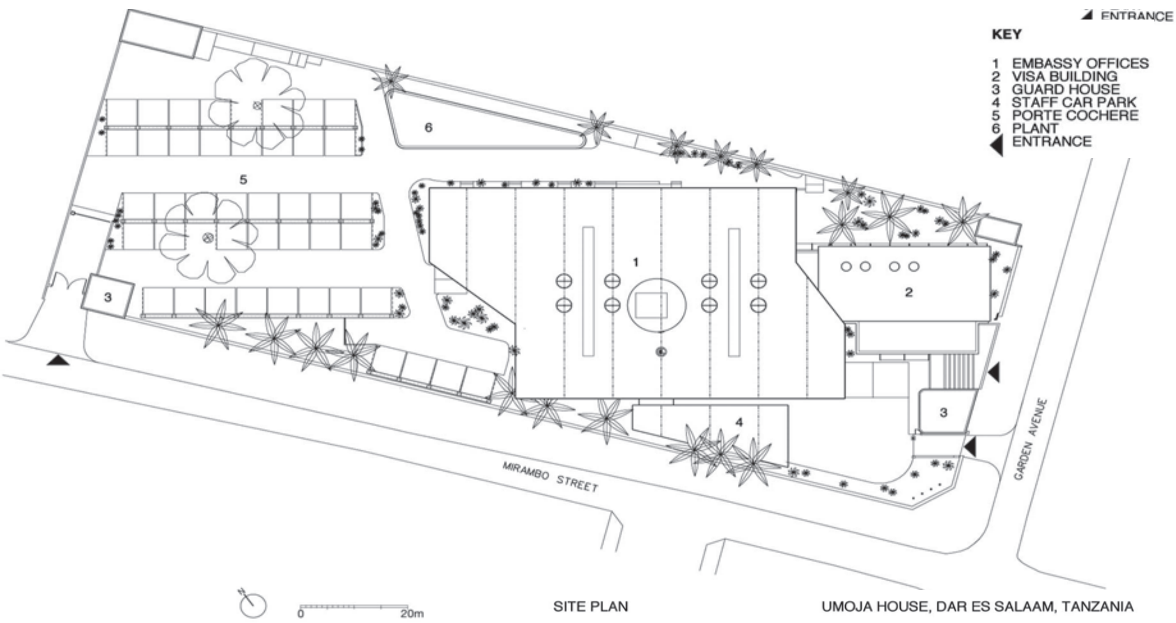
for cleaning the building and irrigation of grass.

This building is a good example of adaptation to the hot humid climate of the city because:

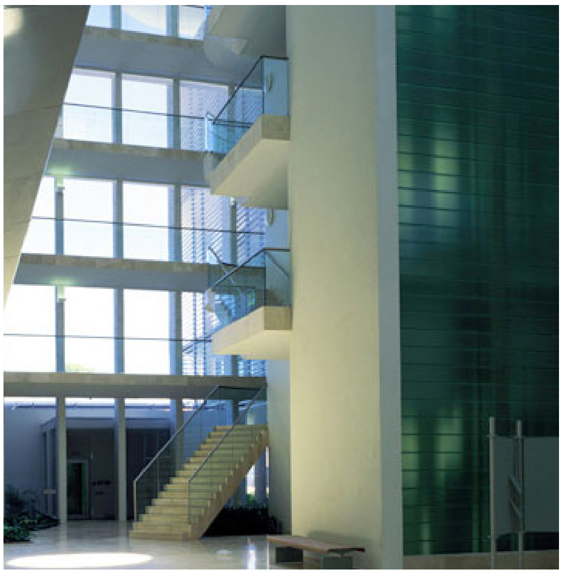
Firstly, the facades are oriented predominantly north south, with the glass windows protected by eaves and steel screens. In this climate solar control devices are crucial in order to avoid excessive thermal gains.

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.



Site planimetry
© Building Design Partnership

Exterior and interior views
© Building Design Partnership

CASE STUDY 08	ENERPOS
Location	Reunion Island, France
Latitude	21.1151° S
Longitude	55.5364° E
Type of climate	Tropical
Type of building	University building
Date of construction	2008
Owner	University of Reunion Island
Design team members	Architect Thierry Faessel-Bohe

The building

ENERPOS (French acronym for POSitive ENERgy), in the La Reunion island (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.

Energy concept

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.

Exterior view
© Jerome Balleydier

Natural ventilation

The building is naturally ventilated with a window to wall ratio (WWR) of 30%.

Interior glass louvers 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.

Solar shading

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).

Natural illumination

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.

Exterior view
© Jerome Balleydier

Interior view - Classroom
© Jerome Balleydier

Interior view - Vegetation
© Jerome Balleydier

It is a positive energy building: that means that through different active and passive systems, the building consumes very low energy and it is able to produce more electricity than it consumes over the year, thanks to PV roof used also for shading.

PV annual production

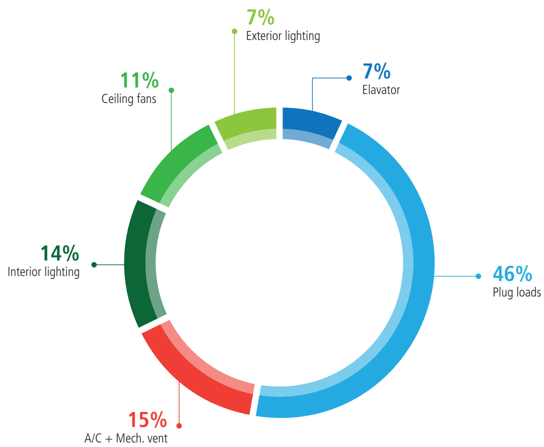
Overall, the first simulation results lead to an energy index below 50 kWh/m².year and a PV supply of 78 kWh/m².year. As an accurate energy monitoring system has been set up, a real scale feedback has been made. In fact, it appears that the building is much more comfortable than it was first indicated by the simulations.

The annual final energy use index, from May 2010 to April 2011 was 14.4 kWh/m².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 only 2 days during the hot season)

The building integrated photovoltaic roof covers an area of 350 m² 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/m². The building thus produces about seven times more electricity than its own consumption. The performance of both the building and the PV systems resulted far better than evaluated in the design phase.

Exterior view
© Jerome Balleydier



The distribution of energy consumption

Exterior view
© Jerome Balleydier

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 claim to design and build sustainable buildings. Unfortunately, in most cases it is only statements that do not correspond to reality. The reasons for the gap between the intentions and the facts are numerous, but the main one is in the lack of knowledge among architects about physics.

In fact, sustainable architecture is based on the ability to let the human product, the building, communicate with the natural environment. To establish a dialogue is necessary to have a language in common. Well, the language that man has developed to communicate with the natural environment is physics, of which the other sciences, chemistry, biology, ecology, are daughters.

There's more. If we consume energy and exert an impact on the environment, constructing and operating our buildings, it is because we want to create and maintain the conditions for thermal, visual and acoustic comfort. But comfort is a physiological phenomenon (as well as psychological) and physiology also use the language of physics.

Finally, our buildings are now filled with more or less energy-consuming equipment, which provide a high quality of life and that contribute to increase the environmental impact of the building. And technologies work on the basis of the principles of physics.

Therefore, an architect cannot design sustainable buildings if he does not know at least the essential rudiments of physics, especially thermodynamics, and of the physiology of comfort. Thanks to the knowledge of these basics 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, 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 are continuously variable over time, therefore the building is a dynamic system, and 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 change continuously its thermodynamic parameters, those that affect comfort and energy demand.

Observing a building through this perspective, changes the way the architect has to look at the design process. The architect is used to draw a component or system and see it realized. The hypothetical and actual functions are the same: the components perform in the same way the designer has decided they should perform: the drawing of a wall becomes a real wall, so a window, 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 to decide what will be the heat flow, in relation to the location, orientation, time and the material used. A common case unfortunately is that of natural ventilation: beautiful drawings with red and blue coloured elegant harrows 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 - physics in many cases decides that things do not go the way as planned. As the architect has learned the gravity law, designing structures capable to resist to every possible mechanical stress, he should - if he wants to take into account the constraints of environmental sustainability – learn also the laws of thermodynamics[1].

The two most well 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

1 *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.*

form to another). The second one is more sophisticated, and for this less understood, and deals with the quality of energy. The same amount of energy can have higher or lower value. To understand this concept, the hydraulic analogy is helpful. If there are not losses along the way, including evaporation, also for water flows the principle of conservation is valid: as much I take from a higher reservoir, for example, the same amount I find at the end of piping, in a lower reservoir, at sea level. But the same amount of water does not have the same quality: some is more worthy and other less worthy, depending on its altitude above sea level. Either with the water of a mountain reservoir and that of a lake in the plain one can wash, drink, etc., but there is something that can be produced with the water at high level but not with that at sea level: mechanical or electrical energy. This is due to the fact that the water of a mountain reservoir has an additional gift: high potential energy that the water at sea level has not. So, the water could and should be also measured in terms of quantity and quality. One million cubic meters in a plain is much less worth than a few thousand cubic meters in altitude. It is the same for the heat: at high temperature it is much more worthy than at low temperature, because in the first case it can produce, with appropriate technologies, mechanical energy, or electrical (which is the most valuable), while in the second it can produce little or nothing. What for water is the potential energy, for heat is what in thermodynamics is called exergy, i.e. the potential of converting heat into mechanical energy through an engine.

What applies to the water, i.e. that moving it from the mountain to the sea level loses forever its gravity energy, 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 deriving 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 is gone forever.

In a building, the required heat - what has to be to supplied or to subtracted - is at low temperature and is therefore of little thermodynamic value (although high for us because it allows us a more comfortable life).

In a building considered as thermodynamic system, the high quality energy that comes into play are the solar and the electrical ones; for space heating and cooling and hot water production low quality of energy is used.

The problem is that we need this energy, even if low quality, and it is not easily available; indeed in most cases to have it, high-quality energy is used, wasting its value. In addition, as far as the air-conditioning is concerned, the second law of thermodynamics provides another constraint: as the water cannot move spontaneously from a lower level to a higher, but it requires a technological system, the pump, similarly heat cannot pass spontaneously from a colder body to a warmer and, to obtain this result with continuity, we have necessarily to use a technological system and high quality energy. Heating, thus, is easy - accordingly with natural spontaneous processes – cooling is not. It is not surprising that heating has been used for millennia and cooling 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 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 that 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 is 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 to other end: the atoms of the warmer part of the body transmit their greater thermal agitation to those adjacent, and the body progressively increases its temperature (Fig. A.1-1).

This type of heat transfer is called conduction.

The higher or lesser availability 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.

The 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 initially colder increases.

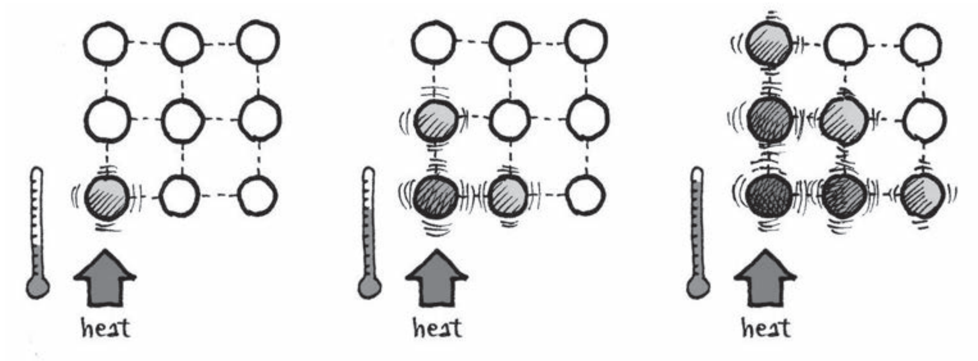


Fig. A.1-1 – Heat transfer by conduction

Materials have different capacity to store heat; they are like sponges with different ability 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, depending on 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 up to a certain temperature the incoming heat flow becomes equal to the outgoing one. When this occurs it is said that steady state has been reached.

The heat required for heating up the body remains stored in it, and it is partially or fully returned when there is a reduction or a stop of 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:

$$\alpha = \lambda/\rho c \qquad \text{(A.1-1)}$$

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. In a substance with high thermal diffusivity, heat moves rapidly through it 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:

$$q_a = c \cdot \rho \cdot V(t_2 - t_1) \qquad \text{(A.1-2)}$$

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:

$$Q_c = \frac{(t_{s1} - t_{s2})}{R_s} S = \frac{\lambda}{s}(t_{s1} - t_{s2})S \qquad \text{(A.1-3)}$$

where:

Q_c = thermal flux [W];

t_{s1} and t_{s2} are the temperatures of the faces 1 and 2 respectively [K, °C];

R_s = s/λ is the thermal resistance of the material constituting the wall [m^{2}K/W];

S = area of the plate or wall [m^2];

λ = 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:

$$Q_c = \frac{(t_{s1} - t_{s2})}{R_1 + R_2 + R_3 + \cdots R_n} S = \frac{(t_{s1} - t_{s2})}{\frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \frac{s_3}{\lambda_3} + \dots \frac{s_n}{\lambda_n}} S \qquad \text{(A.1-4)}$$

If instead, as in real case, the heat flow across the wall is

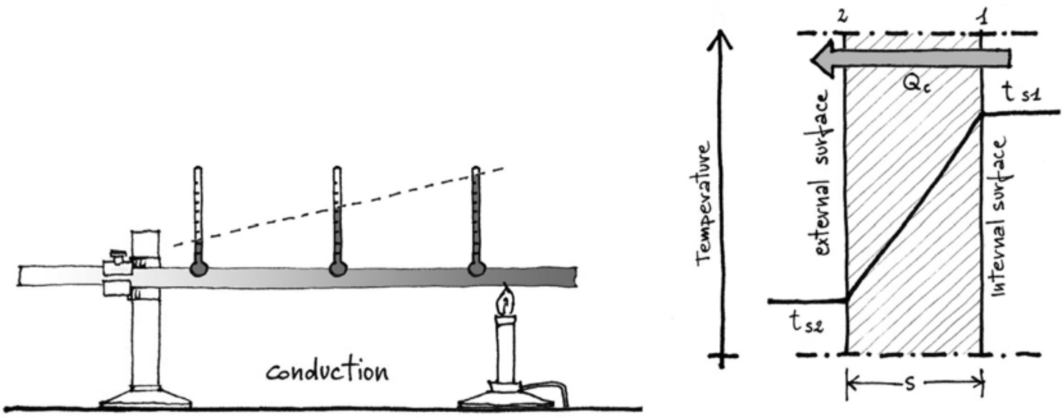


Fig. A.1-2 – Steady state conduction – Single-layer slab

not constant, because the outside air temperature changes with a cyclical pattern in the course of the day, also the heat capacity comes into play, and the heat flow through a wall varies in 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:

$$\varphi=0.023\cdot s\sqrt{1}\alpha \qquad \text{(A.1-5)}$$

$$\psi=exp(-0.003\cdot s\sqrt{1}\alpha) \qquad \text{(A.1-6)}$$

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.

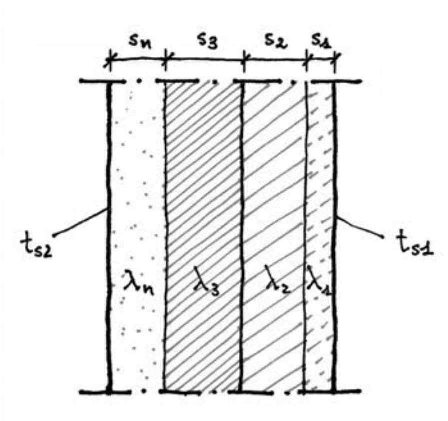


Fig. A.1-3 – Steady state conduction; multi-layer slab

2.1 Convection

With a fluid, the only change is that are its molecules to move, instead of its atoms, in a completely random way and without a binding position, and the heat transfer takes place through the collisions among them. The temperature of a fluid is a measure of the average velocity of the molecules composing it.

The specific heat of the fluids varies much more than the solids. For example, with the amount of heat necessary to raise by 1 °C one litre of water, we can raise by 1 °C 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, the one 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

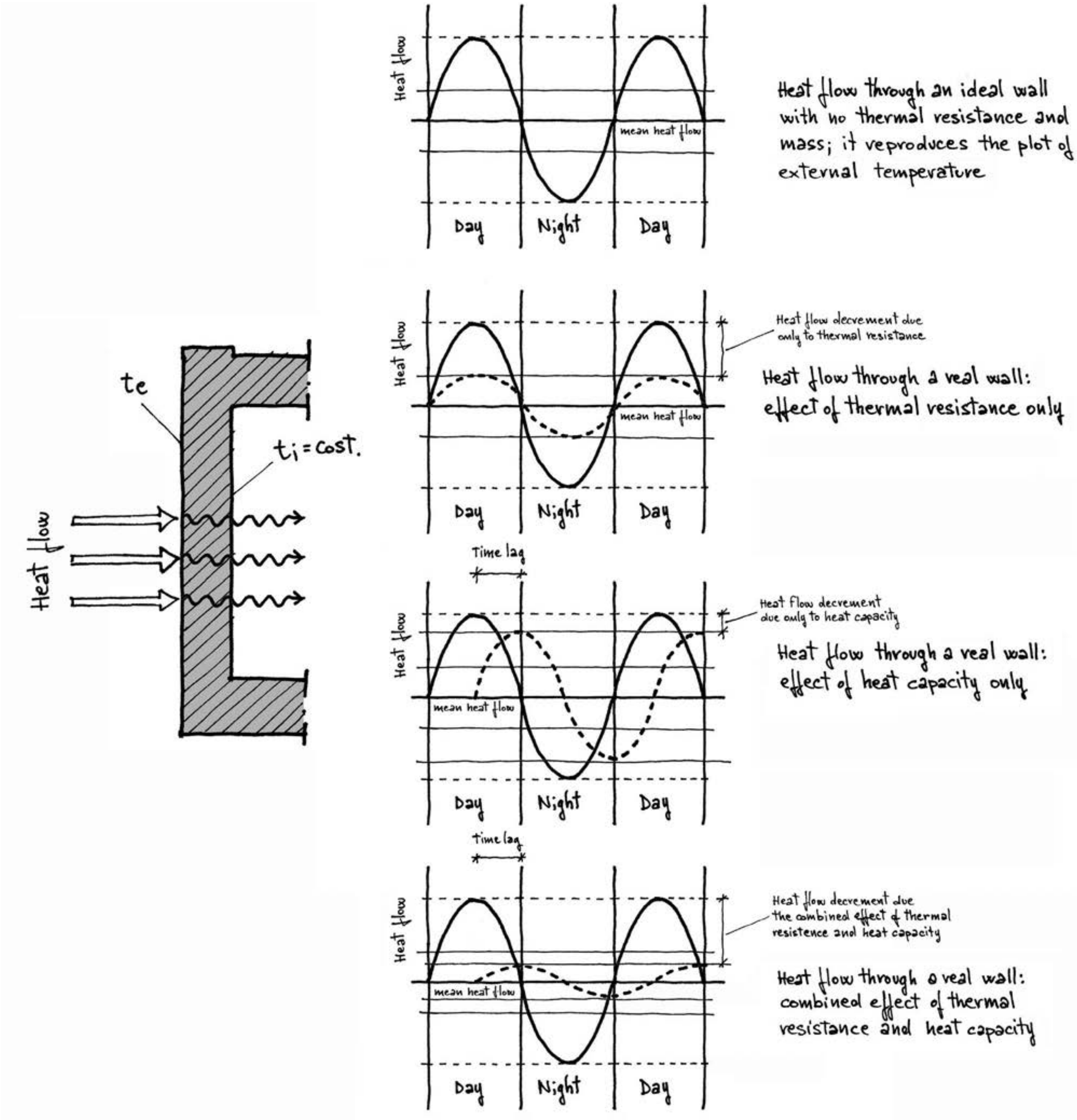


Fig. A.1-4 –Thermal resistance reduces the peak heat flow; the heat capacity reduces and also delays it

solid body, the part in contact looses heat, and cools down; its density decreases compared to that of the rest of the fluid, and tends to "sink" that is, to move downwards (Fig. A.1-6). This phenomenon is called natural convection; it involves - in contrast to the conduction - mass movement and it is the way heat is transferred between a solid and a fluid.

The convection can also be forced. This occurs when a fluid is already moving when touching a solid; if the fluid is air, it is the case where there is wind or when it is moved by a fan. With forced convection more heat is transferred 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[2]:

$$Q_r = h_c \cdot S \cdot (t_s - t_f) \qquad \text{(A.1-7)}$$

where:

2 h_c as a function of the wind speed v can be estimated by means of the following empirical formulas:

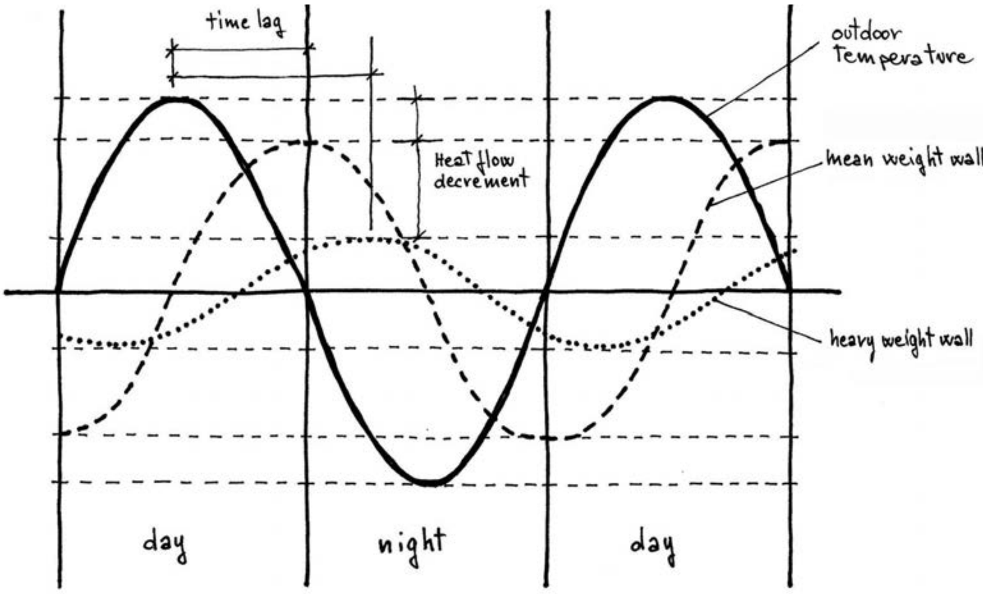


Fig. A.1-5 – Heat flow through the walls of different thermal inertia (very light wall, low inertia; heavy wall, high inertia)

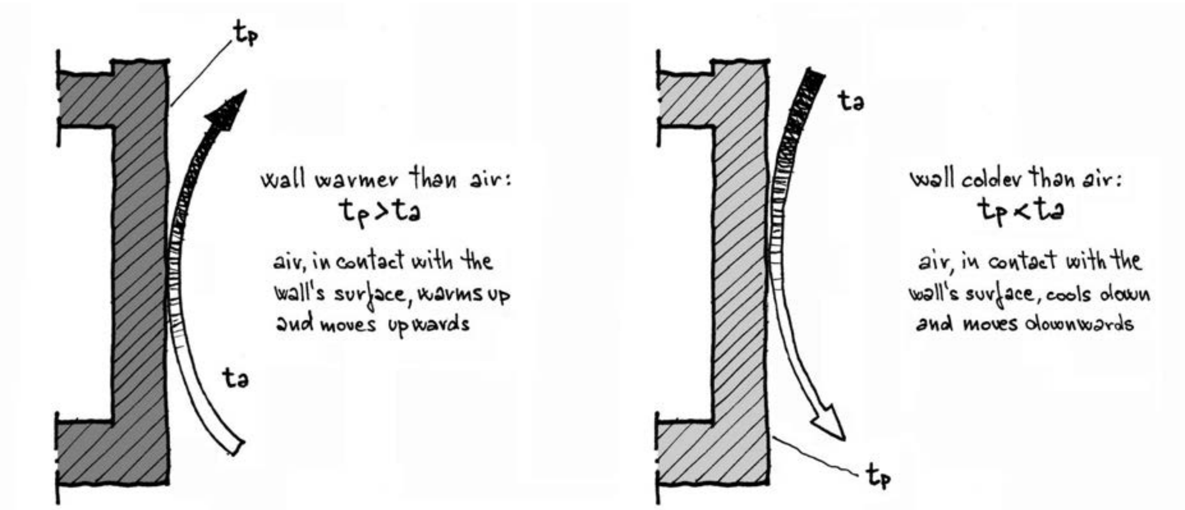


Fig. A.1-6 – Heat transfer wall-air by natural convection

Q_c = heat flux transferred by convection [W];

h_c = convection heat transfer coefficient [W/m²K].

2.2 Radiant heat

We are immersed in electromagnetic radiations, spanning from gamma rays to radio waves (Fig. A.1-7). The range of radiations' wavelength interesting the energy performances 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 function of the wavelength, travelling in the space.

When a photon associated with an electromagnetic radiation hits an atom, the latter changes its state because of the energy transferred. This energy manifests itself in terms of 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 absorb fully the electromagnetic radiation that hits it takes the name of black body. Increasing of the temperature of a body, 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:

$$Q_r=\varepsilon\cdot\sigma\cdot S\cdot T^4 \quad \text{(A.1-8)}$$

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 = 5.7×10^{-8} [$W/m^2 K^4$];

S = area of emitting surface [m^2];

T = absolute temperature of emitting surface [K].

A body not only emits, but also receives it, being surrounded by other bodies that in turn emit. What matters in the end, then, is the net balance of energy, i.e. the difference between the radiant heat emitted and the received one. This balance depends not only on temperatures 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 by the side; this derives by the apparent surface of the fireplace: smaller if we are away or by side. The greater is the apparent surface the greater is the amount of radiant energy we receive. For this reason a fireplace warms us up more if we are close and in front of it.

To take into account this phenomenon, quantifying

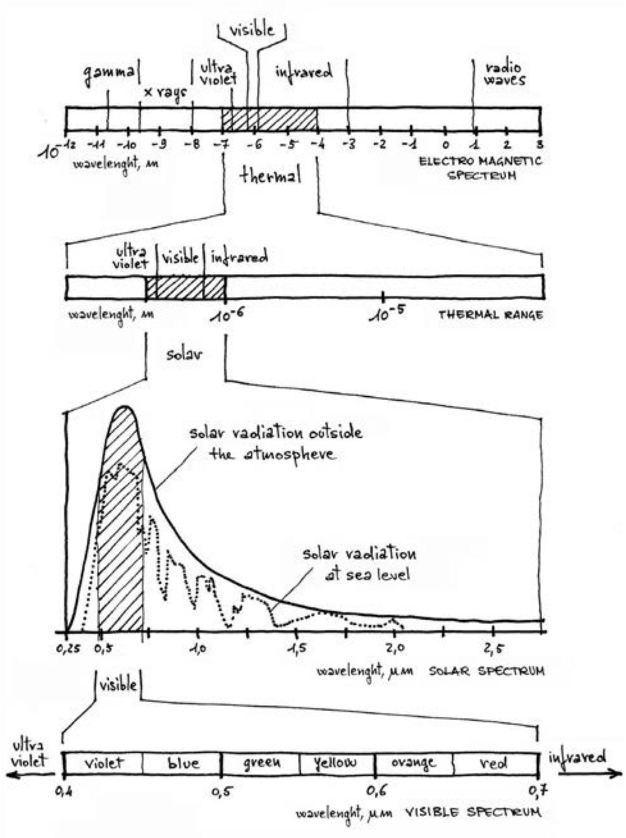


Fig. A.1-7 – Electromagnetic waves spectrum

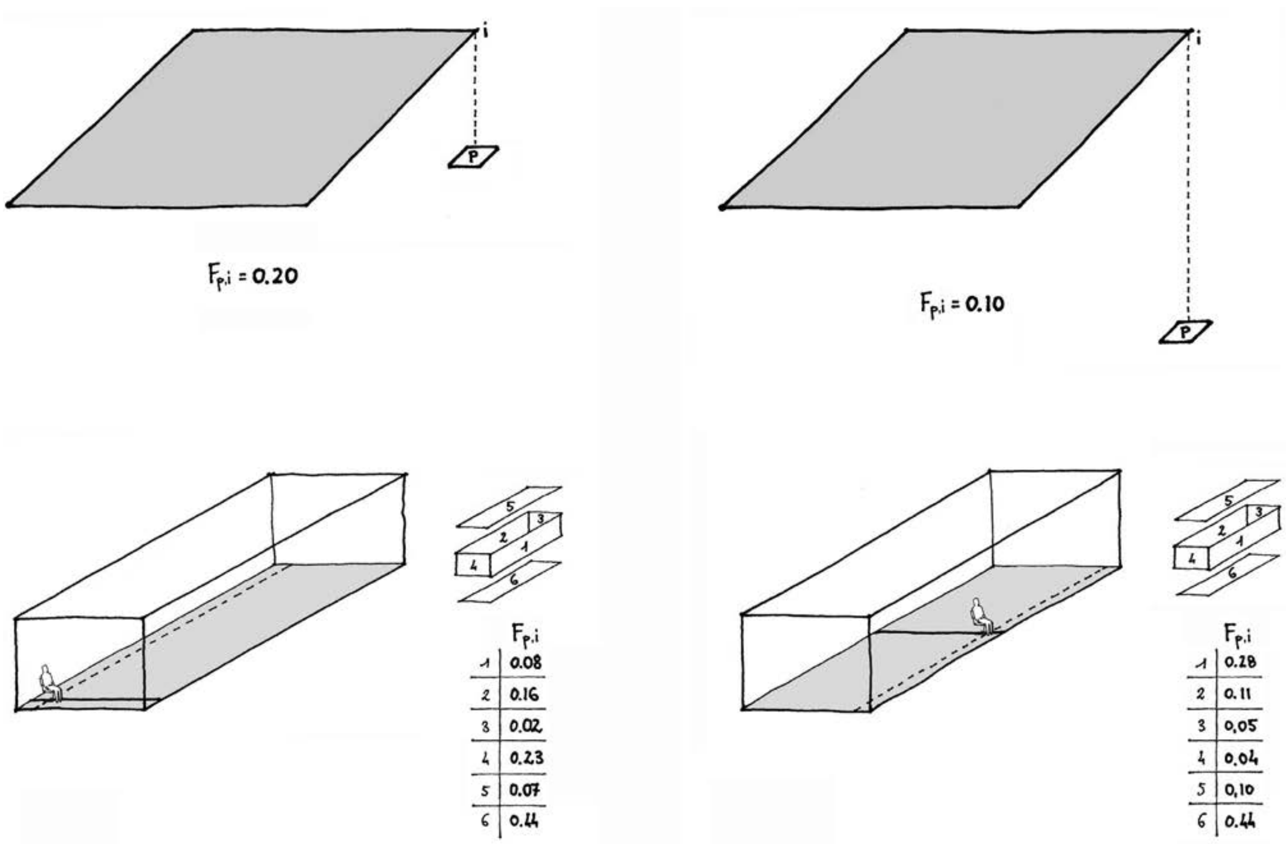


Fig. A.1-8 – Examples of view factor changing with the position of a surface P (top) and of a person with respect to the surfaces of an enclosure it, the view factor $F_{p,i}$ (called also form or shape factor) is used, indicating the proportion of the radiation which leaves surface A that strikes surface B (Fig. A.1-8).

There are four ways in which the electromagnetic radiation interacts with matter; they are (Fig. A.1-9): the transmission, reflection, absorption and emission.

The transmission takes place when the radiation passes through the material; the reflection when it is reflected by the surface; absorption when the radiation is absorbed and converted into sensible heat; emission when the material emits radiation from its surface.

It always holds the relationship:

$$\tau+\rho+\alpha=1 \quad \text{(A.1-9)}$$

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:

$$\varepsilon=\alpha \quad \text{(A.1-10)}$$

Each material, also in relation to the wavelength of the incident radiation (Fig. A.1-10), shows specific characteristics of transmission, reflection and absorption (Fig. A.1-11). 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 that make possible the so-called greenhouse effect, thanks to which the glass lets through the solar radiation but absorbs the long wave radiation coming from the objects. 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 termed as emittance, reflectance and absorptance) at different wavelength for most common materials used in buildings.

2.2.1 Longwave emission towards the sky

Also the atmosphere emits longwave radiation, and the net radiative energy balance Q_{rs} for a horizontal surface seeing the sky is given by:

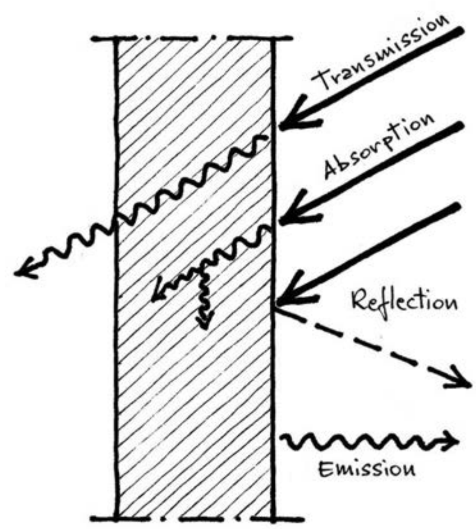


Fig. A.1-9 – Four types of interaction that can occur between radiant energy and matter

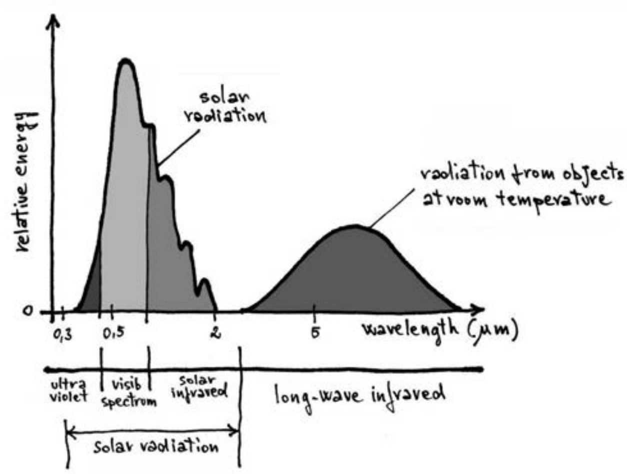


Fig. A.1-10 – Solar radiation spectrum and emission spectrum of radiant energy in the far infrared of objects at room temperature

$$Q_{rs}= Q_r-Q_{sky}=\sigma\varepsilon(T_s^{\,4}-T_{sky}^{\,4})S \quad \text{(A.1-11)}$$

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[3]:

3 R.J. Goldstein, Application of aerial infrared thermography to the measurement of building heat loss, ASHRAE Trans. N. 2482, 1978

$$T_{sky}=0.0553T_a^{1.5} \quad \text{(A.1-12)}$$

where T_a is the air temperature in K and the sky is supposed to have $\varepsilon=1$.

For cloudy sky, the following expression can be used:

$$T_{sky} = 0.0553\, T_a^{1.5} + 2.625\, cc \quad \text{(A.1-13)}$$

where cc is the cloud cover expressed in Octas[4].

If the surface is not horizontal, Q_{rs} is given by:

$$Q_{rs} = \sigma\varepsilon\left[F_s\left(T_s^4 - T_{sky}^4\right) + F_g\left(T_s^4 - T_g^4\right)\right]S \quad \text{(A.1-13a)}$$

where:

Q_{rs} = radiant flux emitted by the surface [W];

T_g = absolute temperature of ground [K];

4 Its an estimate of how much of the sky is covered by cloud. A clear sky is 0 Oktas, A summers 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.

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:

$$F_s = \frac{1 + \cos(\psi)}{2} \quad \text{(A.1-14)}$$

and F_g is the shape factor between the surface and the ground, given by

$$F_g = 1 - F_s \quad \text{(A.1-15)}$$

2.2.2 Radiant energy exchanges for building applications

The calculation of the radiant energy exchanges is rather complex, however for buildings 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:

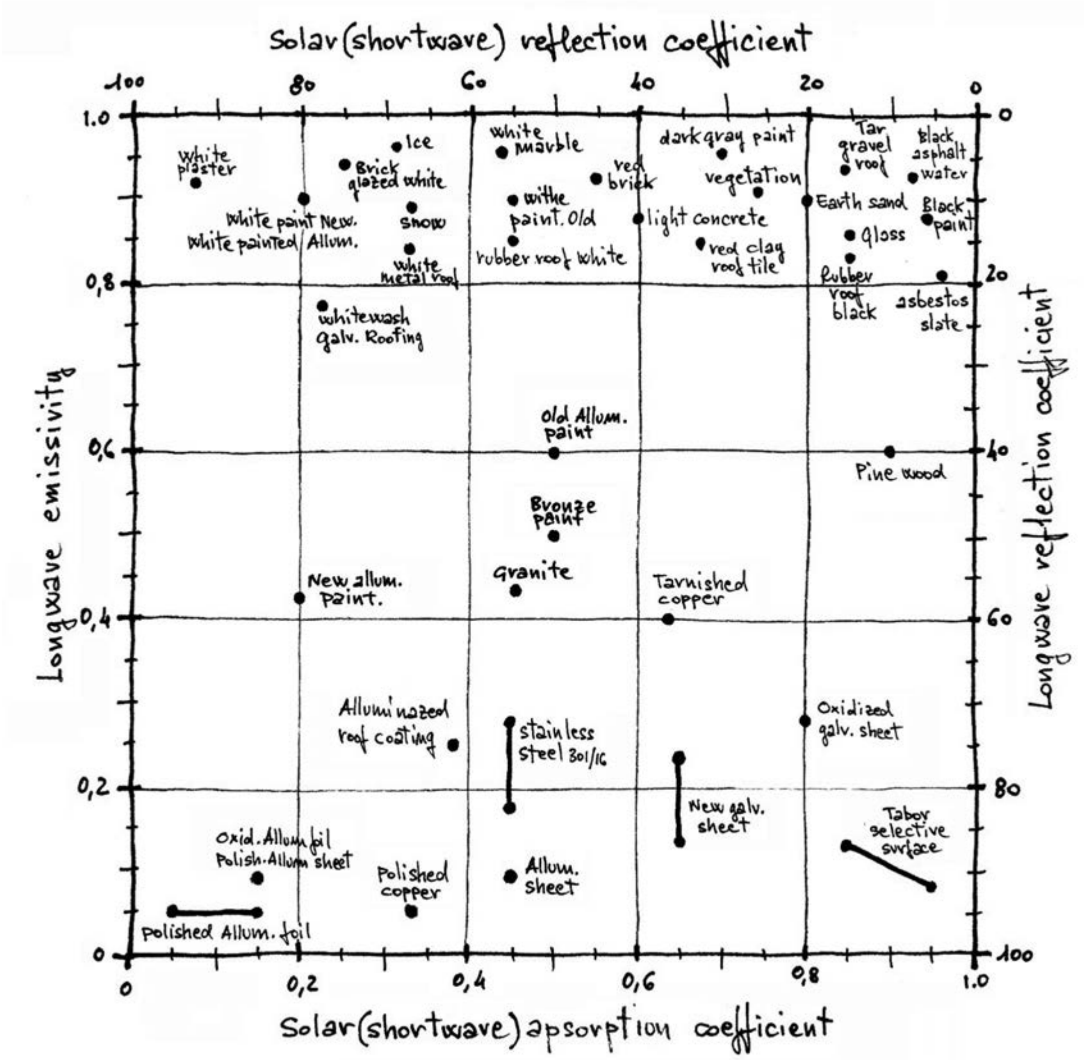


Fig. A.1-11 - Absorption coefficient and emissivity of different materials for solar radiation and far-infrared radiation

$$Q_r = h_r \cdot S \cdot (t_s - t_a) \quad \text{(A.1-16)}$$

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].

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:

$$Q_s = h \cdot S \cdot (t_s - t_a) \quad \text{(A.1-17)}$$

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[5]:

$$Q = \frac{t_o - t_i}{R_s + R_{hi} + R_{ho}} S = \frac{t_o - t_i}{R_t} S = U(t_o - t_i)S \quad \text{(A.1-19)}$$

where:

t_o = outdoor temperature [°C];

t_i = indoor temperature [°C];

R_s = s/λ = 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 is the thermal performance.

In case of a multi-layered slab, eqn. (A.1-5) becomes:

$$Q = \frac{t_o - t_i}{R_{hi} + R_{l1} + R_{l2} + \cdots R_{ln} + R_{ho}} S = \frac{t_o - t_i}{R_t} S = U(t_o - t_i)S \quad \text{(A.1-20)}$$

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:

$$U = \frac{1}{\frac{1}{h_i} + \frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \cdots \frac{s_n}{\lambda_n} + \frac{1}{C} + \frac{1}{h_o}} \quad \text{(A.1-21)}$$

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:

$$Q_{(t)} = Q_m + \Psi \times U \times S \times (t_{o(\tau-\phi)} - t_{o(m)}) \quad \text{(A.1-22)}$$

where:

$Q_{(t)}$ = instantaneous heat flow [W];

Q_m = U x S ($t_{o(m)} - t_{i(m)}$) is the mean heat flow of the day considered [W];

Ψ = decrement factor;

$t_{o(\tau-\phi)}$ = external air temperature at time τ – ϕ [°C];

ϕ = time-lag;

$t_{o(m)}$ = mean external air temperature [°C];

5 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.

$t_{i(m)}$ = 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 by 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 it was obtained with solar radiation acting in conjunction with the actual external air temperature is termed the sol-air temperature (Fig. A.1-12). Hence:

$$Q_{sa} = Q + \alpha I_s \quad \text{(A.1-23)}$$

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[6]:

$$h(t_{sa} - t_p) = h(t_o - t_p) + \alpha I_s \quad \text{(A.1-24)}$$

$$t_{sa} = t_o + \alpha I_s/h \quad \text{(A.1-25)}$$

To calculate the instantaneous heat flow through a slab subject to solar radiation eqn. A.1-22 becomes:

$$Q_{(\tau)} = Q_{msa} + \Psi \times U \times S \times (t_{sa(\tau-\phi)} - t_{sa(m)}) \quad \text{(A.1-26)}$$

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].

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 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 wavelength of the solar spectrum, not only the ones contained in the visible spectrum (Fig. A.1-15).

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 re-radiate long waves, the so called thermal radiation, which, being of a wavelength greater than 2.5

6 *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.*

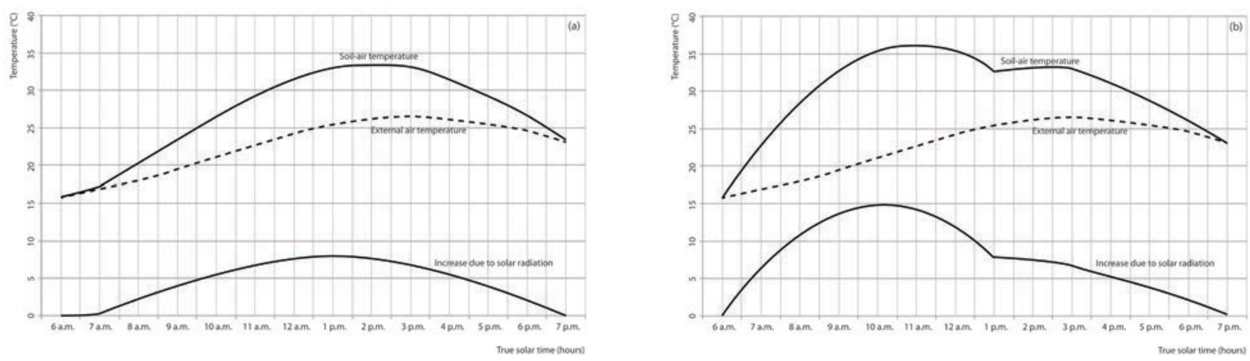


Fig. A.1-12 – Sol-air temperatures for Nairobi during the hottest month (March). R_so=0.05 m²K/W and α=0.6; (a) south-facing wall; (b) east-facing wall

microns are retained in the indoor environment, blocked by the glass, and generating a temperature increase.

The feature of transforming solar energy into thermal energy is an ambivalent factor; if, on the one hand, it allows to heat the room with solar energy in cold climates, on the other hand causes an energy gain that must be removed to avoid overheating in hot climate and seasons.

2.2.6.1 Energy balance of windows

The energy balance of a glass pane is given by (Fig. A.1-16):

$$Q_{gl} = (A + B + C) \times S_g \quad \text{(A.1-27)}$$

where:

Q_{gl} = total energy flux through the glass [W];

A = solar radiation flux per square meter, transmitted through the glass [W/m^2];

B = fraction of incident solar energy flux absorbed by the glass and transferred inside [W/m^2];

C = thermal flux per square meter due to the difference in temperature between inside and outside[W/m^2];

S_g = glass pane area [m^2].

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 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[7], 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];

7 For a 3 mm clear glass, N_i can be considered constant and equal to 0.26.

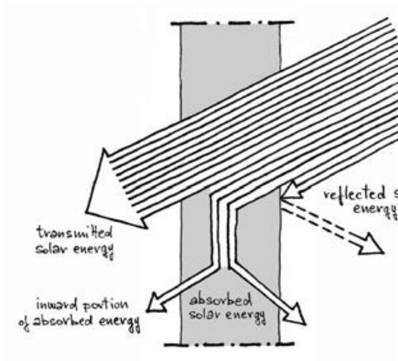


Fig. A.1-13 – Solar energy balance of a single glass

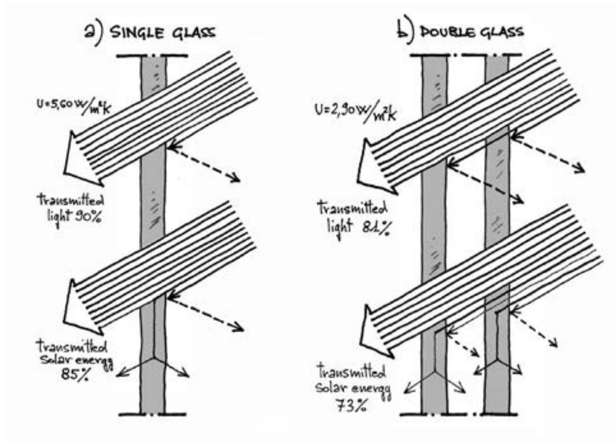


Fig. A.1-14 – Energy and light transmitted in a single and double glass

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:

$$Q_{gl} = [SHG + U_{gl}\,(t_o - t_i)] \times S_g = [SHGC \times I_t + U_{gl}\,(t_o - t_i)] \times S_g \quad \text{(A.1-29)}$$

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

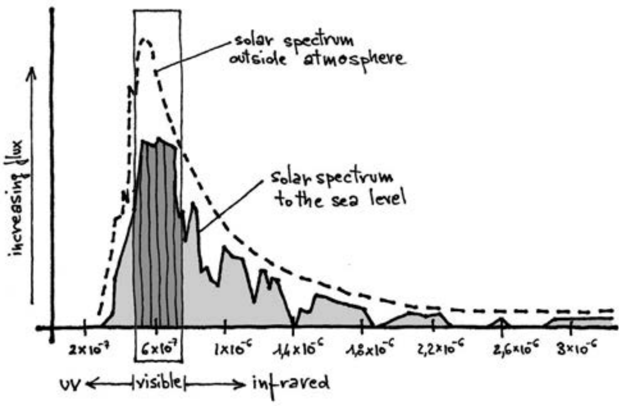


Fig. A.1-15 – Solar spectrum and visible range

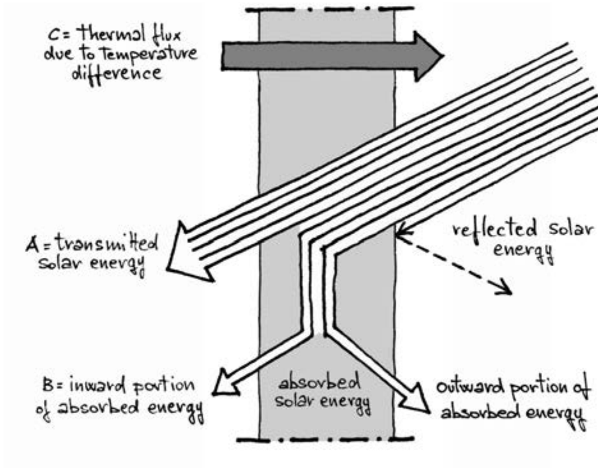


Fig. A.1-16 – Energy balance of a glass pane (indoor temperature > outdoor temperature)

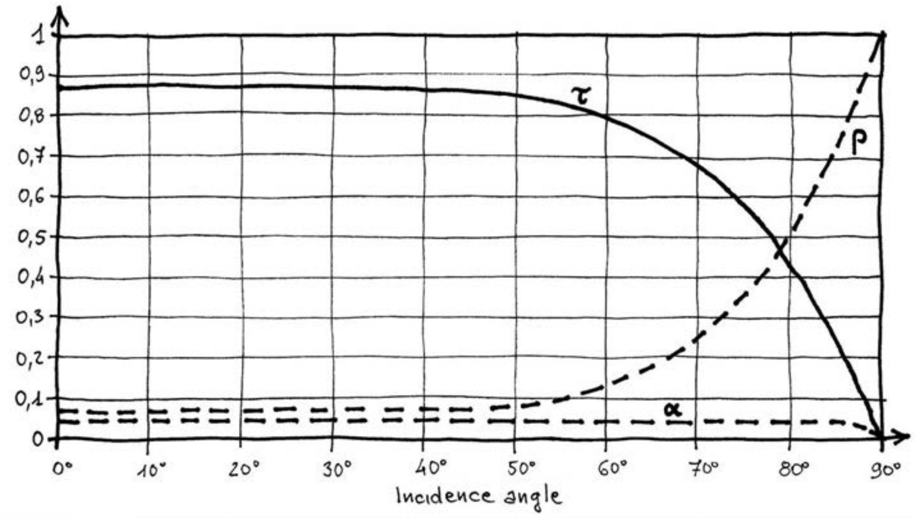


Fig. A.1-17 – Solar transmittance, absorptance and reflectance through a 3 mm single clear glass

If a shading device (internal or external) is used to protect the window from sun, the corresponding shading coefficient can be calculated. In 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 not an 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. Instead, to transform this one kg of water into vapour, 2,270 kJ are required. The phase change always requires high 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 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.

To evaluate the effect of the transformations that the moist air can have, the psychrometric chart is used.

2.3.1 Air and the psychrometric chart

The latent heat, in buildings, 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[8] (Fig. A.1-18). On the X-axis the values of dry bulb temperature (the air temperature measured with a thermometer) are marked, and 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 representing the air properties inside a room or outdoors, through a data pair, which can 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.

8 The interconnection between air temperature and humidity depends also on the atmospheric pressure, i.e. on the altitude above the sea level The chart reproduced in the figure, is for altitude above sea level = 0 m. Psychrometric charts for different altitude above the sea level. Psychrometric charts for different altitude above the sea level are given in figures A.1-27, A.1-28 and A.1-29 at the end of this chapter.

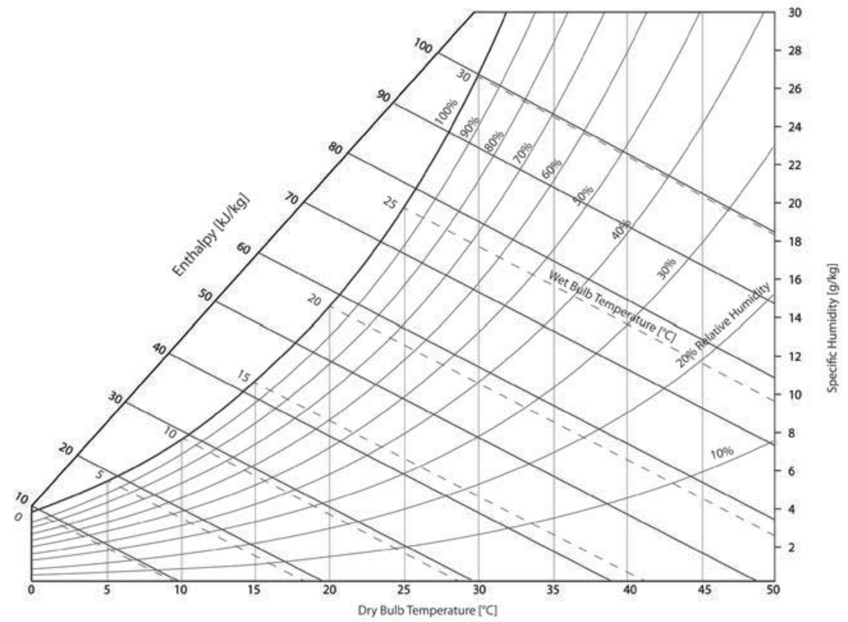


Fig. A.1-18 – Psychrometric chart at sea level

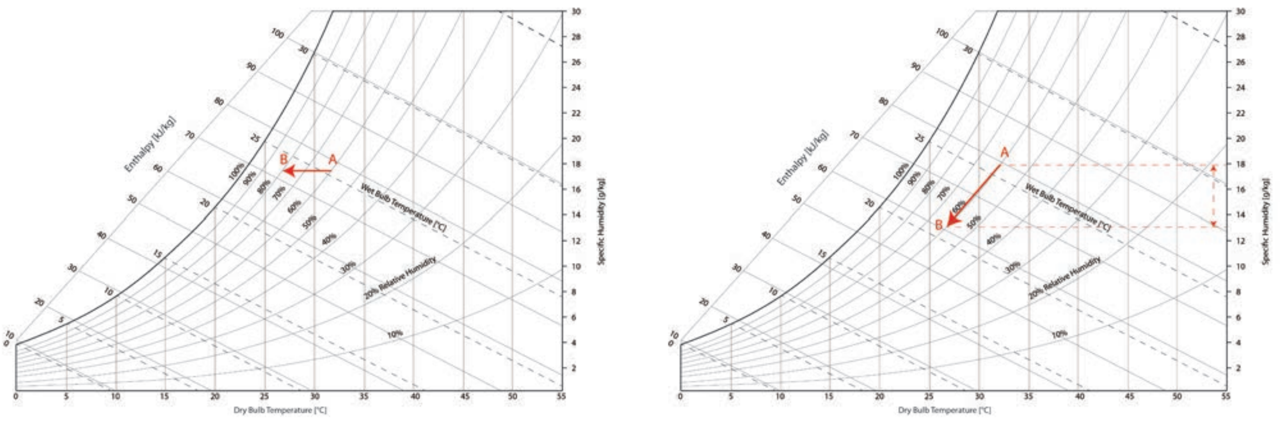


Fig. A.1-19 – Sensible cooling (left); cooling and dehumidification (right)

If we cool the outdoor air, initially at 32 °C and 60% RH and bring it to 26 °C, the resulting process is represented in figure A.1-19 (left) and takes the name of 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.

The transformation actually occurring in air conditioning systems is not the one indicated in figure A.1-19 (right), but involves cooling of air to reach the saturation curve, and move 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 subtracting heat from an environment, at the expense of increasing relative humidity; it takes the name of adiabatic humidification and it occurs when spraying water in 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.

3. Energy balance of the building

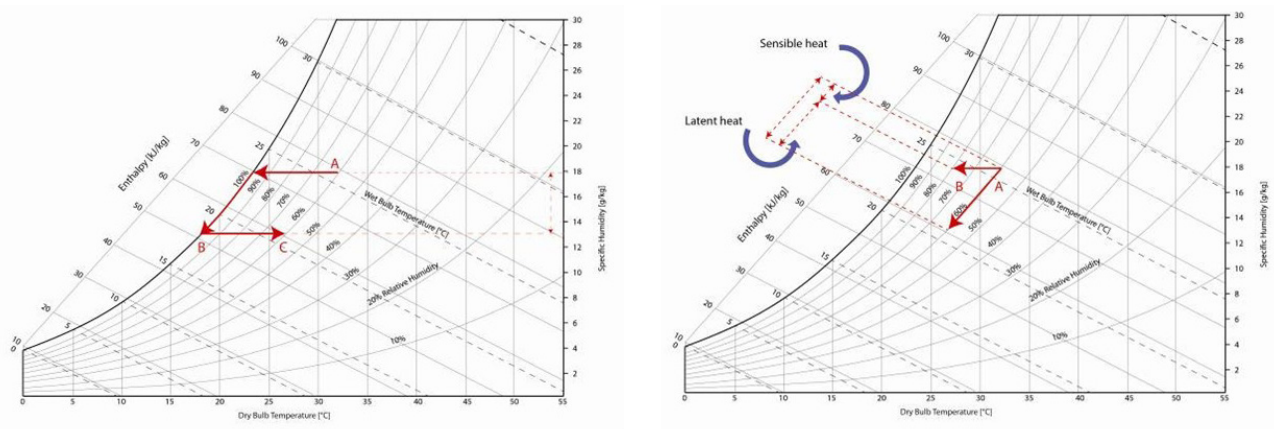


Fig. A.1-20 – Sensible cooling and dehumidification, real process (left); Energy required for sensible cooling and dehumidification (right)

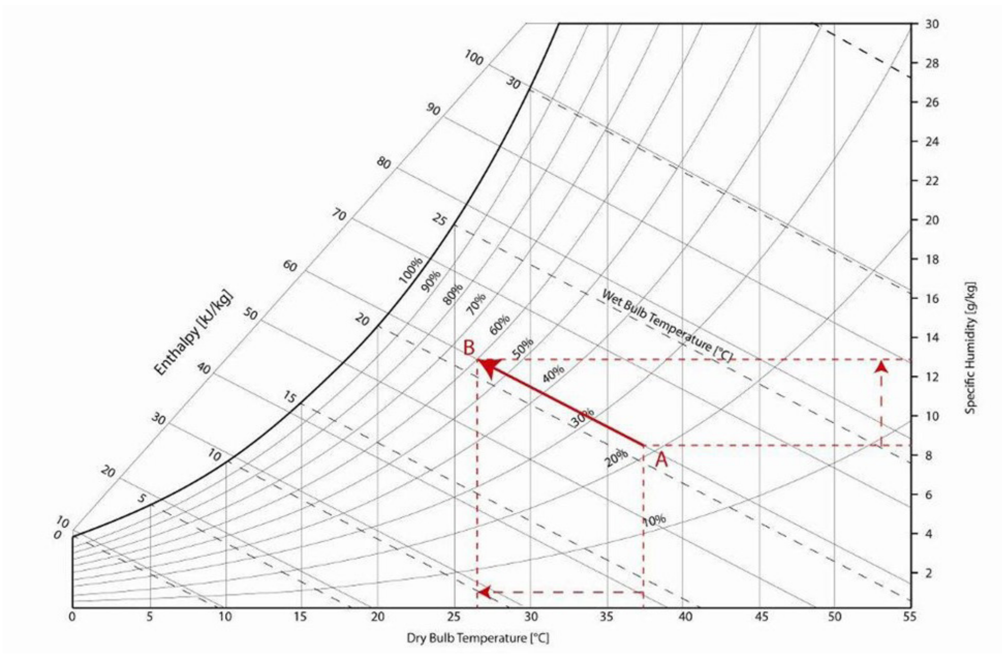


Fig. A.1-21 – Adiabatic humidification

Still in the second half of the nineteenth century it was 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, as the water flows from a reservoir to another if there is a difference in altitude, the 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 to understand the energy balance of a building.

If we imagine a bucket with holes in the bottom and on 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 looses. To maintain, in a cool period, a certain temperature inside a building, 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 the losses (Fig. A.1-23a). The "holes" of a building, in winter, are the transmission heat losses through walls, windows, doors and roof, and 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, with the rain that helps to fill it. To these gains, the internal gains (the heat produced by the persons, lights, and equipment) must be added.

In summer things go in a similar way, but opposite (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. Also in this case there are solar gains, but they now do not help: on the contrary they tend to increase the temperature of the environment, such as rain would fill the boat faster, raising the water level.

The analogy is also useful to 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, goes through the reduction or elimination of holes, i.e. heat losses in winter and gains in summer.

Of course, the analogy is useful, but highly simplifies the problem that, to be addressed properly, must put in place a number of areas of knowledge, first of all thermodynamics and heat transfer.

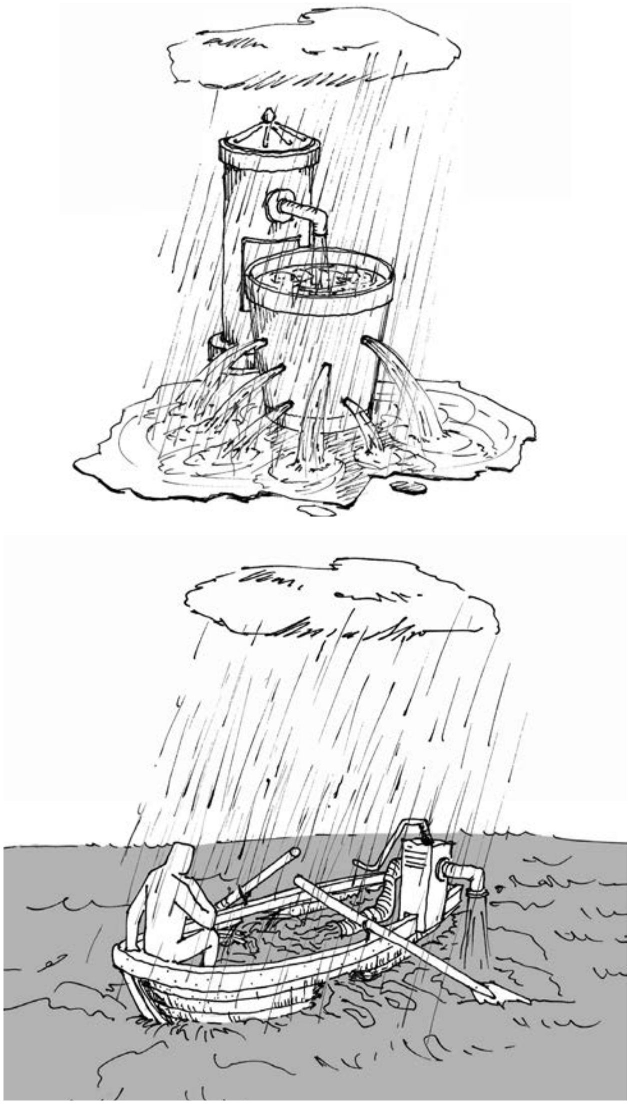


Fig. A.1-22a/22b– Water analogy

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);

$Q_{v\,(\tau)} = 1200 \times V \times (t_o - t_i)$ is the ventilation heat flow [W];

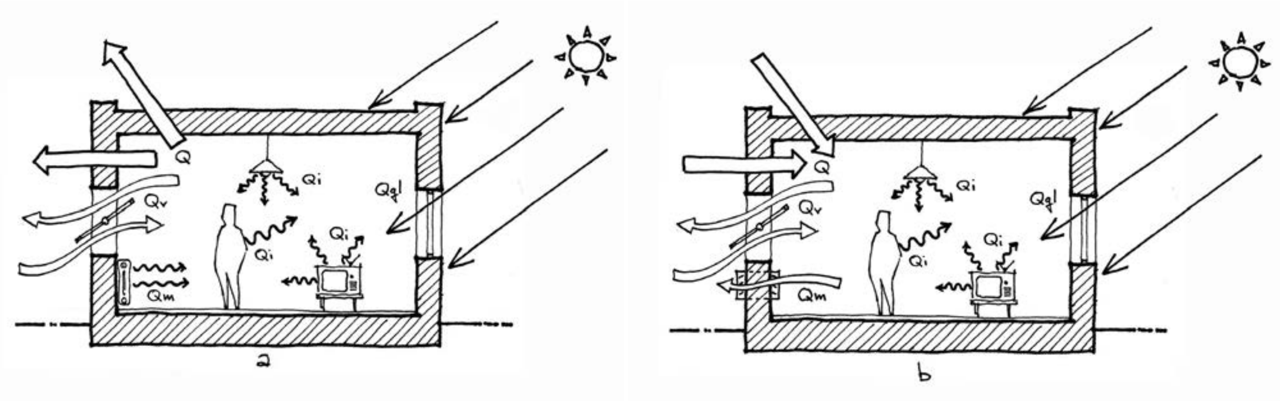


Fig. A.1-23 – Energy balance through building envelope in cool (a) and hot (b) period

V is the ventilation rate [m³/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.1-31) 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].

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 balance that covers the sensible heat. The balance of the latent heat, in fact, depends only on internal sources (people, technological systems and kitchen) and on outdoor air conditions, thus the envelope characteristics have no influence.

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 it 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 directly be 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[9]. 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, must take into account losses due to its performance. That is why using the heat pump

9 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.

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 electricity requires a lot of primary energy for its production. 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 also in this way.

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 case of a building, to this energy should be added the one necessary for the transport 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 transport. For a component, we need to add also the diversity of manufacturing processes.

Another aspect is the recycle. Aluminium, for example, which has the highest value of embedded energy, is recyclable (as steel), and its energy content, in case 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 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 one.

Also glass can 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 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. Actually, other factors should also be taken into account, such as deforestation induced if the cycle cutting/growth is not performed 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 a fair thermal insulation, but it has a rather low thermal inertia. This makes it little recommended for climates with hot climates/periods and 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, derives for 80% from its operation and 20% from the embodied energy of the construction materials, including maintenance and renovation (Fig. A.1-25).

The energy consumption of new buildings and of those significantly renovated is much less, when regulations on energy performance of buildings are implemented. In these conditions, the share of the embodied energy is increasing because of the decreasing consumption for operation, until it ends up to 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).

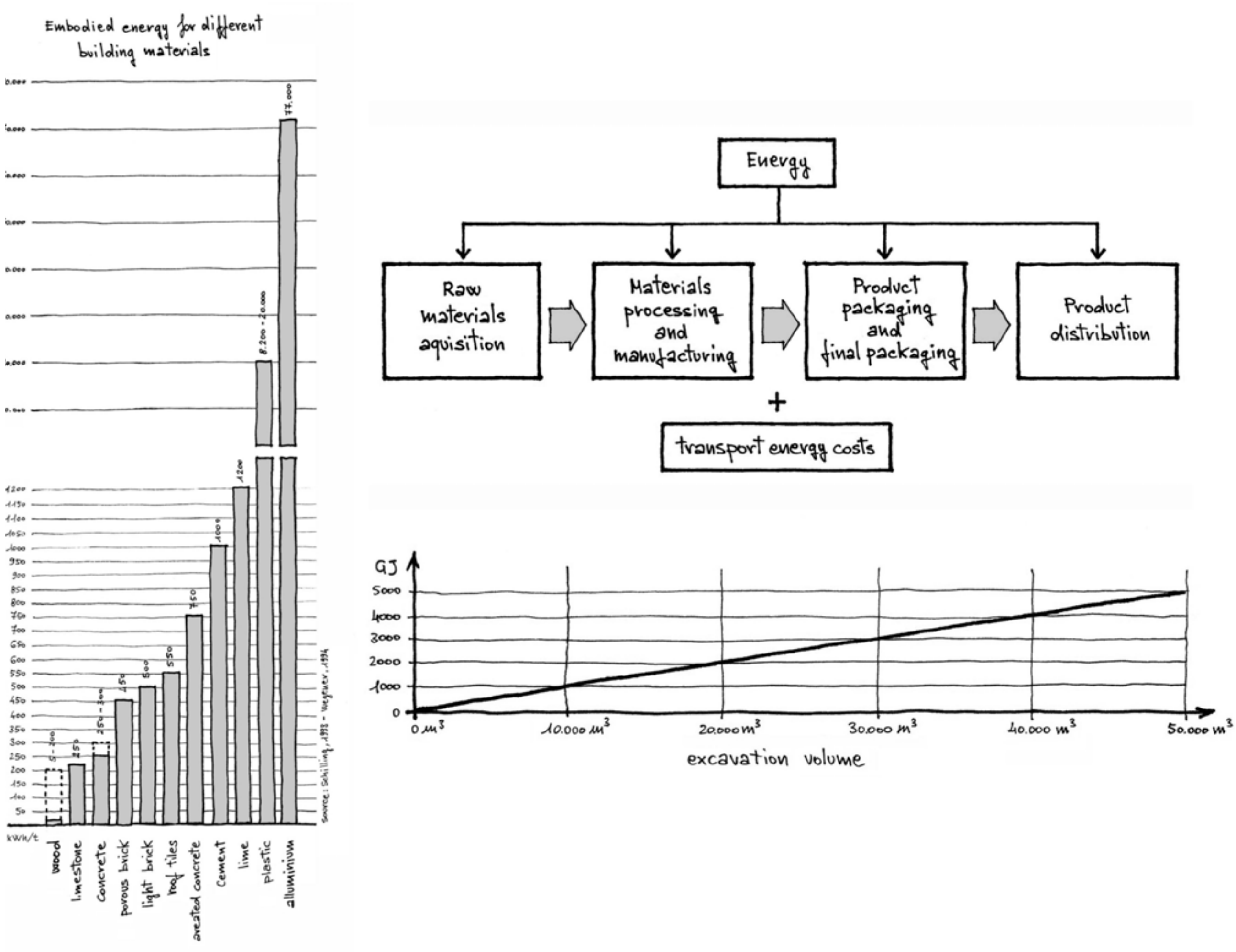


Fig. A.1-24 – Embodied Energy of some construction material10 and Energy expenditure on excavation and fillings11

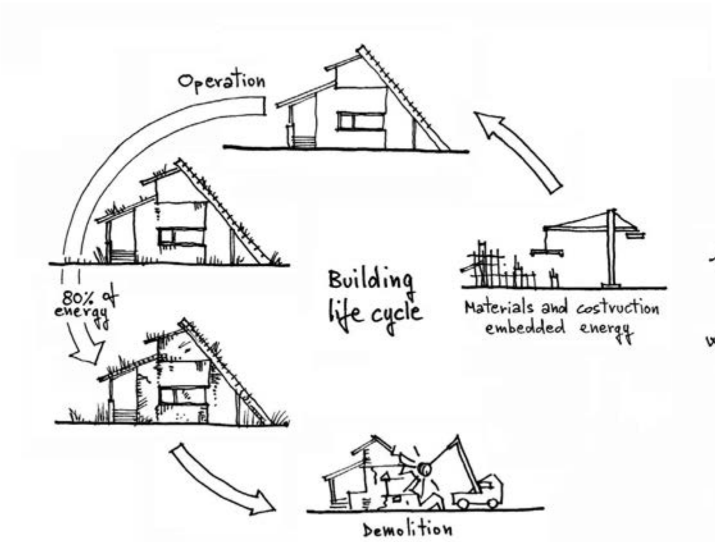


Fig. A.1-25 – Energy used in the building's life cycle in Europe (mean of the building stock)

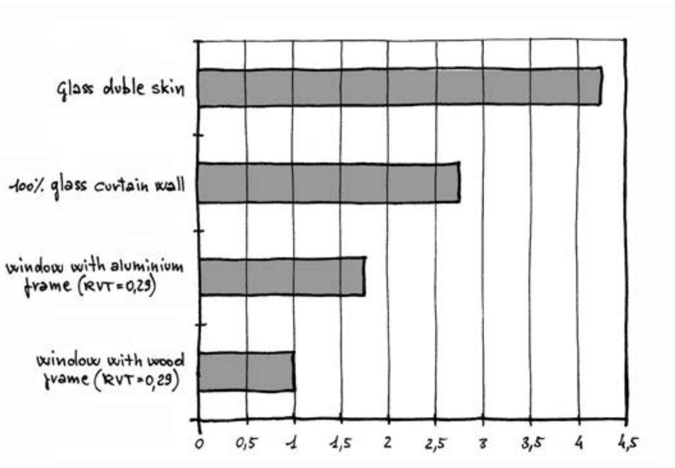


Fig. A.1-26 – Relative values of embedded energy in some types of facade. Facade with wood frame = 1 (RVT is the ratio between the glazed surface and the total of the façade)

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)

		Glass thickness [mm]	Visible Light			Solar energy			U-Value air	U-Value argon	SHGC	SC
			Transmittance [%]	Reflectance (outside) [%]	Reflectance (inside) [%]	Transmittance [%]	Reflectance [%]	UV Transmittance				
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

		Glass thickness [mm]	Visible Light			Solar energy			U-Value (air)	U-Value (argon)	SHGC	SC
			Transmittance [%]	Reflectance (outside) [%]	Reflectance (inside) [%]	Transmittance [%]	Reflectance [%]	UV Transmittance				
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		$[W/m^2\ lux]$
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 m^2 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/m³]	[MJ/m²]
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	\	\

Fig. A.1-27 – Psychrometric chart at sea level

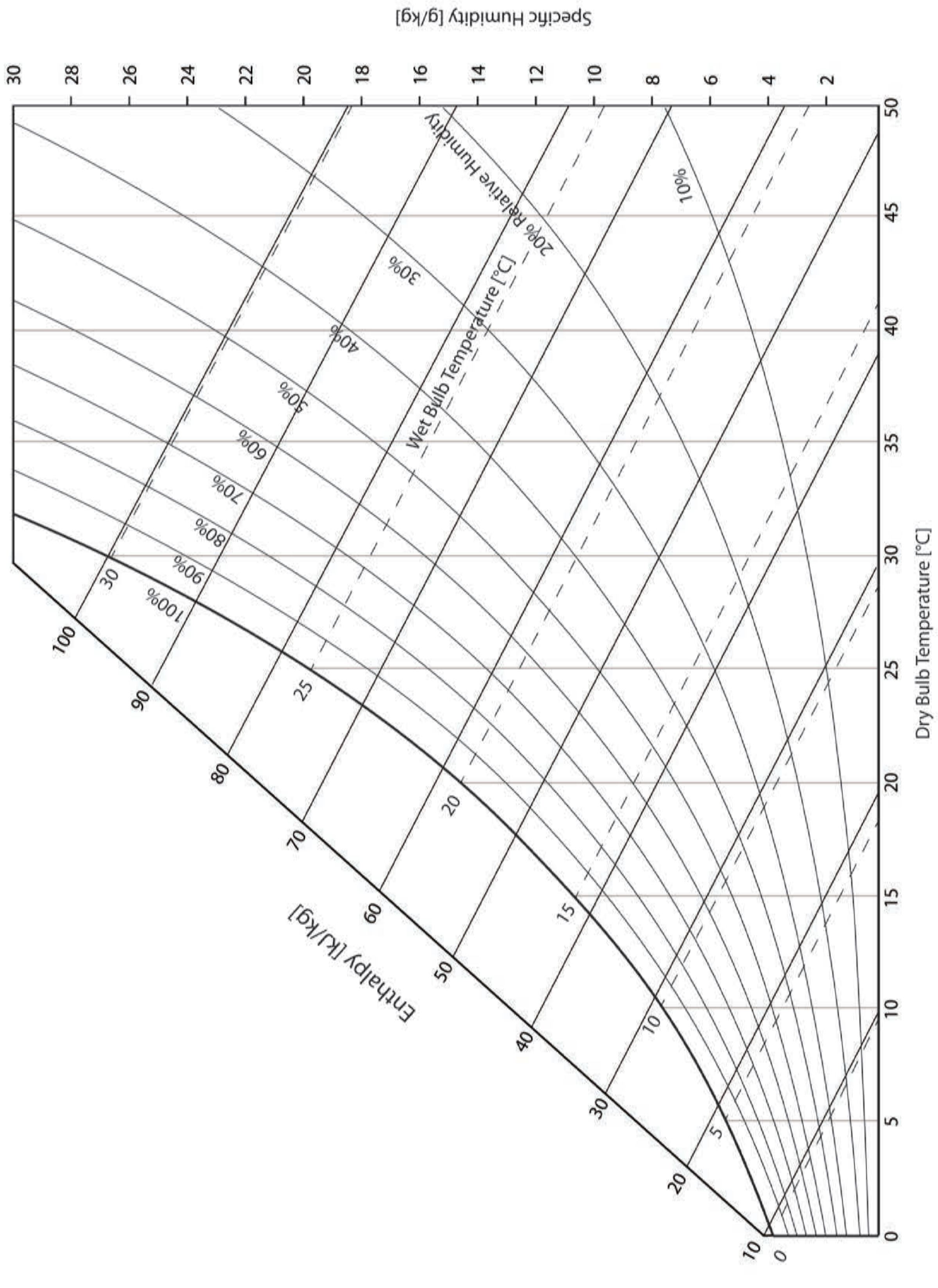


Fig. A.1 -28 – Psychrometric chart at 1500 m altitude above sea level

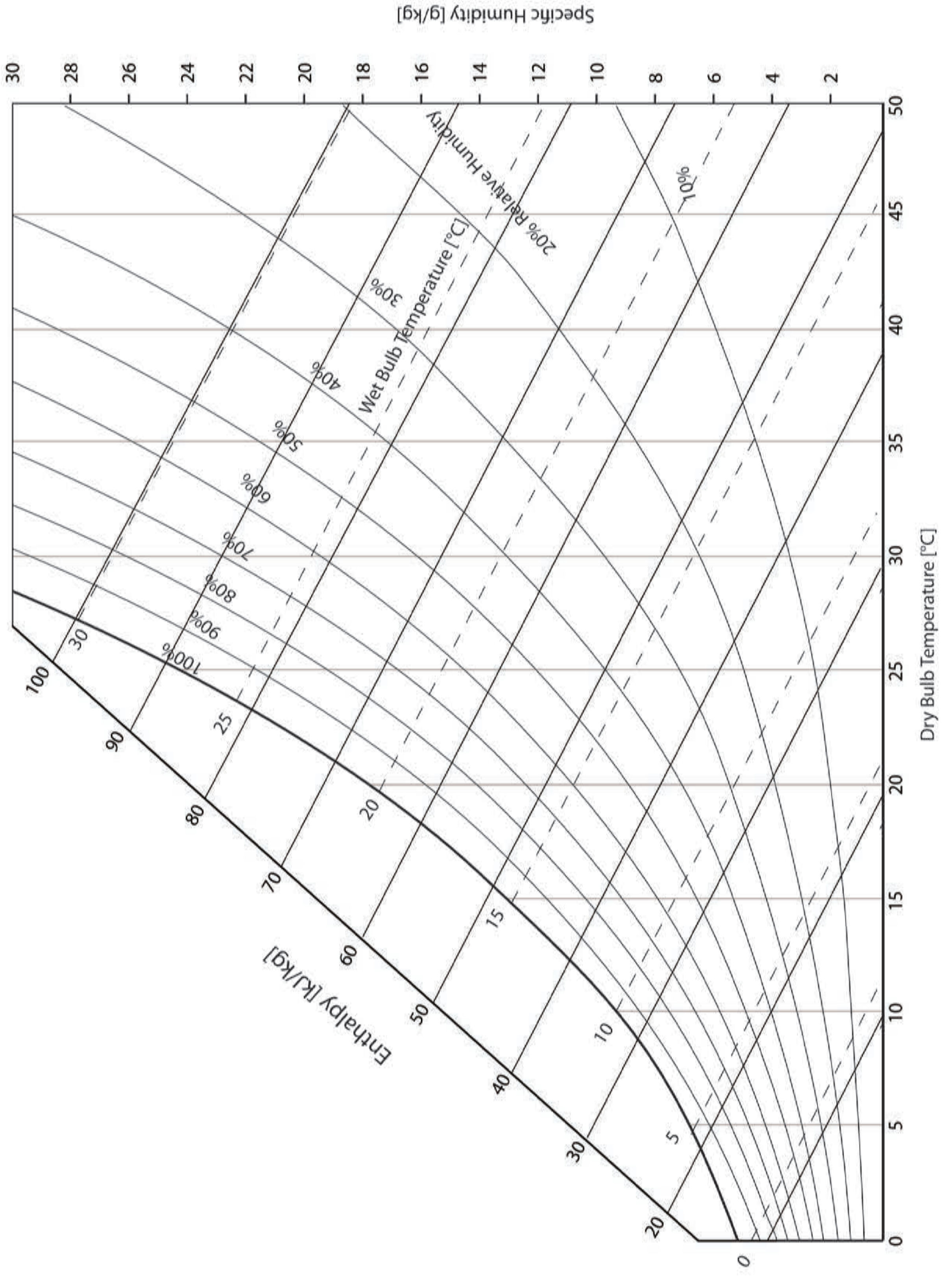
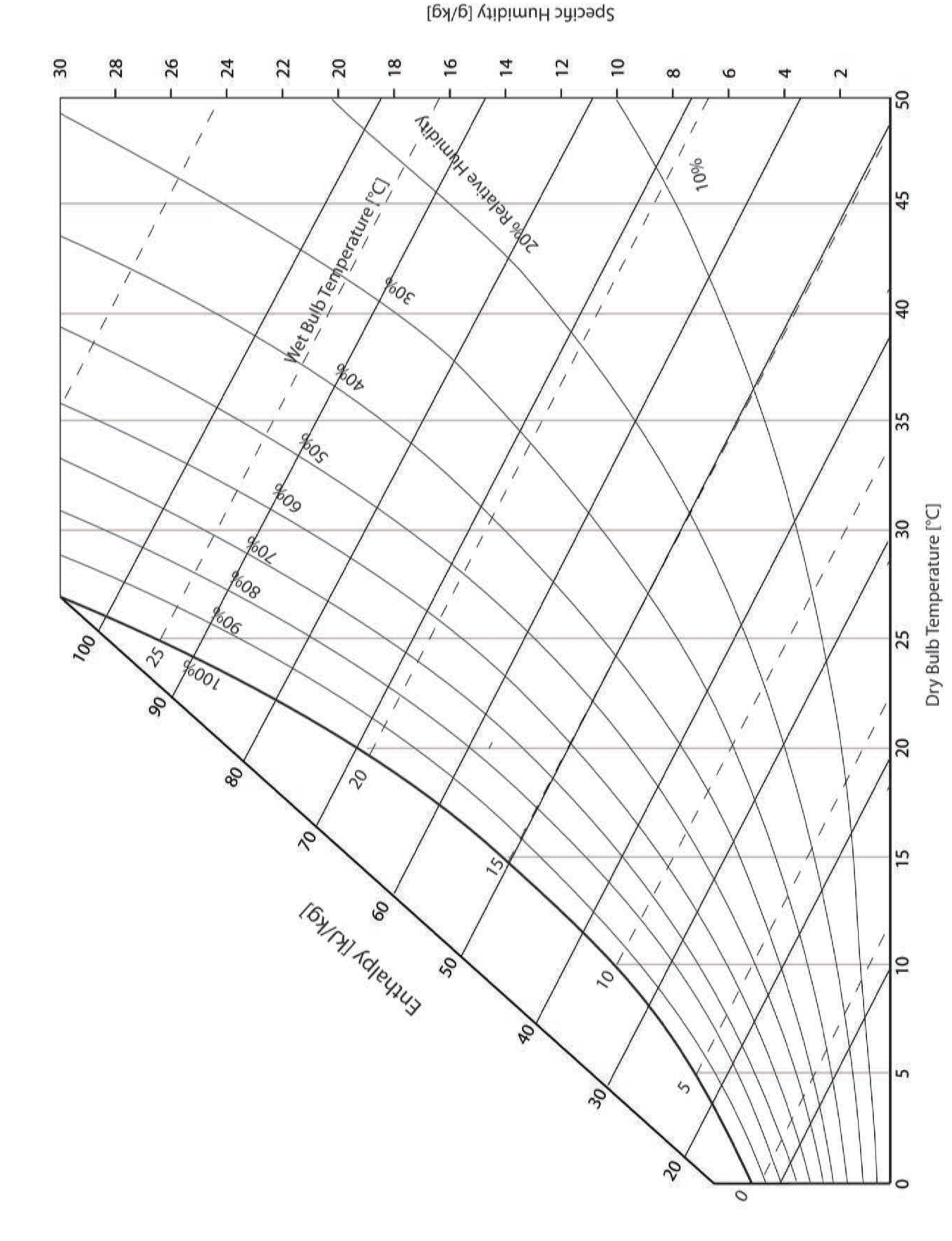


Fig. A.1-29 – Psychrometric chart at 2250 m altitude above sea level



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).

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.

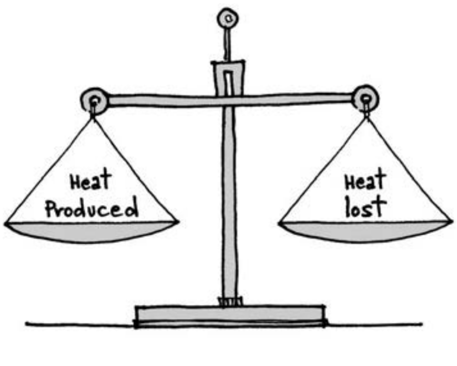


Fig. A.2 1 Thermal comfort can be maintained when heat produced by metabolism equals the heat lost from body

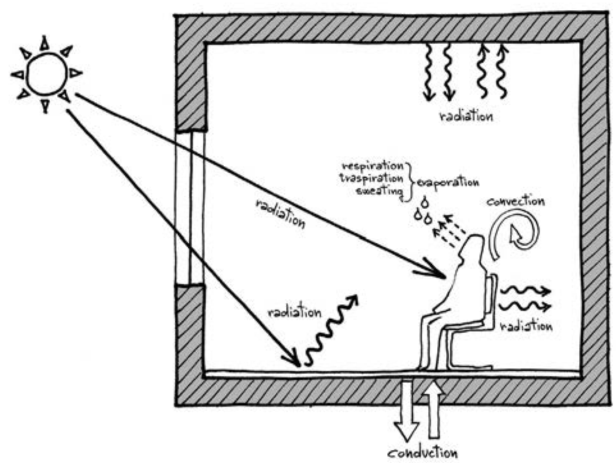


Fig. A.2 2 Factors determining thermal comfort

Clothing highly influences heat transfer, through the additional thermal resistance it generates, the modification of the surface temperature and the transpiration process.

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 feels 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

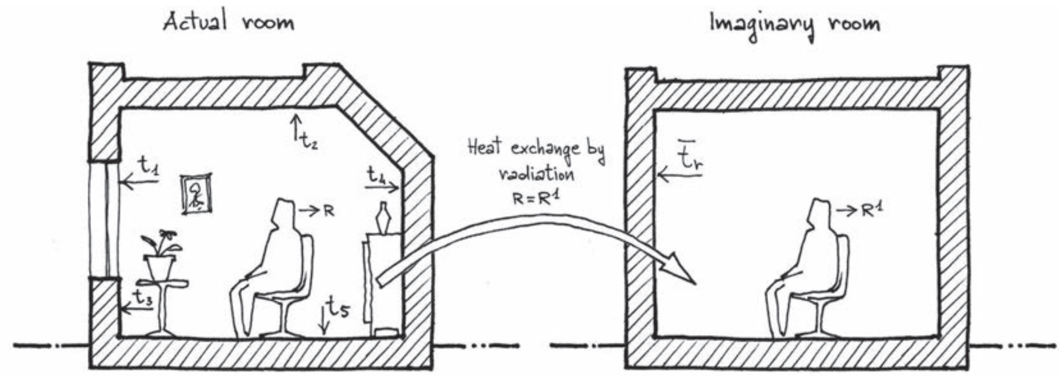


Fig. A.2 3 Mean Radiant Temperature

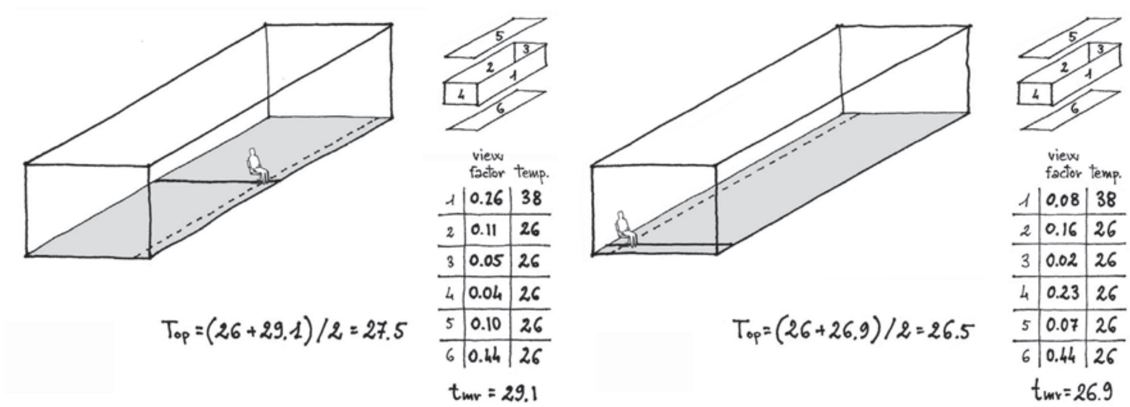


Fig. A.2 4 Effect of position and surface temperatures on mean radiant temperature (trm) and operative temperature (top)

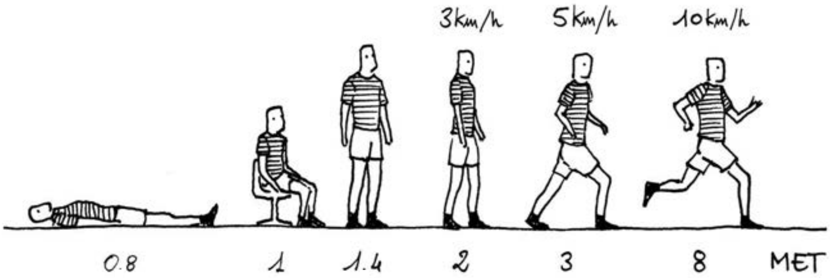


Fig. A.2 5 Metabolic rate for different activities, in met

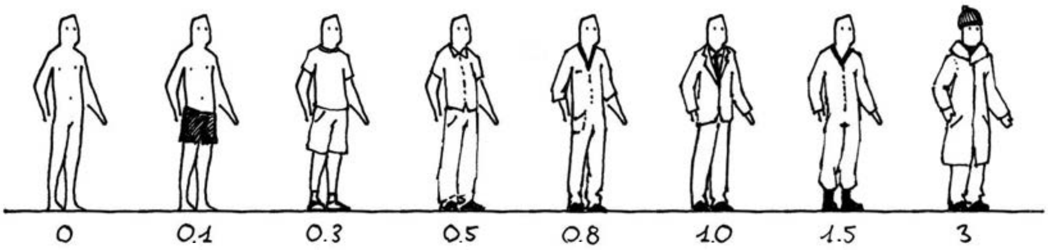


Fig. A.2 6 Thermal resistance values of clothing expressed in clo for various types of clothing

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.

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.

1.1 Predicted Mean Vote (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.

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).

1.2 Thermal comfort in air conditioned buildings

In air conditioned spaces, where air velocity is less than 0.2 m/s and the relative humidity[1] 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

1 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.

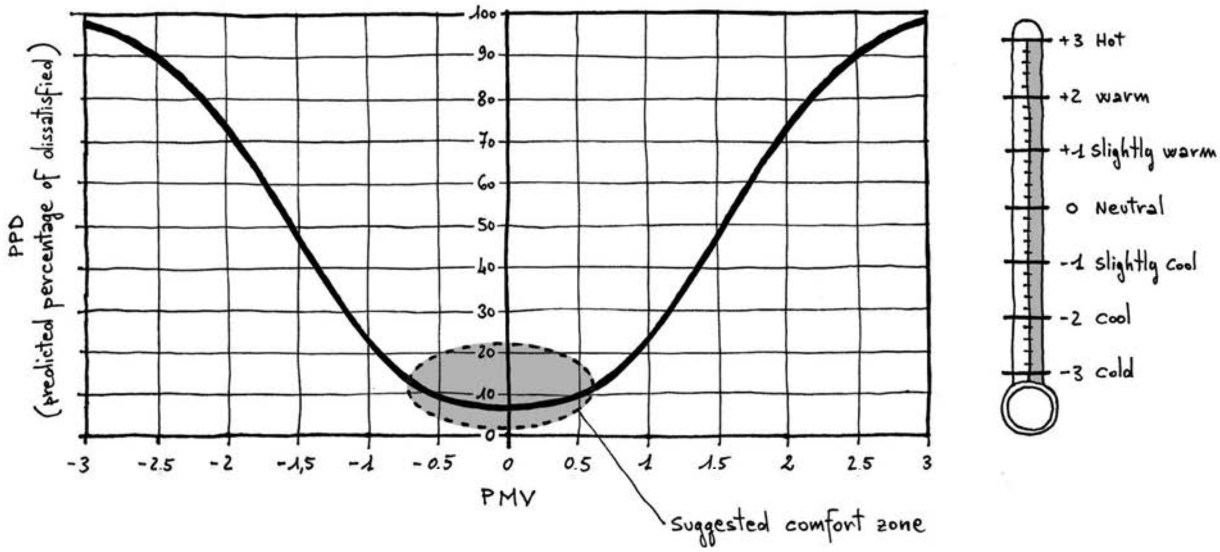


Fig. A.2 7 Thermal sensation scale, PMV and PPD

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 < 0.2	< 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

Table A.2 1 Recommended categories for design of mechanical heated and cooled buildings

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).

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 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.

1.3 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

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

Table A.2 2 Recommended design values of the indoor temperature for design of buildings and HVAC systems

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

Table A.2 3 Air velocity and pleasantness

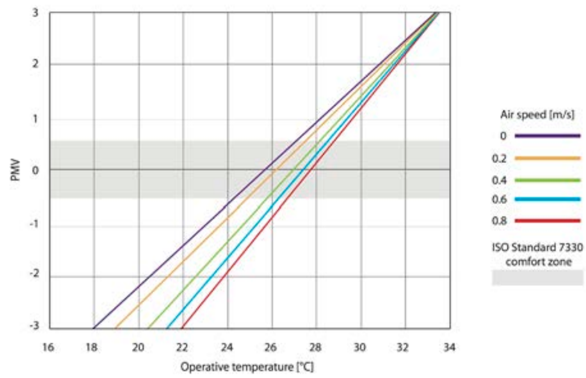


Fig. A.2 8 Effect of increasing air speed on comfort in air conditioned spaces (1 Met, 0.5 clo)

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 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 Δt_{op} is the increment in operative temperature in K and V_a 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.

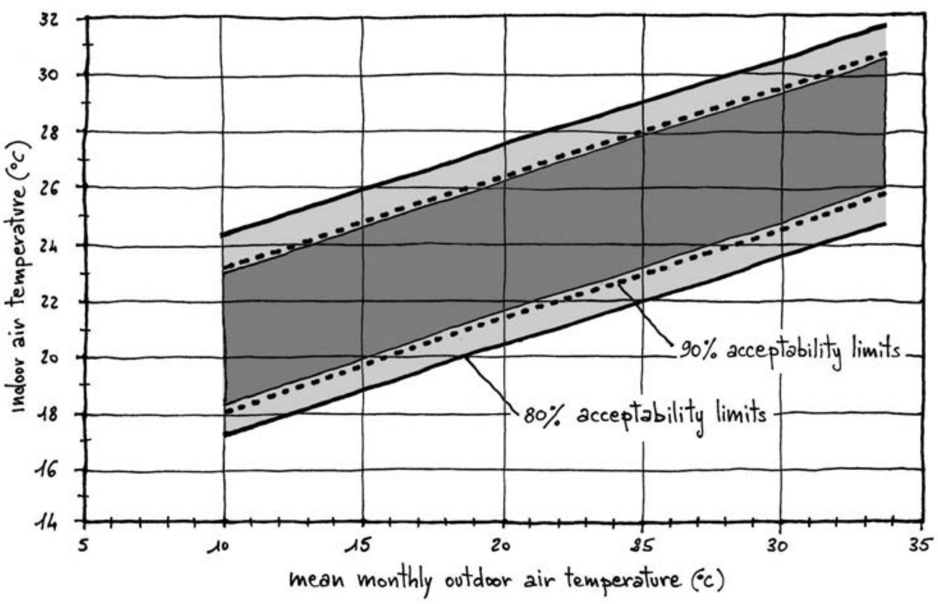


Fig. A.2 9 Acceptable operative temperature for naturally conditioned spaces

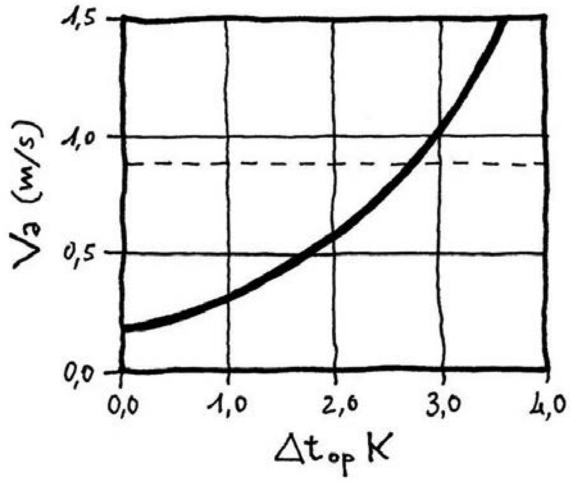


Fig. A.2 10 Air speed required to offset increased temperature (EN ISO 7730)

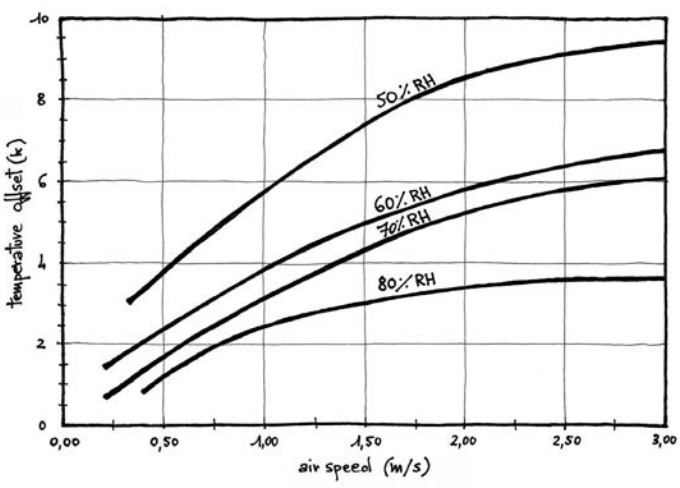


Fig. A.2 11 Cooling effect of air movement

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.

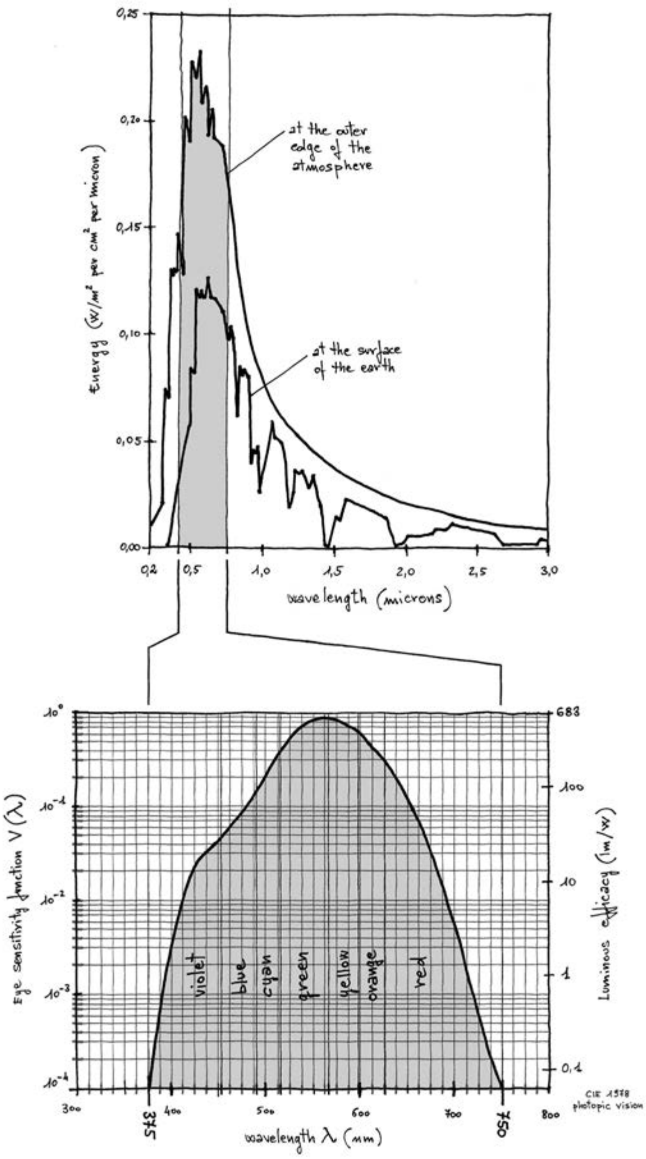


Table A.2 3 Solar spectrum

2.1 Photometry units

2.1.1 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.

2.1.2 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.

2.1.3 Illuminance - Unit: lux [lx = lm/m^2]

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.

2.1.4 Luminance - Unit: candela/m^2 [cd/m^2]

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).

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

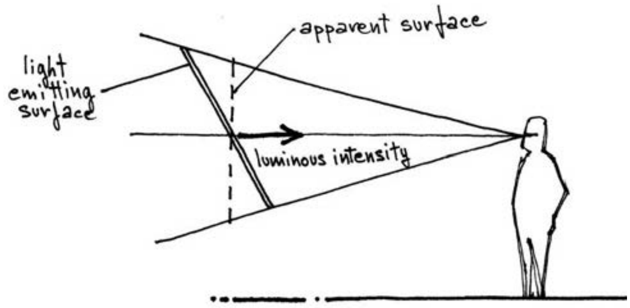


Fig. A.2 13 Luminance definition

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.

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[2].

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[3], provided that the color temperature is not too high, as in the case of blue, green or spectrally selective glasses.

Source	Luminance [cd/m^2]
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 4 Luminance of some sources

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

Table A.2 5 Maximum recommended values of luminance ratio

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

Table A.2 6 Offices Recommended values of illumination

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 illuminance 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

2 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.

3 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*

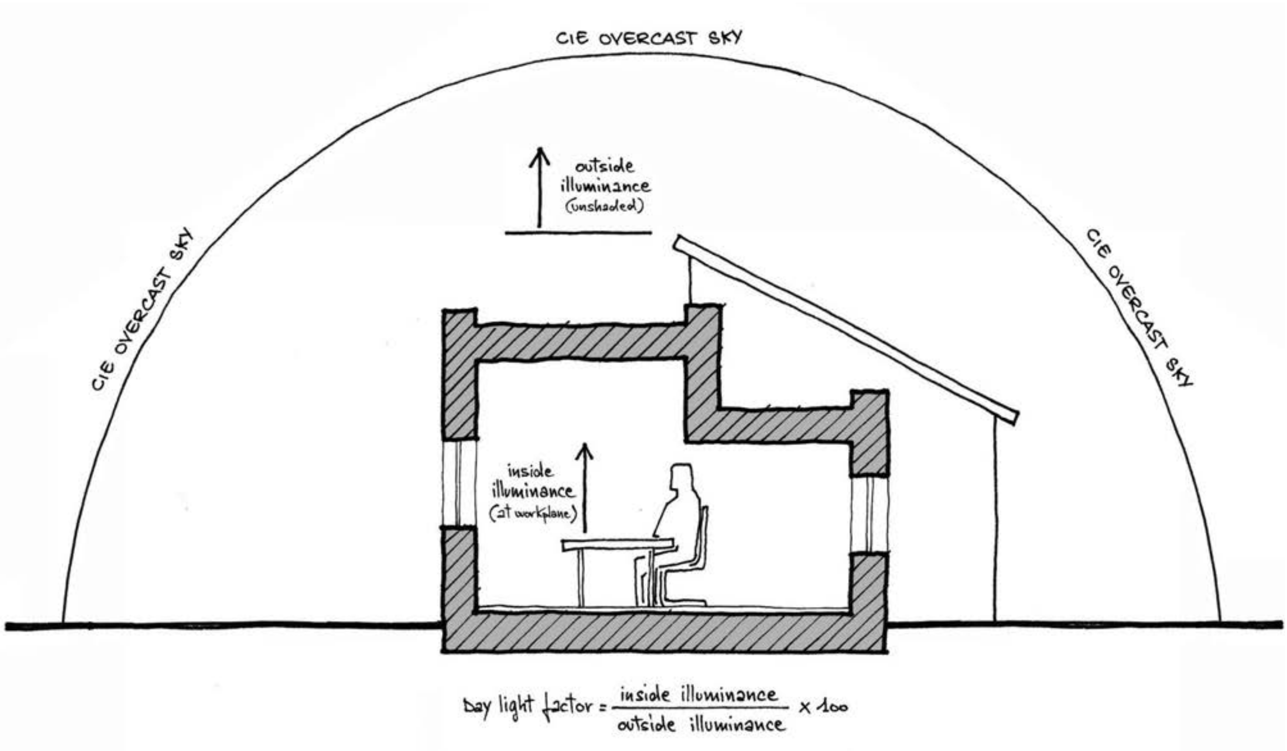


Fig. A.2 14 Daylight factor

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.

$DF\ [\%] = (E_{int}/E_{ext}) \times 100$ (A.2-3)

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):

$E_{int} = SC + ERC + IRC$ (A.2-4)

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. 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

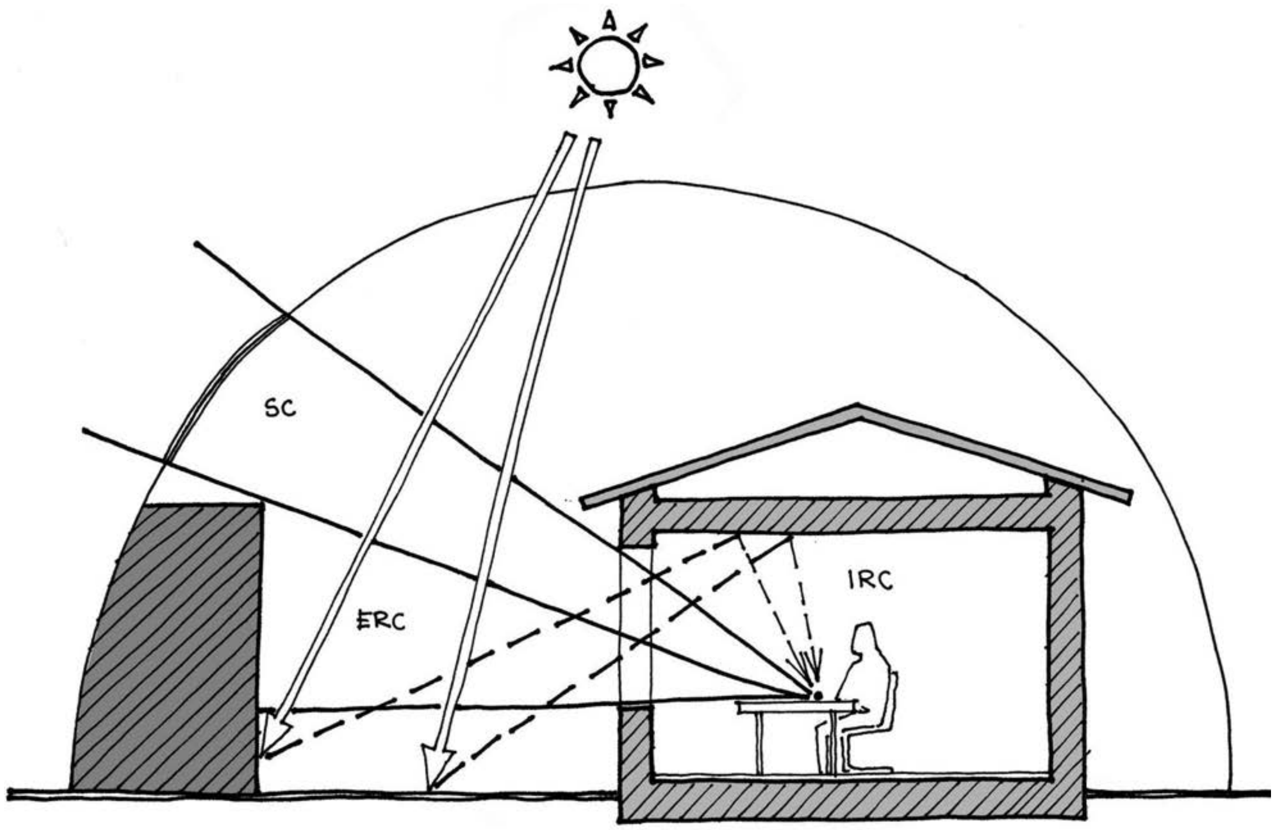


Fig. A.2 15 The components contributing to the illumination of a point (E_{int} = SC + ERC + IRC)

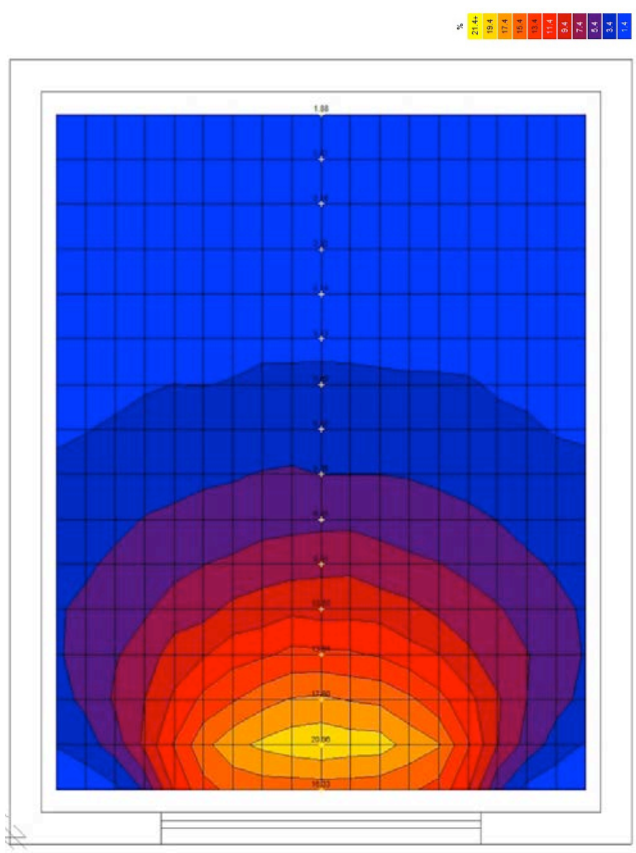


Fig. A.2 16 Change of Daylight Factor moving away from the window

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 7 Mean values of surface reflectance

Type of space	Recommended DF_m
Office/shop	1.0 - 2.0%
Classroom/conference hall	1.0 - 2.0%
Transit area	<1%

Table A.2.8 Recommended Mean Day Light Factor

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, [m^2];

A_{total} = total area of all interior surfaces, including windows, [m^2];

ρ_m = mean surface reflectance, weighted on areas; ρ_m = 0.5 can be used as first approximation.

In Table A.2-7 surface reflectance ranges are given and Table A.2-8 shows examples of recommended mean daylight factor in near equatorial skies.

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.

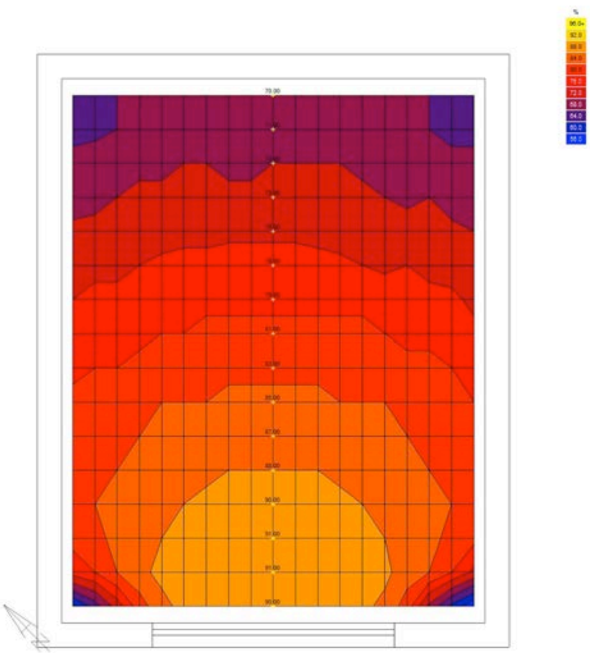


Fig. A.2 17 Daylight Autonomy in the same environment of figure A.2 16

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.

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)[4]. 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.

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/m².

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.

2.2.3.1 Direct and reflection glare

4 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.

Categories of glare	UGR	DGI
Barely perceptible	10-13	8-16
Acceptable	16-19	20-22
Annoying	22-25	24-26
Unbearable	28	28

Table A.2 9 Values of UGR, DGI and corresponding categories of glare

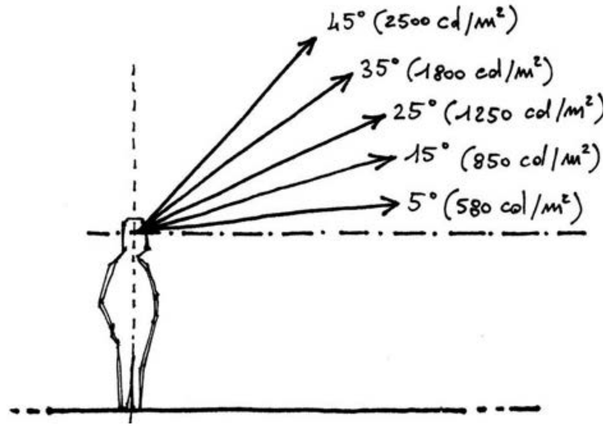


Fig. A.2 18 Luminance limits

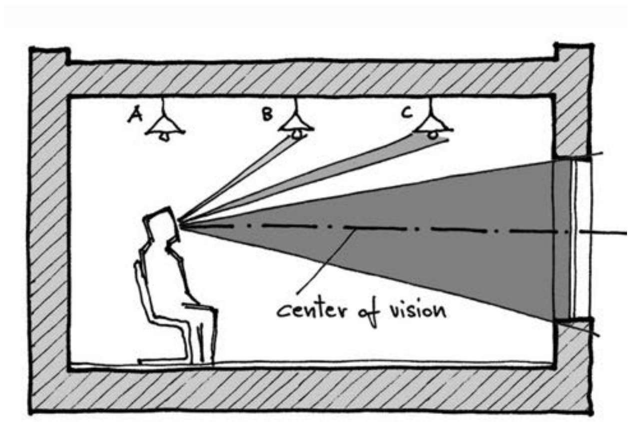


Fig. A.2 20 The closer to the centre of the visual field, the more light sources are potential sources of glare. In the figure the sources are progressively more problematic from A (no problem), gradually to B, C

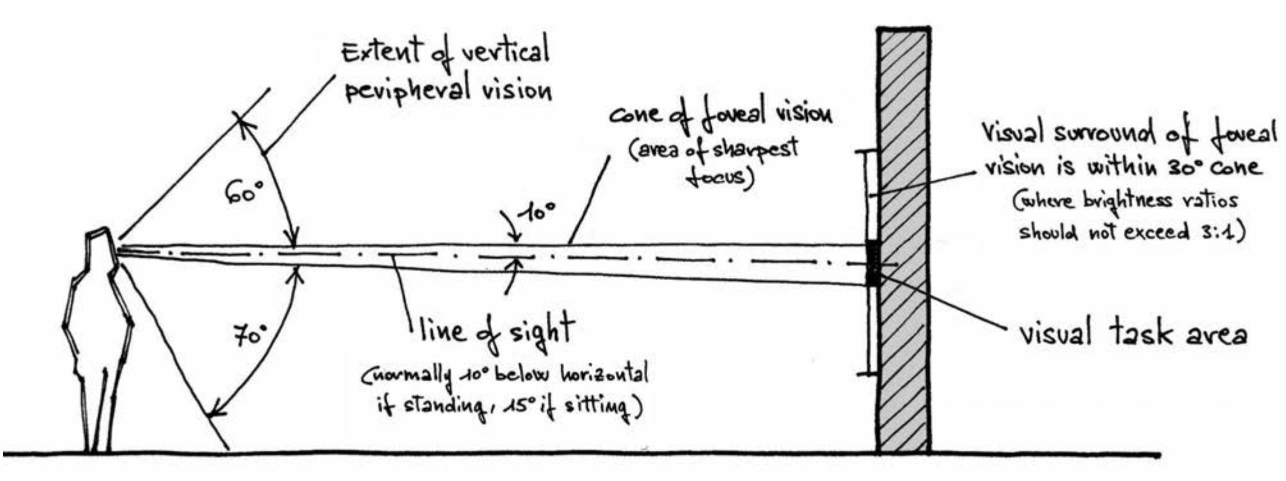


Fig. A.2 19 The visual field

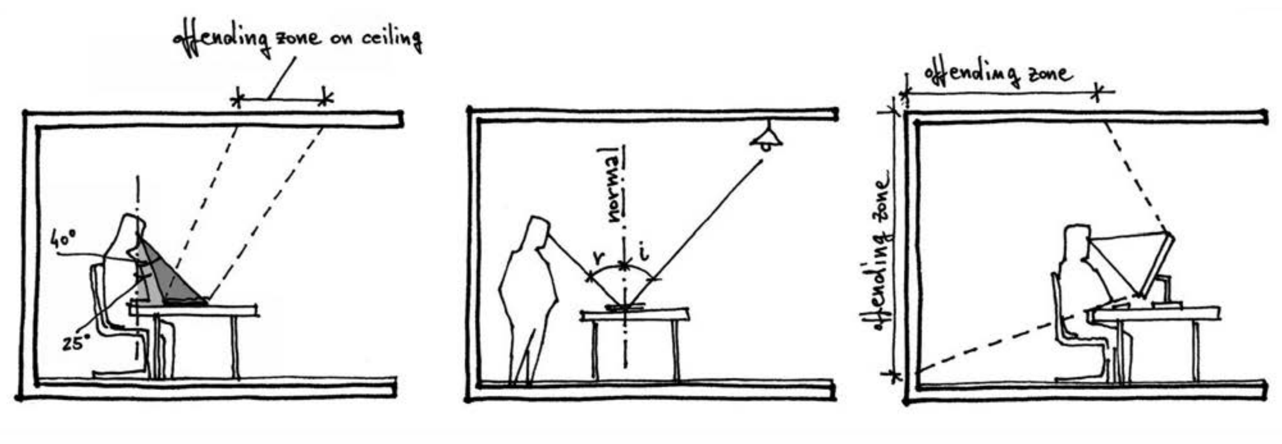


Fig. A.2 21 Different possibilities of glare due to reflection

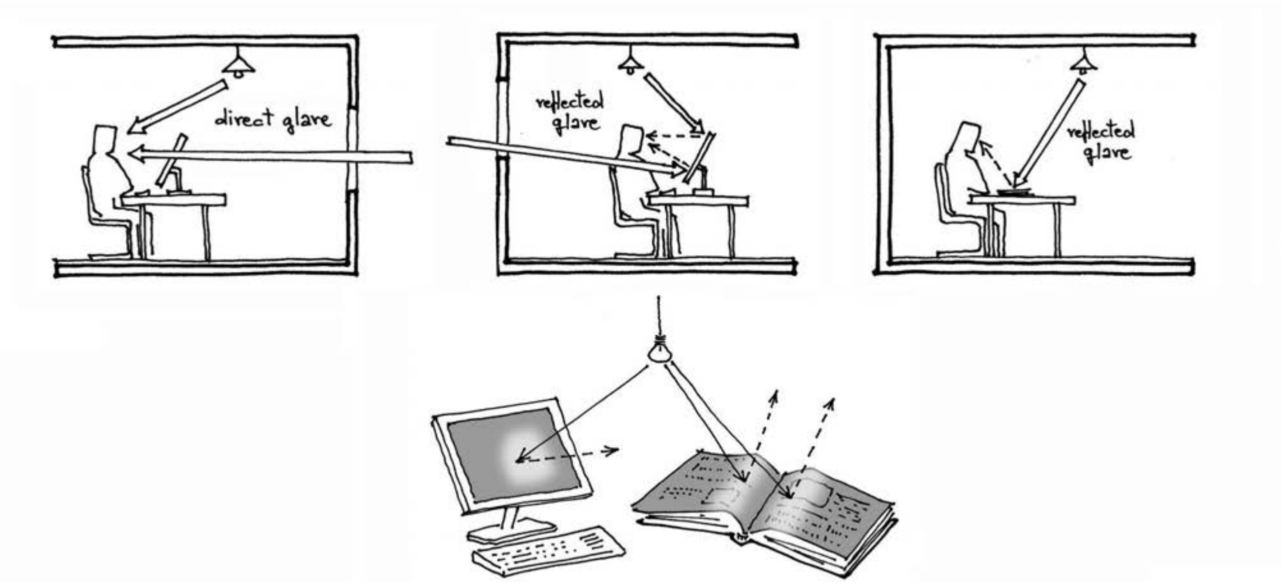


Fig. A.2 22 Direct and reflected glare

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.

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

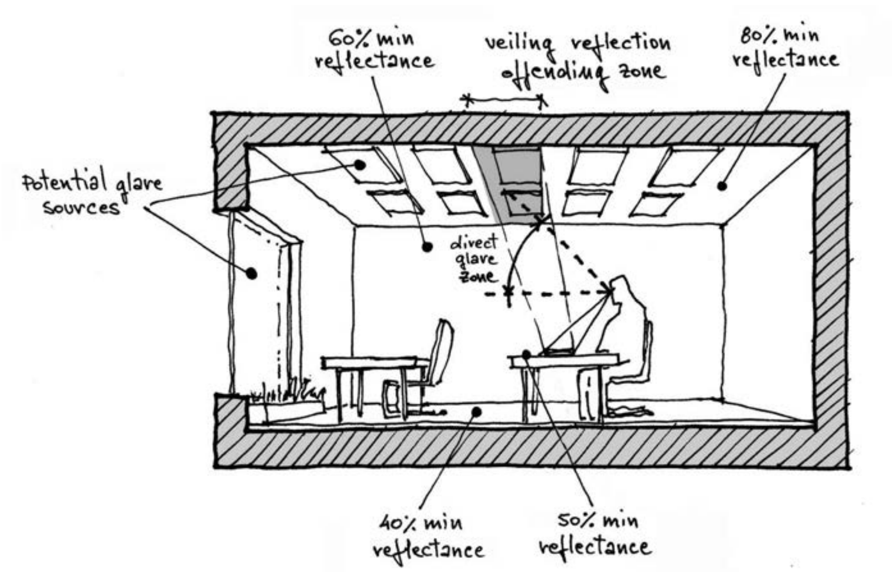


Fig. A.2 23 Potential sources of glare and recommended reflectances.

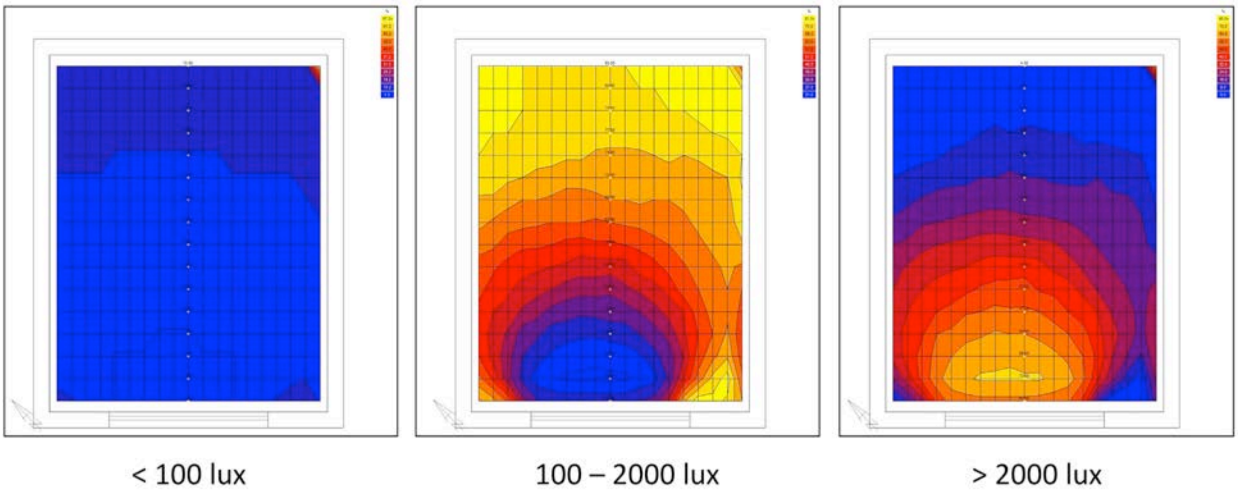


Fig. A.2 24 Useful daylight Illuminance (UDI) for a space; it is shown that the probability that glare may occur is high even at a certain distance from the window

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.

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

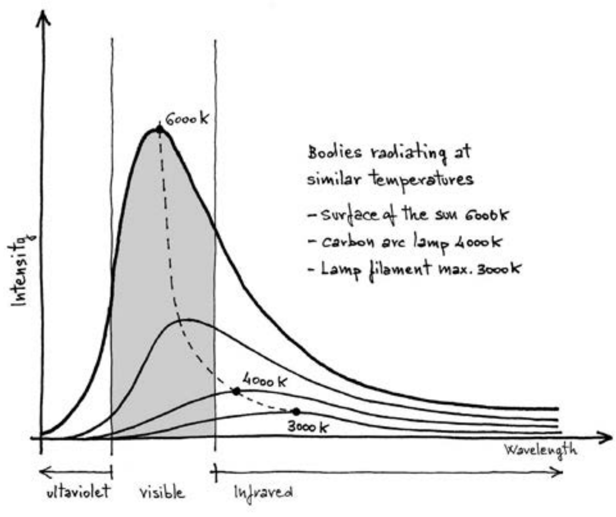


Fig. A.2 25 Black body spectrum

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.

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.

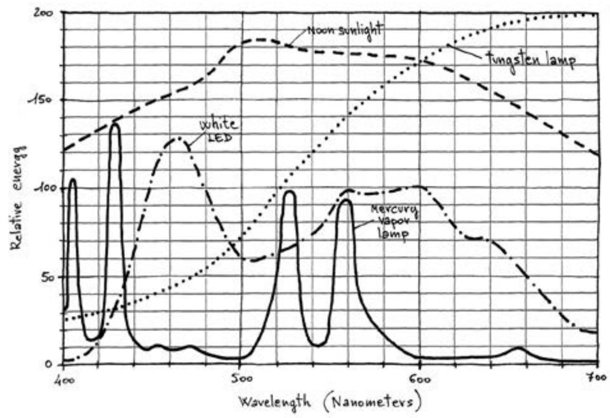


Fig. A.2 26 Spectra from common sources of visible light

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).

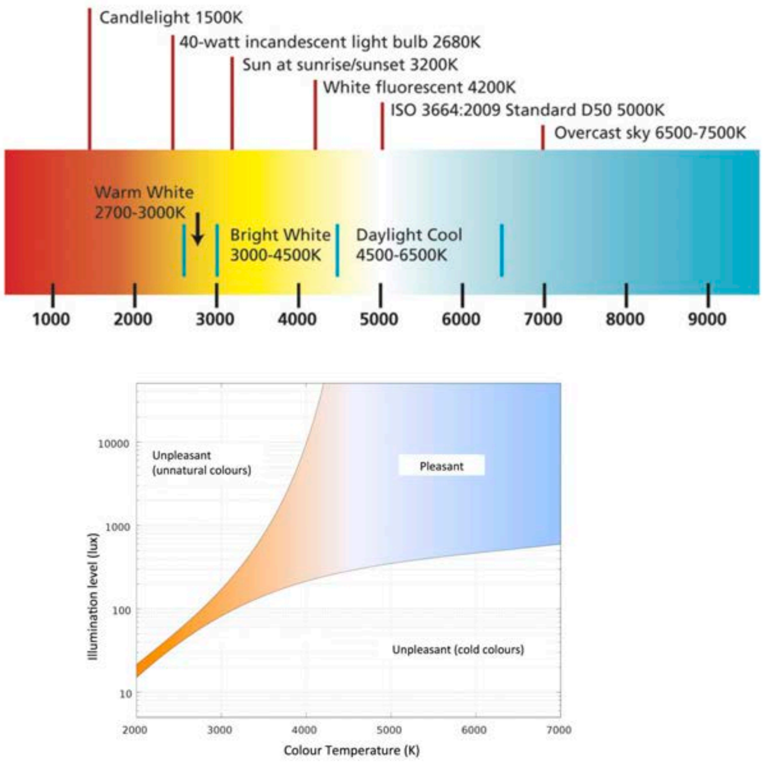


Fig. A.2 27 Top, the colour temperature scale; Bottom, the Kruithof curve which relates the pleasantness of a visual environment with the "warmth" of the light source and the illumination leve

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°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.

Jalousie window or louvre window (UK) – 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. (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 temperature measured using a thermometer with a wetted bulb moved rapidly through the air to promote evaporation. The evaporating moisture and changing phase lowers the temperature measured relative to that measured with a dry bulb. Wet bulb temperature accounts for the effects of moisture in the air. It can be used along with the dry-bulb temperature on a psychrometric chart to determine relative humidity.

Zenith – the top of the sky dome. A point directly overhead, 90° in altitude angle above the horizon.

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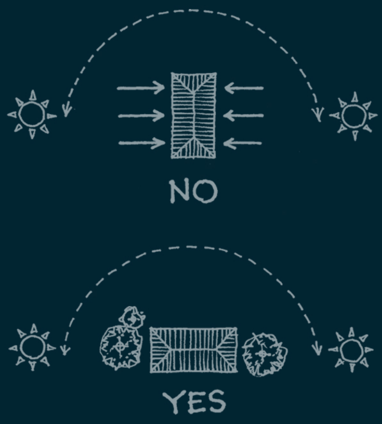

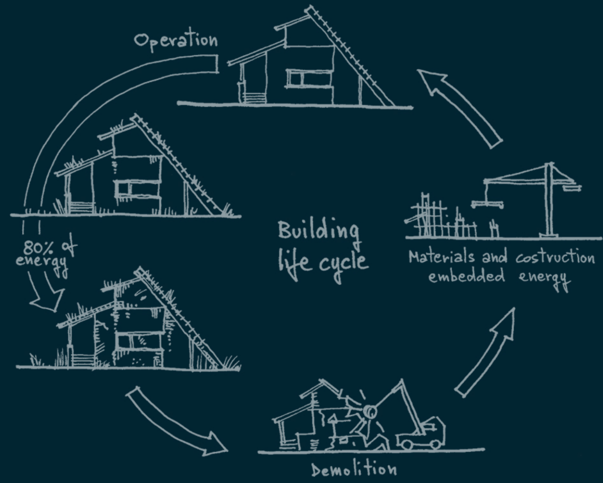

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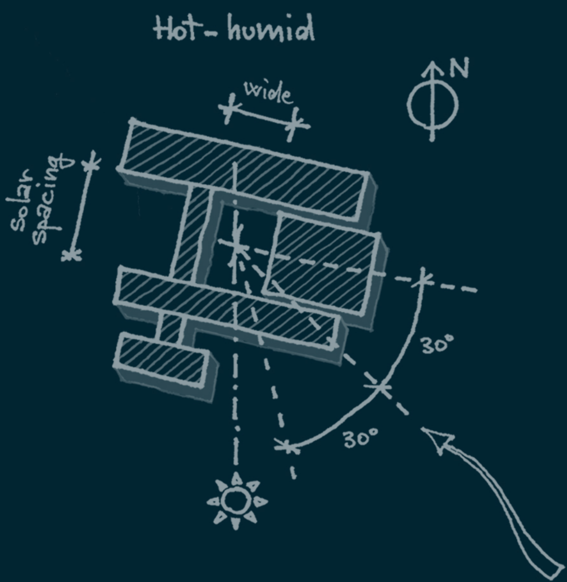

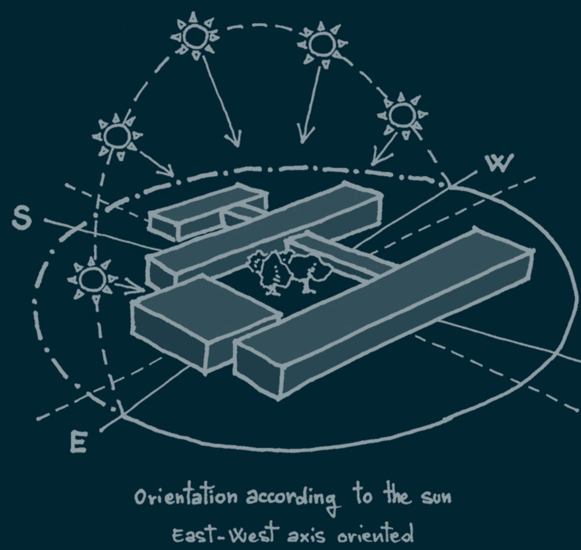

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