Imagine entire cities that, for their heating, cooling, hot water, electricity, industrial production, and transportation, only need the energy they produce themselves! Imagine that the carbon emissions of these cities are almost zero. This is nothing utopian; this ambition is achievable. The time of great decisions is at hand. This book offers solutions to achieve these goals, which are applicable everywhere on the planet, and they are illustrated with examples from all continents.

Dr Modeste Kameni Nematchoua is an engineer and Professor of Sustainable Architecture, Energy and Environmental Sciences. He is the author of over 80 recent journal articles, and serves as the Principal Investigator of the project “Towards Zero-Energy Cities”.

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Modernizing All the Cities of the World

Towards Zero-Energy and Zero-Carbon Emissions by 2050

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Modernising All the Cities of the World Towards Zero-Energy and Zero-Carbon Emissions by 2050

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This book is the fruit of an agreement established between the University of Liège, Belgium, and AXA Research Fund, Paris (France).

The main objective of the AXA Research Fund is to support the science which will be protecting us tomorrow. Another objective of the AXA Research Fund is to multiply the scientific discoveries supporting societal progress. Moreover, AXA aims sharing scientific knowledge, fuelling public debate, and enabling everyone to make informed decisions for building a better future.

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Introduction

By 2050, more than 75% of the population will live in cities. Better understanding of the interactions and energy exchanges, occurring in the urban environment between buildings, transport, and local renewable energy sources, is thus an absolutely crucial research step on the road to global sustainability. This book was written with the aim to help stakeholders to identify new opportunities regarding the implementation of zero-energy and zero-carbon policies and to provide community planners, traffic engineers, buildings engineers and designers with a tool, information and data aiding in the renovation of old cities and the design of new cities.

Nowadays, the industry, building, and transportation sectors are denounced as the main sectors that produce an important quantity of carbon, which accelerates global warming. In the aftermath of rapid industrialization, neither the concentration of world emitted carbon nor the energy demand stopped increasing (Wang et al. 2011, 2610-6216). Between 2000 and 2020, the average concentration of carbon dioxide (CO_2) emitted increased by approximately 2 to 3% each year (Liu et al. 2016, 201-206). In 2018, China (29.7%), the United States (13.9%), the EU28 (9.1%), India (6.9%), Russia (4.6%) and Japan (3.2%)- the world's largest CO_2 emitters - together accounted for 51% of the population, 80% of total fossil fuel consumption and 67.5% of total fossil CO_2 emissions in the World (Crippa et al.2019, 246). In recent years, China has been denounced as the main polluter but also the main force for mitigating carbon emissions and energy consumption worldwide (Liu et al.2013, 143-145). Additionally, China was recognized as the largest consumer of primary energy, consuming approximately half of the coal in the world in 2012 (Liu et al.2013, 143-145), and 46.7% in 2018 (according to the BP Energy year book).

A significant increase in carbon emissions by countries with strong economies has substantially affected the climate (Jakob and Marschinski 2013, 19-23), but CO_2 emissions within the EU28 have decreased in the last decades (Crippa et al. 2019, 246), with EU28 emissions 21.6% lower in 2018 than in 1990.China's per capita carbon dioxide emissions are now higher than those of the EU, although historically the situation was reversed. The European Union and Russia are the only industrialized economies (among the major emitting regions) whose GHG emissions are significantly below 1990 levels, while the United States and Japan increased both their CO_2 and GHG emissions by 4-5% compared to 1990 levels, and the emerging economies of China and

India have respectively 3.7 and 3.4 times more CO_2 emissions in 2018 compared to 1990, due to their rapid industrialization in the past two decades (Crippa et al.2019, 246).

Friedlingstein et al. (2014, 709-715) claimed that the efforts, asked by the Intergovernmental Panel on Climate Change (IPCC) to limit climate change below a fixed temperature threshold, required a quota limit for the most polluting countries in the world. Indeed, according to the Kyoto Protocol, global CO_2 emissions fluctuated from 22.7 to 33.9 billion tons from 1990 to 2011 (Schiermeier 2012, 656-658). Liu et al. (2013, 304-305) believed that the substantial carbon emissions margin between the most polluting and least polluting countries in the world could be related to the indifference existing in international climate negotiations.

Nevertheless, efforts to reduce the carbon rate have been observed by the most polluting countries. Advanced economies (including Australia, Canada, Chile, the European Union, Iceland, Israel, Japan, Korea, Mexico, Norway, New Zealand, Switzerland, Turkey, and the United States) saw their emissions decline by 3.2% in 2019, with the power sector responsible for 85% of this drop, thanks to the development of renewable energy sources (mainly wind and solar PV). The European Union climate mitigation policies aim at cutting greenhouse gas (GHG) emissions by at least 40% by 2030 compared to the 1990 levels in order to meet the EU's nationally determined contribution to the Paris Agreement. One strategy in China aimed at increasing energy efficiency in the building sector, as well as in various manufacturing processes (Liu et al.2015, 279-281). The major objective China had set was to reduce the carbon intensity of its economic production by up to 45% from 2005 to 2020 (Guan et al.2014, 1017-1023). However, statistical data, published by each country with respect to energy demand and the rate of carbon emitted, have proven erroneous at times. For example, Liu et al. (2015, 335–338) found that the energy consumption of China between 2000 and 2012 was actually 10% higher than the value published for the same timeframe by national statistics.

Another important environmental criterion to watch is population growth. World average CO_2 emissions per capita were 4.8 tons of fossil fuel carbon dioxide per person, in 2018. This number was considerably higher in Australia (16.9 tons per person), the United States (16.6), China (7.0), and the EU (6.7), while India produced only 2 tons of fossil fuel CO_2 emissions per capita but was the country with the highest growth in CO_2 emissions per year (+7.2%). There are therefore two types of drastic changes to be applied to reduce polluting emissions in the world: it is necessary to reduce the GHG emissions per person in the most polluting countries, but it is also essential to reduce the current strong growth of the world population. Note that the least developed countries, where life is the most precarious (due to malnutrition, lack of clean water, overcrowding, inadequate housing, lack of health care, etc.), participate the most in current population growth, especially in Africa, the Middle East, and Southeast Asia. According to the International Energy Outlook (U.S. EIA 2010, 328), the most rapid growth in energy demand from 2007 to 2035 will occur in nations outside the Organization for Economic Cooperation and Development (OECD). World energy consumption will increase by 49% in 2035 compared to 2007, while total energy demand in non-OECD countries will increase by 84%, as opposed to only 14% in OECD countries.

Carbon emissions vary according to the sources of energy production. Global warming has attracted great attention this decade because of its very significant impact on the environment and occupants' behaviour. Indeed, the various catastrophes that have occurred in many countries have typically been considered as indirect consequences of human actions on nature. In 2019, the International Energy Agency (IEA) assessed the impact of fossil fuel use on global temperature increases (IEA, 2019, 1-2). It found that CO_2 emitted from coal combustion was responsible for over 0.3°C of the 1°C increase in global average annual surface temperatures above pre-industrial levels. This makes coal the single largest source of global temperature increase.

43.75% of the world total CO_2 emissions is produced by the power industry, due to electricity and heat generation. But if electricity and heat generation are reallocated to the sectors that use them, 38.84% of the world total CO_2 emissions are generated by other industries, 28.31% in buildings, 27.4% for transportation, and only 5.81% are related to other sectors. All these sectors generated an overall increase in the world global CO_2 production between 1990 and 2018. However, only the transport sector increased (+ 21%) in the EU28 during the same period, while the EU28 managed to reduce its CO_2 emissions in all other sectors (-20 to -40%) from 1990 to 2018 (Crippa et al. 2019, 246). Thus, strategies to reduce CO_2 emissions of a country, while continuing its economic growth, do exist.

Primary energy demand and CO_2 emissions are two interrelated environmental impacts. According to the IPCC (IPCC 2014, 1419), the global energy consumption of buildings corresponds to 8,800 megatons of the total CO_2 emissions worldwide. Energy awareness is an effective strategy aimed at encouraging the integration of energy efficiency in the building, transportation and industry sectors. Carbon dioxide emissions attributed to buildings, transportation, and industries can be considerably reduced by the judicious application of techniques requested in this book. For example, increasing the use of renewable energy sources would participate in the protection of the planet and reduce CO_2 emissions from all the sectors.

The main objective of this manual is to show architects, engineers, urban planners, investors, politicians, and even non-specialists in energy and the environment, a simple methodology, allowing to design and build new zero energy and low carbon cities, as well as to promote the transition of already urbanized territories towards zero energy and low carbon objectives. This guide to zero energy and low carbon cities is tackled by combining the literature review and practical case studies from different continents. It is presented on three complementary parts seeking mastery and knowledge from several fields: energy, sustainable architecture, urban planning, and the environment. To facilitate understanding of the content of this work, we have presented the detailed structure of the book in the table of contents. Indeed, this table contains all the titles of the three parts, each consisting of three chapters, and all subtitles, in order to help the reader to freely select the different parts of the manual which interest him more particularly. Note that the references of the literature are detailed at the end of each chapter.

The first part of this book presents the main sectors responsible for energy consumption and CO_2 emissions in cities, which are the building and transport sectors. The first chapter presents application strategies of zero energy in the building sector; the second chapter describes how to reduce carbon emissions in the building sector; and the third chapter presents strategies to apply zero energy and low carbon objectives in the transportation sector.

The second part of this manual focuses on the other most polluting sector: industry, as well as on 20 summary questions about zero energy and low carbon in future cities. The fourth chapter addresses the strategies of sustainable power generation, and the fifth chapter presents strategies to reduce carbon emissions due to waste treatment, while the sixth chapter offers 20 summary questions and answers related to the topics covered in the five previous chapters.

The last part of this book, which also consists of three chapters, describes some applications of the concepts zero energy and low carbon at the building scale (chapter 7), and the district scale (chapters 8 & 9). These case studies make it possible to highlight different strategies both to increase the transition of existing cities towards the zero-energy objective (chapter 8) but also to design new cities that will emit less carbon (chapter 9). These examples, located in several continents, will also allow us to address some issues related to other environmental impacts (preservation of biodiversity, human health, water consumption, etc.).

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Part 1: Analysis of the main sectors responsible for CO_2 emissions and energy consumption in cities

Chapter 1: Strategies to reach zero energy target in buildings

Chapter 2: Strategies to reach low carbon target in buildings

Chapter 3: Strategies to reach zero energy and low carbon targets in transportation sector

Chapter 1: Strategies to reach zero energy target in buildings

The Pajol hall, a 1920s railway warehouse,rehabilitated by "Jourda Architectes" into a huge positive energy building, in Paris (France)

1.1 Zero-energy buildings

Population growth has increased the demand for energy in buildings in various climates; as a result, the building sector is becoming one of the most energy-intensive sectors and a huge carbon emitter (EU 2010, 13-35; Nematchoua et al. 2019, 24). This situation is multiplying tensions globally (Beccali et al. 2013, 283-293). According to the European Commission, today, the built environment accounts for more than 40% of the overall energy consumption and 36% of the overall CO_2 emissions in Europe. The energy efficiency and low carbon emission of both new and existing constructions are a crucial issue in winning the fight against global warming. A **zero-energy building (ZEB)**, also known as a net zero-energy building (net ZEB), is a building that consumes only as much as it can produce locally, on an annual basis, through renewable energy resources.

Experts proposed the concept of zero-energy building for improving energy efficiency of the building sector, while reducing non-renewable energy demand in buildings. Over the past few decades, the concept of ZEB has been deeply explored by combining energy efficiency strategies and renewable energy sources, in the building sector (US DOE 2008, 1-6; Marszalet al. 2011, 971-979; Voss and Musall 2012, 192; Ayman et al. 2014, 385-399). Zero-Energy Building is a building with zero net energy consumption, which means that the total amount of non-renewable energy used, calculated on an annual basis, is approximately equal to the amount of renewable energy created on the site. This concept is very interesting, but difficult to carry out in the field, especially in the case of cold climates and tall buildings.

While zero-energy building seem like a concept of the future, new technologies are constantly emerging that make them possible to achieve today. High-performance buildings prove that it is possible to reduce energy consumption, while providing good comfort (Chlelae et al. 2009, 982-990; Kalz et al. 2010, 632-646). In practice, several examples have recently been built that prove the feasibility of zero-energy buildings. To achieve zero-energy buildings, architects and engineers need to design buildings with passive strategies (thermal insulation, solar shading devices, etc.). They have also to increase the building energy efficiency and to offset residual energy demand for heating and cooling by renewable energy produced on site.

The technologies most often used in the design of zero energy buildings are:
- Compact buildings, well oriented to the sun,
- Thermally insulated thick walls with air sealing,
-Double glazing with high thermal performance or triple glazing, limiting energy losses,
- Solar shading solutions, high inertia materials for interior wall surfaces, and intensive night ventilation to naturally cool the building,
- A building ventilation system, which is efficient both for the air quality and for reducing energy consumption,
- A high performance heating system associated with a smart thermostat system,
- The use of photovoltaic solar panels for electricity production.

The concept of zero-energy is becoming more and more popular as the production costs of alternative energy technologies decrease, while the costs of traditional fossil fuels increase (Voss and Musall 2012, 192). However, there are several challenges that must be overcome globally, not only by using new techniques but also by a suitable building design. For example, cultural, economic and social issues of architecture and their various environmental impacts (loss of biodiversity, eutrophication, etc.) should also participate in the design and the choice of technologies used in buildings. Note that photovoltaic systems, for example, are still expensive for developing countries. In addition, the concept of net zero-energy building is not easily applied to multi-storey buildings.

It is recommended but not mandatory that a zero-energy building meets the basic requirements of the **Passive Building label** (PMP 2020, 1), related to thermal loads, total primary energy consumption, building airtightness and management of the overheating risks. Table 1.1 presents the 4 current levels of the Passive Building label (from 2020): passive classic, passive plus, passive premium and passive renovation (PMP 2020, 1).

The passive PLUS label, reducing the maximal primary energy consumption but also requiring compensation by self-production of renewable energy, is therefore an interesting interpretation of the zero-energy objective but which, in this case, imposes high-performance criteria in terms of quality of the building envelope, in addition to renewable energy production. To be passive certified, a tertiary building must meet at least the criteria of the PLUS label, which should therefore contribute to the production of more zero-energy buildings in the tertiary sector. A passive PREMIUM label, which requires even higher building energy performance and renewable energy production, aims to generate "positive" energy buildings, producing more renewable energy than what the building consumes. Finally, a passive RENOVATION label was created to relax the passive label rules developed for new buildings in the case of building renovations.

Table 1.1: Criteria for passive buildings (PMP 2020, 1)

Labels	Heating thermal loads (kWh/m^2.year) and cooling thermal loads (kWh/m^2.year), based on total actual built m^2	Air tightness (volume / hour)	Annual overheating hours (≥ 25˚C)	Total primary energy consumption (kWh/m^2.year, based on total actual built m^2)	Minimum total renewable primary energy production (kWh/m^2.year, based on built m^2 of the building footprint)
Passive classic building	≤ 15	≤ 0.6	≤ 5%	≤ 60	/
Passive plus building	≤ 15	≤ 0.6	≤ 5%	≤ 45	60
Passive premium building	≤ 15	≤ 0.6	≤ 5%	≤ 30	120
Passive renovation building	≤ 25	≤ 1	≤ 5%	≤ 80	/

It is interesting to note that a zero-energy building does not necessarily meet the criteria for a passive building, if it produces enough energy onsite to cover annually its energy consumption. The principle of the zero energy building, therefore, differs from passive buildings principle, since it consists in compensating for total consumption, whatever it is, and not in optimizing the conditions favouring the energy sobriety of the building. Conversely, the passive plus label solves the problem of applying zero-energy buildings for multi-storey buildings and in dense urban areas. Indeed, in this label, the assessment of building primary energy consumption is carried out on total built m², while the minimum necessary energy production is calculated according to the built m² of the building footprint, which is better suited for sizing potential solar renewable energy. Thus, for a three levels building (ground floor and two additional floors), the total surface area corresponds to 3 times the area of the building footprint. The passive plus label thus adapts its renewable energy production requirement to the building footprint and does not require a renewable production which completely compensates for the energy consumed.

We must distinguish two types of zero-energy buildings: a building called **energetically sufficient** and a building called **energetically autonomous**. A zero-energy building is capable of producing, over a year, an amount of energy equivalent to the amount of energy it consumes. However, it will not necessarily consume the energy it needs when it produces it. Example: consider a building for which we install photovoltaic panels. During sunny periods (in summer), the panels will generate electricity at their optimum efficiency, and the house will supply energy to the grid. During the cold period such as in winter, the panels will not always supply enough electricity. However, the total annual balance is zero, since the excess production in summer compensates for the lack in winter. On the other hand, energetically autonomous buildings do not need to be connected to the electrical distribution network. When the panels cannot produce as much electricity as needed, the batteries used to store the excess electricity produced during sunny periods provide the electricity. To achieve energy independence, the building needs also above-average levels of insulation. Although currently zero-energy buildings most often meet the basic definition, it will be essential to develop more energy-autonomous buildings in the future to achieve zero-energy cities.

Going even further, the concept of zero-energy can be applied to entire urban blocks, neighbourhoods or cities. Linking transportation and building energy consumption with local renewable energy production, Marique and Reiter proposed a framework to assess the feasibility of **zero-energy at the community scale** (Marique and Reiter 2014, 114-122). This study considers calculation of the zero-energy concept according to annual energy consumption due to buildings and daily mobility (transportation), as well as annual production of local renewable energy. The zero-energy community goal can even be achieved in existing urban environments through major retrofitting works and sustainable transport policies (Nematchoua et al.2021, 1-11).To enable and facilitate the implementation of such schemes, a myriad of parameters need to be taken into account, assessed, and coordinated (Marique et al.2017, 418-428).

The concepts of zero-energy and zero-carbon have evolved over the last few years in countries that adopted an integrated energy policy. The precise definitions of net zero-energy building (net

ZEB) and net zero-carbon building (net ZCB) to be implemented at a territorial scale vary according to the political ambitions and specific conditions of a country. In 2002, in Europe, a directive to evaluate the energy performance of buildings (EPB) was established by the European Commission. In addition, in its new strategy towards sustainable development, the European Union (EU) has suggested that 100% of all new constructions and deep renovations must be buildings consuming almost zero energy from 2021 onwards (EU 2010,13-35). This EPB directive imposes a course of action that all European member states must follow. In other parts of the world, several researchers have agreed to work in collaboration with the U.S. Department of Energy (DOE) for designing zero-energy buildings by 2025 (US DOE 2008, 1-6). Therefore, in many countries, buildings design, urban development and energy policies are oriented towards a better energy efficiency of the building stock (Beccali et al. 2013, 283-293). Today, this concept remains a major concern for leadership worldwide.

Several researchers have proposed various techniques to implement the concept of net zero-energy buildings. **This chapter presents a design strategy for zero-energy buildings,** based on three steps, including the choice of location and the design of building with passive strategies, then the design of energy-efficient heating, cooling, ventilation and lighting systems, and finally the addition of renewable energy production systems. These three types of solutions, which have to be combined to reach the zero-energy level, are developed below. Moreover, this chapter summarizes the most common passive strategies and used technologies in zero-energy buildings.

1.2 Building design with passive strategies

To reduce the energy consumption of a building, a variety of passive and active design strategies can be incorporated. Passive design measures consist in strategies aiming to reduce the size or even to remove the need for energy systems (heating, cooling, ventilation and lighting) in buildings. Active strategies use various energy-efficient systems, such as heat pumps, ceiling fans, heat recovery ventilation, or presence detectors, to improve heating, cooling, ventilation and lighting systems. Passive strategies are designed to reduce the building's energy consumption and its environmental footprint, while ensuring the comfort of the occupants. Passive strategies depend a lot on the way the building is designed. Finding the right combination of active and passive strategies to incorporate into a project comes down to balancing the budget, program and the specificities of the site and microclimate (Marro 2018, 1). However, passive strategies should be used as a priority, because they are the most environmental strategies and they allow creating more resilient and adaptable buildings (Nguyen and Reiter 2017, 16-29).

To achieve the target to design comfortable but vey energy-efficient buildings, passive strategies take advantage of natural energy opportunities, based on local microclimate, location of the building, built density, building typology, bioclimatic design and properties of building materials. Passive strategies formed the basis of the concept of bioclimatic architecture (Liébard and De Herde 2005, 368), developed at the end of the 20th century, by combining the qualities of vernacular architecture, ideally integrated into its environment, and the properties of modern construction materials and techniques. Bioclimatic design includes design strategies related to the building orientation, air sealing, continuous insulation, daylighting, sun protections for windows, thermal mass, and natural cooling strategies. These various passive strategies, and how they can be used to reduce buildings energy consumption, are described below.

1.2.1 Local climate and microclimate

The Earth has 5 major types of climates, classified according to their temperature and humidity: tropical climate, dry climate, warm temperate climate, cold temperate climate and cold climate (Liébard and De Herde 2005, 10). Five climatic parameters must be given a special attention when designing a building: outdoor temperature, direct and diffuse solar radiation, humidity, and winds. A bioclimatic diagram can be used to optimise bioclimatic architectural design: it is an analytical tool to better define the strategies to be adopted in the design of the building, based on local climate and the hygro-thermal comfort of its occupants (Nguyen and Reiter 2014, 756-763).

Topography, and more particularly the altitude, and urbanisation are two parameters which influence mainly the microclimatic outdoor temperature. Each elevation of the terrain of 100 meters is accompanied on average by a proportional decrease in temperatures of 1° C.Temperatures can also vary depending on the immediate environment of the site and in particular the urban density. Urban areas create urban heat islands in city centres, with higher outdoor temperature than in the nearby countryside. The heat island is due both to the increase in the radiative balance of cities in relation to their environment and to the production of heat due to human activities. On average, the urban heat island is + 0.5 ° C to + 3 ° C in cities around the world compared to open peri-urban areas. In general, the urban heat island is perceived negatively because it increases the risk of overheating in buildings, but in cold climates it reduces their heating energy consumption. The heat island effect depends mainly on the climate, the city morphology, the number of inhabitants, the energy efficiency of buildings and the construction materials used. Albedo effect and building characteristics (especially composition of unbuilt ground and buildings roofs, and their more or less reflective properties) also play a role in the urban heat island: to reduce it, light colours and green surfaces must be favoured.

Buildings constitute fixed screens for their neighbourhoods. Their role can be positive if a sun protection is needed: this is the case of traditional Mediterranean cities and villages, where the narrowness of the street and the height of the buildings considerably reduce the direct radiation and provide a welcome shade. On the other hand, this role can be negative when the neighbouring buildings hide the sun and prevent taking advantage of direct solar radiation as a source of renewable energy.

Relative humidity influences the internal comfort of a building and the use of air conditioning systems. In humid climates, it is especially needed to favor good ventilation systems.

Winds can have an impact on buildings energy consumption: for poorly insulated and not enough airtight buildings, winds generate important heat losses. But for buildings with high insulation level and a good airtightness, wind influence is mainly related to its impact on buildings ventilation and wind energy production. Wind also has an influence on the comfort of pedestrians in public spaces: tall buildings often generate discomfort zones due to wind gusts, at the foot and at the corners of these buildings (Reiter 2010, 857-873).

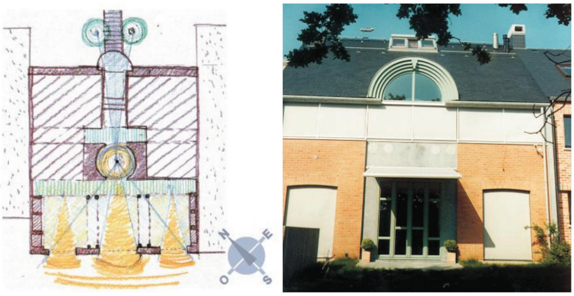

Figure 1.1: The PLEIADE house, designed by the architect P. Jaspard according to the principles of bioclimatic architecture (Reiter and De Herde 2004, 265).

A contemporary example of the judicious use of the local microclimate in the design of a building is given by the strategies of bioclimatic architecture, which make it possible to take advantage of the resources of the local climate (solar gains, natural ventilation, etc.) and to protect buildings from its constraints (building insulation, solar protection, etc.) (Liébard and De Herde 2005, 368). Figure 1.1 presents the PLEIADE house (Passive Low Energy Innovative Architectural Design), located in Louvain-la-Neuve in Belgium (Europe). It is an excellent example of application of the principles of bioclimatic architecture: large windows oriented to the south, outdoor sun protections, good levels of envelop insulation and airtightness, opening in the roof to promote natural cooling, efficient energy systems, etc.

1.2.2 Built density and building typology

Urban heat island and building shading, caused by neighbouring buildings, increase with greater built density, which has an influence on the energy consumption of buildings depending on the local climate. But the most influential urban density indicator on energy consumption is the dwelling service level (m²/cap) (Resch et al.2016, 800-814), which is generally lower in denser urban areas. Compact urban form is identified by the IPCC as an important climate change mitigation measure (IPCC 2014, 151), attributed to lower per capita energy use and a reduction in transportation energy. There is, however, a much greater energy benefit, in dense urban areas, per capita than per m², which suggests that the floor area per capita is an important determining factor (Larivière and Lafrance1999,53-66; Resch et al. 2016, 800-814). From the energy point of view, it is thus essential to design well-sized buildings in relation to their actual occupational needs.

Trigaux et al. (2017,516-523) studied the impact of urban morphology on housing units heating energy consumption using identical housing units of 100 m² which are clustered in different ways. For each model the Floor Space index (FSI), defined as the ratio of the total building floor area to the land area, is calculated, which gives FSI= 0.2 for detached bungalows, FSI= 0.9 for a medium built density (urban building blocks of two floors, surrounding courtyards of 50 m by 20 m), and FSI = 2.25 for dense urban blocks with five floors. This theoretical research shows a potential reduction of up to about 40% in average heating energy demand for the urban building block model with the highest built density, compared to the lowest built density model with detached bungalows. But the increased built density of the five floors urban block only results in a limited decrease of the average heating energy demand because of the reduced availability of solar radiation in this block. Marique and Reiter (2014, 114-122) found a difference of 25% in heating energy consumption between poorly insulated urban blocks made of terraced houses and detached houses (with two floors). In any case, to reduce buildings heating energy consumption, the envelope insulation is the most important parameter. These results are in line with conclusions of other studies (Ratti et al.2005, 762-776; Salat 2009, 598-609; Rode et al.2014, 138-162).

However, it should be noted that heating or cooling consumption only forms a minority part (around 35-40%) of the total energy consumption of thermally efficient residential buildings. For recent buildings and neighbourhoods, which are well insulated, the reduction in total energy consumption in relation to a more compact urban morphology therefore only corresponds to approximately 9-15%. Conversely, Marique and Reiter (2014, 114-122) showed that the potential for energy production by photovoltaic and thermal solar panels is higher in peri-urban districts than urban areas, thanks to their lower density.

Even for an insulated building, its typology and shape has an impact on its energy consumption. The role of the architect is thus important. Indeed, for an equal area, a compact building will have less contact area with the outside than buildings with scattered forms, so it will lose much less heat. So, in climates and building types where heating consumptions are predominant, the compactness of buildings is very important. Comparing various building shapes, Gelekta and Sedlakova (2018, 46-53) found an overall difference up to 20% of heating energy consumption with different shapes having the same volume and the same heating floor area. The more compact a building is the less heating energy it consumes. The shape of a building has also an impact on the construction costs and implicitly on the energy and maintenance costs.

On the contrary, in climates and building types (such as data centres) where the cooling period is the longest, the most important design parameter is to create shapes that facilitate passive cooling, which requires more facade surfaces, atria, ventilation chimneys, etc. Note that an elongated and narrow building footprint allows the best possible use of daylighting and natural ventilation.

Nowadays, tall buildings are requested in some urban districts. Note that high-rise buildings generally consume much more energy per built square meter (m²) than low-rise multi-storey buildings, due to the height constraints (such as wind) and the energy needed to circulate in the building (for example caused by elevators). Designing green skyscrapers is a potential way to a more sustainable urban development. With a height of 88 meters, Bolueta in the Spanish city of Bilbao is now the tallest Passive House building in the world, followed by the Passive House students' residence (86 m) at Cornell Tech in Manhattan (New York) which opened to residents in 2017.

1.2.3 Building orientation

Orientating a building to take advantage of the sun movements is one of the passive design strategies most often used in vernacular and bioclimatic architecture. Building energy consumption is dependent on its orientation and the percentage of glazing in external walls. In particular, the optimum percentage of glazing area depends on the local climate, its orientation and the type of glazing installed. Solar radiation passing through the windows provides free heat to the building during the heating season but it has to be limited during the hot season to reduce the building cooling needs. So, all the building design has to be adapted to the chosen building orientation and its passive opportunities. For example, overhangs on the south façade should be sized so that the sun can enter the building during the cold period, when the sun is lowest in the sky, while being blocked during the hot period, when the sun is higher in the sky (Reiter and De Herde 2004,265).

An ideal orientation of buildings makes it possible to greatly reduce energy consumption of poorly insulated buildings. For very efficient buildings, such as passive houses, influence of orientation on the heating consumption of buildings is only 10 to 15%, and it is even smaller on the total consumption of houses, including electricity and hot water. Buildings designed for the best energy-efficiency are facing south and north, to allow better solar energy management (Reiter and De Herde 2004, 265; Nematchoua et al.2015, 1192-1202; Nematchoua et al. 2019, 24). It is typically better for the longest façades to face north and south, so that a building can take advantage of indirect sunlight from the north and control direct solar heat gain from the south (Watis et al. 2015, 754-762). Direct solar heat gain from east and west-facing windows can be minimized with exterior shading devices (for example through egg-shading devices), but it is easier to control direct solar heat gain from south-facing windows. Exterior horizontal shading elements on the south façade are ideal to protect the building from direct solar heat gain during the summer months, while allowing the building to take advantage of direct solar heat gain in the winter months (Wati et al.2015, 754-762). The shape and orientation of the roof will also impact building energy consumption and on-site potential for renewable solar energy production. Roofs should be oriented so that more solar radiation can be captured using solar panels.

In countries where the energy consumption of buildings is mainly linked to heating, the south is preferred for residential living spaces, while the north orientation is optimal for less heated spaces. In climates where the majority of consumption is linked to cooling loads, the north façade is the best. Since tertiary buildings produce more internal heat than residential buildings, their best orientation is therefore north, even in temperate or cold climates. This is the reason why the BedZED neighbourhood (Beddington zero energy development), located in the London Borough of Sutton (UK), combines dwellings facing south and office spaces facing north (see figure 1.2).

Figure 1.2: In BedZED neighbourhood, residential functions are oriented to the south, while the north facing parts of buildings are dedicated to tertiary functions.

1.2.4 Thermal qualities of building materials

The knowledge of all the materials is complex, but the choice of building materials should not be a matter of chance. It must simply result from taking into account the characteristics which must be evaluated and preferably certified, in order to check whether the materials selected are able to fulfil the role assigned to them or not. To be able to judge their real usefulness from a thermal point of view, there is no other solution than to know their physical characteristics, which mainly influence the quality of insulation, but also inertia by transmission and by absorption (PassivAct2020, 1):

- The ability of a material to conduct heat, its conductivity, is characterized by the coefficient of conductivity **λ** (Lambda). Measured in the laboratory, it must be certified by independent organizations. It is expressed in (W/m.K);

- The diffusivity and effusiveness of materials are almost never known. They result from simple calculations requiring knowledge of the characteristics of density ρ and of specific heat **C** of the materials;

-The diffusivity **D** of a material, its speed of heat transmission, expresses its capacity to slow down the heat transfer and results from the calculation, $D = \lambda/(\rho C)$ expressed in (m^2/s);

- The effusiveness **E** of a material, its capacity to regulate the interior atmosphere, presents its ability to play a role of thermal sponge and is defined by the formulas $E = \sqrt{(\lambda \rho C)} = \rho C \sqrt{D}$, which give an expressed result in ($J/m^2.K.s^{1/2}$).

Thermal inertia of a building is its capacity to store and release heat. In winter, the storage capacity of solar energy and its gradual return makes it possible to make the best use of solar gains and to facilitate regulation of the heating system. In summer, coupled with ventilation that allows thermal discharge of the accumulated heat, high inertia improves summer comfort and limits overheating. To maximize building inertia, materials with high effusiveness and low diffusivity are the most interesting.

Knowledge of the thermal qualities of a material can only result of the comparison of these characteristics of conductivity λ, diffusivity D and effusiveness E with those of materials already known for their effectiveness in one of these particular fields. The most effective materials are polyurethane for its conductivity, wood fiber for its thermal inertia by transmission and concrete for its thermal inertia by absorption.

Table 1.2: Thermal characteristics of building materials (PassivAct 2020, 2)

Number	***Material***	***Conductivity (W/mK)***	***Density (Kg/m^3)***	***specific heat J/Kg.K***	***Diffusivity (m^2/S).10^8***	***Effusiveness (J/m^2.K.S$^{1/2}$)***
1	Polyurethane	0.022	34	1400	63	38
2	Wood fiber Steico Therm	0.04	160	2100	12	116
3	Polystyrene extruded	0.04	34	1450	81	44
4	Glass wool	0.04	25	1700	94	41
5	Polystyrene expanded	0.04	26	1450	106	39
6	Rockwool	0.044	100	1030	43	67
7	Cork	0.05	120	1560	27	97
8	Aerated concrete	0.09	350	1000	26	177
9	wood wool	0.1	400	1700	15	261
10	OSB panel	0.12	600	1150	17	288
11	Fir wood	0.15	500	1600	19	346
12	Plasterboard	0.25	825	1000	30	454
13	Plaster tile	0.25	820	1000	30	453
14	Oak wood	0.29	870	1600	21	635
15	Solid brick	0.74	1800	1000	41	1154
16	Stone	1.7	2000	1000	85	1844
17	Full concrete	1.8	2300	1000	78	2035
18	Steel	50	7800	450	1425	13248
19	Aluminum	230	2700	880	9680	23377
20	Copper	380	8900	380	11236	35849

Table 1.2 gives some materials and their thermal characteristics. Note that a material is considered as an insulating material if its conductivity is less than 0.065W/mK. Conventional insulators have conductivities of the order of 0.04W/mK. The best insulating materials have conductivity of the order of 0.022W/mK. Wood fiber is one of the least diffusive materials and one of the materials with the highest inertia efficiency by transmission. Concrete is one of the most effusive materials, with a diffusivity that remains not too high. Concrete is also one of the materials with the highest inertia efficiency by absorption.

The conductivity of materials is the only characteristic, among the three taken into account in this chapter, which makes it possible to guarantee the limitation of the energy needs throughout the year, whatever the season, at night and during the day. Thermal insulation protects all year round and reduces energy consumption related to heating as well as cooling. Diffusivity and effusiveness of materials are thermal characteristics that should never replace the quality of the envelope's insulation. Their influences on buildings energy consumption are very weak during the heating season, but can help reduce summer indoor temperatures and thus cooling loads. Inertia by absorption and inertia by transmission are mostly of interest in summer, when they are coupled with intensive night ventilation (natural or artificial). Inertia by absorption is the more effective of the two types of inertia to reduce overheating of buildings. Inertia by absorption, provided for example by concrete, allows in many situations to ensure thermal comfort in the buildings during the cooling season, without air conditioning (PassivAct 2020, 1).

An ideal envelope: insulation, airtightness, and thermal inertia

A facade wall is a wall that separates the comfortable interior atmosphere from the exterior atmosphere, which is only rarely so. To be ideal thermally, it must participate in indoor comfort in all seasons. This last factor is crucial. Comfort cannot be guaranteed in the same way during cold seasons and hot seasons. The daily variations in temperature can be very different between seasons in the same climate as well as between various climate types. In addition, the ideal solution from a thermal point of view should be combined closely with solutions that are structurally and financially efficient.

To maintain a comfortable and practically constant daily interior temperature during cold days, it is needed to provide walls whose quality of thermal insulation limits heat loss to the quantity of heat which can be produced, on the coldest days, by the building heating system. But to minimize energy consumption, the thickness of thermal insulation required is generally much greater. In addition, the constructive implementation of the building envelope and its resulting air sealing become essential parameters in order to be able to create buildings with high energy performance. Insulation materials should be placed outside of the wall to minimize heat loss. Also, remember to choose energy-efficient windows because these are generally the surfaces that generate the most heat exchanges between outdoors and indoors. Low-emissivity double or triple glazing can solve this problem.

Continuous insulation of building envelopes and good airtightness may generate extremely high reduction of buildings heating consumption, but also significant reduction of their cooling consumption. It is important to know that the quality of insulation of the envelope (related to the coefficient of conductivity of the materials, the insulation thickness and the airtightness) is also very important during hot days, because it reduces the heat transmission from outside to inside. Passive buildings offer excellent examples of energy efficient buildings, suitable for both cold and hot climates. Thermal bridges are defects in the design or realization of the insulating envelope, generating particularly dense heat losses, which result in indoor lower surface temperatures and a risk of condensation of air humidity. Thermal bridges appear mainly through the constructive nodes of the building.

High-performance thermal insulation must always be supplemented by good airtightness of the building and an efficient ventilation system. The attention to be paid to continuous insulation and good airtightness of buildings is the most important in compact and well insulated buildings. Infrared thermography (IRT) is a non-destructive evaluation technique for the building envelope. By visualizing surface temperatures, it is possible to detect construction deficiencies (e.g. thermal bridges, incomplete insulation of cavity walls, etc.) in a fast way in-situ (see figure 1.3). The blower door testallows the quality of the airtightness of building envelope to be checked.

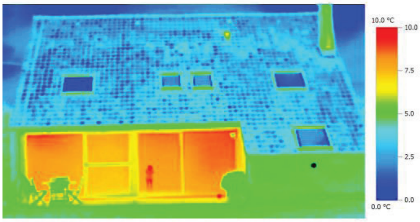

Figure 1.3: Infrared thermography showing the high conductivity of glazing as well as a thermal bridge where the chimney meets the roof (Barbason 2015, 159)

However, during hot days, the building must not only be well insulated but he also should have **solar protections** that prevent direct solar radiation from entering the insulated building. In the conditions where cooling consumption is the majority, interior surfaces with high **thermal inertia** and the possibility to benefit from a **natural cooling** are needed to avoid installation of air conditioning, resulting in a reduction of cooling energy consumption. Thermal inertia alone is not enough to reduce overheating, but it works well in combination with sun protection and natural cooling.

The thermal inertia of materials in contact with indoor air is especially useful when a building can use a natural cooling system (for example, intensive night ventilation) or an intermittent artificial cooling system. The time lag provided by thermal inertia then makes it possible to reduce the building's cooling needs. During hot days, the daily outdoor temperature differences can be very large, much larger than during cold periods. The incidence of direct sunlight on buildings envelope can cause increases in surface temperature which can exceed 70 °C. This is for example the case of tiles in Madagascar, which can reach and exceed 85 °C in full sun while their temperature can drop below 15 °C during cloudless nights. Even if building compactness, efficient sunshades, insulation materials, and a good nocturnal ventilation system reduce the daytime hot air intakes, the risk of overheating remains high when the thermal inertia of materials in contact with indoor air is too low. Understanding thermal inertia is essential to ensure summer comfort and the stabilization of day and night temperatures. A high inertia by absorption (for example with concrete surfaces) for the interior surfaces (ceiling, floor or walls) and/or a high inertia by transmission (for example thanks to wood fiber) of overheated roof and walls exposed to the sun are needed.

All exterior walls of a building should always be optimised on the basis of thermal characteristics of their materials. For each building, this thermal design should concern at least its roof, walls and lowest floor. The exact choice of materials and insulation thickness has to be chosen specifically in relation to local resources and climate. The optimal thickness of building insulation varies depending on the type of building and the type of climate (often between 2 and 40 cm). Recent building optimisation studies exist for different regions of the world and several climates, which could facilitate the choice of these values according to the local context (Nguyen and Reiter 2014,68-81; Nematchoua et al. 2015, 1192-1202).

__Phase change material (PCM)__

We call phase change material (PCM), any material capable of changing physical state in a restricted temperature range. This range is roughly between 10°C and 80°C (Noel et al. 2007, 1-7). In this temperature range, the predominant phase change remains fusion/solidification. These temperatures are naturally accessible and are ubiquitous in everyday life (ambient temperature of a house, the temperature of a human body, domestic hot water, etc.).

Any material, solid, liquid, or gaseous has a capacity to store or transfer energy in the form of heat (Noel et al. 2007, 1-7). There are two types of heat transfer:

-Thermal transfer by sensible heat (CS): in this case, the material in question can yield or store energy by seeing its own temperature varying, without changing state.

- Thermal transfer by latent heat (CL): in this case, the material can store or transfer energy by a simple change of state, while keeping a constant temperature.

The application of phase change materials (PCMs) is an effective method reducing cooling energy and improving occupants' comfort requirements in buildings under different climatic conditions but especially in warm climates, by covering interior walls or ceiling with PCMs (Ahangari et al. 2019,120-129). PCM materials are very useful for buildings with low thermal inertia, such as light frame buildings (wood, etc.) (Noel et al. 2007,1-7). Combination of PCMs with thermal insulation, sun protections, and natural cooling further increases its efficiency.Intensive night ventilation allows heat to be released from the PCM and resets a new phase change cycle.

Figure 1.4: PCM installed on internal faces of a roof and a wall.

Examples and types of phase change materials

There are many types of phase change materials, of very different physicochemical nature from each other. It is their melting-crystallization characteristics that make them interesting for the storage of latent heat. Among these materials, there are three main families. The first family includes mineral (or inorganic) compounds. Among these compounds, only the hydrated salts are of interest for their use as PCM. They come from an alloy of organic salts and water. They have the advantage of having great latent heat and low prices. On the other hand, their main fault concerns their tendency to supercool. The second PCM family includes organic compounds. Their thermal properties (latent heat and thermal conductivity in particular) are less effective than the hydrated salts, but the organic compounds have the advantage of being not or very little affected by super cooling. In particular, for the storage of latent heat, paraffin and fatty acids, which belong to this family, are used. The third PCM family includes eutectics, which is a mixture of pure bodies having a constant melting temperature for a particular value of concentration. It can be inorganic and/or organic. Some PCM application systematic studies and categorisations are given in Table 1.3.

Table 1.3: PCM application systematic studies

Name of PCM	**Melting point (°C)**	**Latent-heat (KJ/Kg)**	**Reference**
Emerest 2325 (butyl stearate + butyl)	17–21	138–140	Osterman et al. 2012, 37–49
Hexadecane	18	236	Koschenz and Lehmann 2004, 567–578
Heptadecane	18	214	Koschenz and Lehmann 2004, 567–578
KF, $4H_2O$	18.5	231	Osterman et al. 2012, 37–49
Butyl stearate	19	140	Liang et al. 2009, 723–729
Paraffin C16–C18	20–22	152	Thambidurai et al. 2015, 74–88
Paraffin RT20	20–22	172	Butala and Stritih 2009, 354–359
Paraffin FMC	20–23	130	Kamali 2014, 131–136
Dimethyl sebacate	21	120–135	Thambidurai et al. 2015, 74–88
Eutectic E21	21	150	Butala and Stritih 2009, 354–359
Capric-lauric 45/55	21	143	Hawes et al. 1993, 77–86
Salt hydrates Na_2SO_4,$10H_2O$	21	198	Kamali 2014, 131–136
ClimSel C 21	21	122	Butala and Stritih 2009, 354–359
Octadecane	22	244	Koschenz and Lehmann 2004, 567–578
Capric-palmitate 75.2/24.8	22.1	153	Kauranen et al. 1991, 275–278
Paraffin RT25	24	164	Kamali 2014, 131–136
$CaCl_2 \cdot 6H_2O$	24–29	192	Tyagi and Buddhi 2008, 891–899
$Zn(NO_3)_2$_$6H_2O$	25	130	Thambidurai et al. 2015, 74–88
$MgCl_2$_$6H_2O$	25	127	Thambidurai et al. 2015, 74–88
$Mn(NO_3)_2$,$6H_2O$	25.8	125.9	Futane et al.2011, 4556–4563
Paraffin R27	26–26	179	Thambidurai et al. 2015, 74–88
SP27	27	180	Kamali 2014, 131–136

1.2.5 Daylighting and solar protections

Designing a building that provides good daylighting will reduce lighting energy consumption. Moreover, daylighting design improves visual comfort in buildings, thanks to well-sized windows, pleasant views, and glare protection. Daylight is also manly related to thermal comfort through correct sizing of external solar shading solutions. All living spaces and all rooms used frequently during the day should benefit from daylighting. The climate in which a building is located may dictate the type of windows needed. Building orientation and exterior shading options are important considerations when locating windows and sizing glazing surfaces. It's also important to understand the impact of natural light, heat gain and glare on building systems design. By coordinating orientation of windows and daylight harvesting with efficient shading devices, building designers can downsize the building lighting and HVAC systems (Reiter and De Herde 2004, 265)

Daylight penetrates into a room until a depth approximately equal to twice the height of the lintel. To ensure sufficient daylighting in a room, it is necessary to provide glazed windows equivalent to at least 12-20% of the floor area of this room or skylights equivalent to at least 5-8% of its footprint (Reiter and De Herde 2004, 265). However, large glazing surfaces and skylights, without external shading devices, generate a significant risk in terms of overheating. It is more difficult to control direct solar heat gain and glare generated by skylights than windows on building facades. However, skylights may help to maximize daylighting in a building. Their orientation to the north and their use to illuminate an atrium are interesting skylight uses. Typically north-facing glazing is best for quality daylighting, for example needed for painting, sewing, or other high visual acuity actions. It may also be useful taking into account advanced window systems and technologies, including cutting-edge glazing and coatings that are available today.

Overhangs, external sun protections, awnings, exterior shades, and deciduous trees can help keep summer sun outdoors (Reiter and De Herde, 2004, 265; Nematchoua et al. 2019, 24). The main indicator of the effectiveness of sun protection is the sun factor; it represents the fraction of the incident energy that actually passes through the sun protection and the glazing. A solar factor of less than 0.45 is adapted if the windows are openable (with a possibility of intensive ventilation), while a solar factor of less than 0.25 is necessary if the windows are not openable. Interior sunscreens are useful in reducing glare, but their effect does not reduce overheating.

1.2.6 Natural cooling

Natural cooling of a building uses an intensive ventilation of this building to cool it naturally. The most effective natural cooling is based on intensive night ventilation, which takes advantage of the coolness of the night through intensive night ventilation. The conditions for natural cooling with high efficiency are:

- Outside temperature is lower than inside temperature.
- Daytime thermal loads (solar gains and internal gains) are reduced. The feasibility limit for natural cooling only corresponds to internal loads of maximum 40 W/m². External solar protection is therefore essential for all windows, except for those facing directions between north-west and north-east.
- Access to thermal mass (materials with good internal thermal inertia, such as concrete floor or walls).
- Intensive ventilation is provided thanks to high ventilation rates (8 to 10 volumes/hour).
- Free air circulation in the building.

The natural cooling of buildings is provided by a combination of wind effects and stack effect. The wind tends to push the air from the windward facade to the leeward facade. Stack effect pushes air from the bottom up. For the comfort of occupants, the maximal air renewal rate accepted for daytime ventilation is 4 volumes per hour, while during the night (if the building is occupied) it is 8 volumes per hour. One-sided ventilation is most effective in windy climates (such as islands); cross-ventilation and stack ventilation are ideal for ensuring good ventilation even when wind conditions are weak and in urban areas (see Figure 1.5).

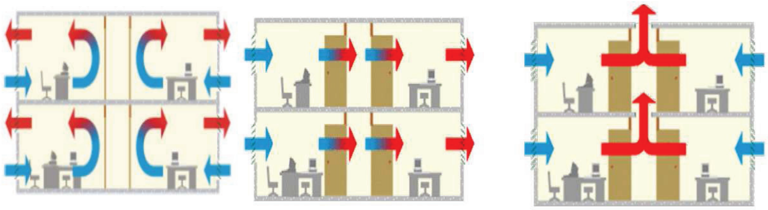

Figure 1.5: One-sided ventilation (left), cross-ventilation (middle) and stack ventilation (right) (Gratia and De Herde2006, 313)

Some building shapes are therefore better suited to natural cooling than others. For example, a building depth shallow enough to be able to create cross ventilation facilitates its natural cooling. One-sided natural ventilation (even between two separate openings on the same façade) rarely exceeds a flow rate of 4 volumes per hour, which can help reduce overheating but is generally not sufficient for a totally natural cooling of buildings. On the other hand, natural cooling based on cross-ventilation and stack ventilation using the chimney effect offer possibilities to reach the required 8 to 10 volumes per hour air flow rate, even during periods when the ambient air speed is low (0.5 m/s or less) (Niachou et al.2005,503-513).

Air inlets for natural cooling should have dimensions significantly larger than those used for hygienic ventilation. Ventilation grids can optionally be installed in existing windows, without disrupting the window opening, allowing them to be installed during the hot season and removed during the cold season. But permanent ventilation grids, with opening and closing mechanisms, are also very useful. Air inlets for natural cooling should cover at least 4% of the room area and always be combined with solar protection and indoor materials with a good thermal inertia. It is necessary to install openable well-sized air-inlets protected from break-ins and insects.

Solar chimneys and ventilation towers can help to significantly increase the natural air flow through buildings, improving natural cooling. Ventilation towers induce significant initial investment costs but they facilitate the removal of an air-conditioning system. Figure 1.6 shows devices participating in natural cooling of existing buildings.

Figure 1.6: Intensive ventilation grid, integrated in an opening window (left), solar chimneys of the BRE building in UK (middle), and ventilation towers of the IVEG building in Belgium (right)

However, two reasons limit the use of buildings natural cooling in cities: outdoor air pollution and high noise levels in urban public spaces. Cooling a building with intensive natural ventilation requires low levels of noise and air pollution. When the levels of air or noise pollution are too high, it is necessary to ventilate the building with a mechanical ventilation system which filters the air. Other environmental solutions such as Canadian wells can then be used for cooling buildings.

1.3 Energy-efficient systems for buildings

Energy efficiency is the ratio of the useful energy produced by a system to the total energy consumed to operate it. It designates also all technologies and practices reducing energy consumption, while maintaining an equivalent or high final performance of the system. The active solutions act on the exploitation, the uses, and the optimisation of energy flows by means of efficient/intelligent systems of energy production, distribution, measurement, control, and regulation (such as high efficiency mechanical and electrical systems, variable speed drives, presence detectors, etc.). Smart management of heating, cooling, ventilation, and lighting systems may reduce their energy consumption. Efficient management requires the installation of tools to monitor consumption. Moreover, it is necessary to ensure maintenance and operation adapted to the complexity of each installation.

1.3.1 Heating system

Energy-efficient heating system is an important strategy to reduce heating energy consumption in buildings, which can be achieved using performant equipment, such as condensing boiler, heating pump, cogeneration system, etc. The condensing boiler consumes up to 30% less energy than a traditional boiler and 6-9% less energy than a high efficiency boiler, thanks to the phenomenon of condensation: the boiler reuses the heat contained in the flue gases to heat the return of the heating circuit. The gas condensing boiler is more energy-efficient than the oil-condensing boiler and the wood-condensing boiler, but it requires access to a gas network. Its additional cost is reimbursed in less than 3 years thanks to energy savings generated.

Heat pumps use the heat present in the environment (air, water, ground) with reduced energy consumption: 1 electric kWh to the compressor produces 3 to 4 thermal kWh to the condenser, depending on the operating conditions. Moreover, the electricity used during its operation can be produced by a renewable energy source. Reversible heat pumps can generate both cold and heat. They do not require a chimney. The price of a heat pump is 2 to 3 times higher than the price of a boiler (without taking account potential boreholes). There are several heat pump types:

- Aerothermal heat pumps: the cheapest, easy to adapt to existing buildings, but less attractive from an environmental point of view and often noisy.
- Horizontal geothermal heat pumps: requiring large spaces of unbuilt ground, difficult to install in existing urban areas but interesting for new neighbourhoods.
- Vertical geothermal heat pumps: for large projects because they need boreholes, and generate a risk of overexploitation of the soil (hot/cold balance to be preferred).
- Hydrothermal heat pump: this is the one with the best performance, but it is expensive and requires an available water table or river.
- Heat pump powered by fatal energy. It enables the use of waste heat sources present in the building: heat from a datacenter, humid air from a swimming pool, heat produced by refrigerators, etc.

Cogeneration makes it possible to produce electricity locally and simultaneously recover heat (in the generator exhaust gases, cooling water and lubricating oil). The overall yield is therefore better than producing electricity and heat separately. For example, to obtain 35 kWh of electricity and 50kWh of heat, 1.2 times more fuel is needed in the case of separate production of energy than using cogeneration. High efficiency cogeneration is cogeneration with a primary energy saving of over 10% compared to separate productions. This solution is suitable for buildings that consume at least the equivalent of 100,000 liters of fuel oil or m³ of gas per year. It is an ideal solution for buildings and networks with large and fairly constant heat needs: hospitals, district heating networks, etc. Cogeneration can be powered by gas, bio-fuels or wood.

It is also possible to reduce energy consumption through a better management of the heating system and by making occupants aware of less energy-consuming behaviours (de Meester et al. 2013,313-323). Optimal thermostat management, for example by reducing the heating temperature during hours when the building is unoccupied, is a very useful parameter to reduce building heating consumption. A study in Belgium, under a temperate climate, shows that housing heating consumption may be reduced by 26% thanks to two strategies: a reduction of the heating temperature from 20°C to 18°C or using alternating heating temperatures at 20°C and 16°C depending on the occupancy of the residential building, compared to a constant heating temperature at 20°C (de Meester et al.2013, 313-323). However, the balance between optimal comfort and good energy management is sometimes very tenuous, particularly if people have varied schedules. It is thus quite advantageous to be able to switch on the heating and ventilation systems by remote control. Moreover, the more a building is insulated, the more the lifestyle and occupants' behaviours proportionally influence heating loads.

1.3.2 Ventilation system

The air inside buildings must be constantly renewed; it is important for occupants' comfort and health. That is why, in old buildings, you have to open the windows every day for at least a quarter of an hour even in winter. It is also for this reason that ventilation must be well thought out when designing buildings. An ecological building must be both well insulated and well ventilated. It is not always necessary to use heating and cooling systems in buildings. Indeed, a bioclimatic building does not always need heating and/or cooling devices. It depends from the climate, the city design and the building design. However, a good ventilation system is always needed to help reducing the number of pollutants, bacteria and odor in a building. Indeed, even without heating and cooling systems, a good indoor air quality (IAQ) has to be achieved, as well as the thermal comfort criteria, thanks to building design strategies and a ventilation system.

Humans, when breathing, consume oxygen in the air and emit CO_2. Ventilation renews the air inside a building and thus maintains the oxygen level and evacuates humidity, excess CO_2, and other indoor pollutants, such as formaldehyde and radon. A good ventilation system is therefore essential for the health of occupants. Moreover, when ventilation of a building is insufficient, it generates often condensation and development of molds. As energy-efficient buildings require high airtightness of the walls to reduce their heat transmission, sufficient air exchange rates should especially be brought in these buildings during their use.

Natural ventilation is a method bringing fresh outdoor air into indoor living spaces without mechanically driven device. A good distribution of the fresh air in all the building zones is difficult to ensure with only a natural ventilation system. It is necessary to size this type of system with great care; indeed, it almost always requires a high chimney or a double skin facade, using its chimney effect, to ensure a constant airflow. Natural ventilation does not generate energy consumption for its operation, but the supply of colder or warmer air than the desired comfort temperature can lead to increased heating or cooling consumption. Natural ventilation is therefore very suitable for climates which have low buildings heating and cooling loads, because the outside temperature remains fairly stable, often close to the comfort temperature.

To be sure to provide sufficient air quality, **hybrid ventilation** is an interesting solution. Hybrid ventilation is a mixed system, which combines a natural ventilation system and a mechanical air extraction (through the addition of a fan in the ventilation chimney, for example). This mechanical extraction only works when the air quality supplied by the natural ventilation system is insufficient in the occupied rooms, based on measured values of CO_2 sensors. This system guarantees excellent air quality, while keeping ventilation energy consumption very low. Preheating of new ventilation air can be achieved by passing this air through built spaces which recover solar heat or heating loads from the building, such as double skin façade, atrium, etc. However, natural and hybrid ventilation systems are difficult to implement in polluted urban areas.

For a good quality of the air, performant buildings often use continuous mechanical ventilation (CMV). There are single and double flow mechanical ventilation systems. A single flow ventilation system uses natural ventilation for the air inlet and mechanical extractor for the air outlet. This system generates more energy consumption than a hybrid system without providing any other advantage. A **mechanical double flow ventilation system** is based on a mechanical impulsion of the incoming air, which can be filtered, preheated, humidified or dehumidified, and a mechanical extraction of the outgoing air. It helps to reach occupants' breathing comfort through indoor air quality, by removing pollutants (odors, humidity, products of combustion from heating appliances, microbes, etc.) thanks to constant air renewal, while allowing good filtration of incoming air against pollution, noise and insects. This type of ventilation is best suited to dense or polluted built environments. In addition, these systems can be coupled with a heat exchanger on the extracted air and/or with Canadian wells. Figure 1.7 illustrates four advantages of dual flow ventilation systems: air treatment in polluted environment, quiet rooms in a noisy environment, recovery of heat from the air extracted during heating season and cooling through a Canadian well during cooling season.

Some double-flow CMV systems use the heat of indoor air extracted to preheat the outside air that enters the building through the ventilation system. These systems are the double-flow CMVs with **heat exchanger on the exhausted air**. These systems are the most efficient for reducing energy consumption due to ventilation in buildings with high heating loads. A mechanical double flow ventilation system, coupled with a heat recovery unit (current efficiency of 90%) on the extracted air, offers the best energy performance during the building's heating period. The consumption of the ventilation devices is therefore very quickly offset by reduction of building heating consumption, which is very profitable from an environmental point of view. This system should be the preferred choice in cold climates and temperate-cold climates, because it greatly reduces buildings heating loads.

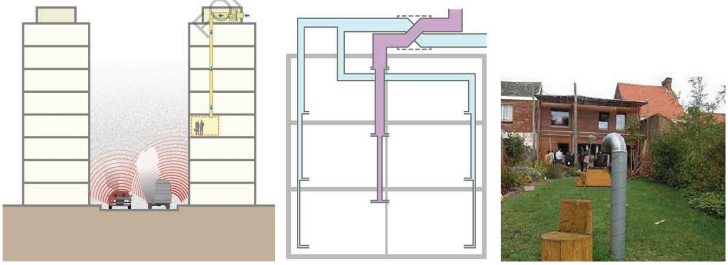

Figure 1.7: Potential benefits of dual flow ventilation systems: pollution and noise protection, and possibility to add a heat recovery system on the exhausted air or a Canadian well.

The Canadian wells, also called the provincial wells or air-ground exchanger, uses geothermal energy. This is a double-flow ventilation installation which heats or cools the outside air as it passes through pipes installed in the ground (at least 25 meters long), before it enters the building. The pipes are buried at a depth of 1.5 to 2 m to be protected from frost, and because the average monthly temperature at this depth varies less over the seasons. Air intake, equipped with anti-rodent grid and filter, must be at least at rise 1.1 m from the ground to limit its clogging. It will be positioned far from sources of pollution (roads, etc.). One tube can be used for a ventilation volume of 300 m³/h. Several tubes may be needed depending on the volume of air to be pre-treated. It takes around € 3,000 to € 4,000 for a complete installation sized for a house.

In winter, the soil has a higher temperature than the outside air; the air passing through the pipes in the heating season heats up and reduces building heating loads. However, this benefit is small when a building is already equipped with a double flow ventilation system with heat recovery on the extracted air. An efficient Canadian well (thermal efficiency of 80% and pressure drops limited to 100 Pa) connected with a double flow ventilation with a heat recovery unit provides additional energy savings of around 5 to 10% on the overall heating demand of the building. Conversely, the ground is colder than the outside air during the cooling season and the air passing through the pipes then cools building indoor air and reduces its cooling loads. Canadian well makes it possible to gain 6 to 7 °C on the air entering building compared to the outside air, in winter as well as in summer, for temperatures of the order of 0 to 33 °C. Reduction in air temperature of the ventilation air can even reach a drop of 19 °C for extremely hot temperatures. However, its cooling effect in buildings is limited by the hygienic ventilation flow rate, which is limited in a majority of buildings to 1 volume per hour. The Canadian well is therefore often used for reducing cooling energy consumption in buildings with high fresh air requirements (laboratories, concert halls, conference rooms, meeting rooms, etc.) or in buildings which need a light daytime cooling effect, complementary to an intensive natural night cooling, to avoid an air conditioning system.

A second generation of Canadian wells uses the same principle but with coil filled with glycol water which runs through the ground and which will, by means of a heat exchanger, preheat or cool the incoming air.

1.3.3 Cooling system

It is not always necessary to cool a building. If heat gains (including internal and solar gains) are less than 60 W/m², it is possible to cool the building without an artificial cooling system, thanks to the natural cooling of intensive night ventilation (combined with insulation of the envelope, good solar protection and internal thermal mass) as well as the possible addition of Canadian wells. However, it will be necessary to perform thermal simulation of the building over an average typical year to verify that thermal comfort criteria are met. When a natural cooling solution by intensive night ventilation is adequate, possibly supported by the use of Canadian wells during the day, this solution should always be favored because it is the best solution for reducing buildings cooling consumption.

Beyond 60 W/m² of internal and solar gains, the building must be equipped with a mechanical cooling system. Here are some rules to reduce energy consumption of mechanical cooling systems, when their use is necessary:

- Choosing a cooling system using a renewable energy source.
- Choosing an energy-efficient cold transport fluid, suited to the level of building thermal gains.
- Designing a cooling system partly based on passive cooling techniques.
- Correct sizing of the cooling system, taking into account the possibility of occasionally using passive cooling techniques.
- Increasing energy performance of the cooling system, thanks to a smart management of the cooling system.

The first strategy is choosing a cooling system using a renewable energy source. The reversible heat pump is useful especially when there is a need for cooling all year round. The reversible heat pump on a water loop, which alternately produces hot and cold successively or simultaneously, will preferably be used for small heating and cooling networks as well as for shopping centers. For other cooling systems, renewable generation of electricity can power the cooling system.

The second rule is choosing an energy-efficient cold transport fluid, suited to the level of building thermal gains. Water is the best transport fluid for cold (on average, energy consumption of the pump represents 2% of thermal energy transported), then refrigerant itself, finally cold transport by air (on average, fan energy consumption represents 10 to 20% of thermal energy transported). Cooling a building with an air conditioning system should therefore be reserved for buildings where ventilation needs are very important, i.e. buildings with high occupancy density, such as concert halls, congress centers, etc., for which hygienic fresh air flows are very important and allow efficient use of free-cooling.

The third strategy is designing a cooling system partly based on passive cooling techniques. These are three passive cooling solutions with very low energy consumption:

- Free-chilling, which is direct cooling of the cooling water from a rooftop cooling tower or a natural cold-water source (river, lake, etc.), thanks to a by-pass of the refrigeration machine;
- Free-cooling, which is direct use of the outside air in the cold distribution network when the outside temperature is lower than the inside temperature or using Canadian wells. Free-cooling can be applied in air-conditioning systems and individual refrigeration machines.
- Indirect adiabatic cooling, which cools a first air stream by vaporizing water and then uses this air to cool the air entering the building through a heat exchanger. This system has the advantage of cooling the air entering the building with water without humidifying it. Indirect adiabatic cooling can be implemented in all buildings with a dual flow ventilation system and takes up very little space. Direct adiabatic cooling (which directly cools the air entering the building by spraying water) is not used in buildings because of the high risk of Legionella. However, indirect adiabatic cooling generates water consumption and requires regular maintenance.

The next solution is a correct sizing of the cooling system, taking into account the possibility of occasionally using passive cooling techniques. When internal and solar gains reach 60-90 W/m², cooling a building thanks to cold ceilings is possible. If the thermal gains reach 90-120 W/m², building cooling will generally be done by fan coil units. For areas with a very high heat load, such as computer rooms which have heat loads around 200 W/m², an individual refrigeration machine will be chosen, because it allows a separate operation from the main building cooling system and therefore it will reduce its cooling consumption.

The last rule is increasing energy performance of the cooling system thanks to its smart management. Data analytics of the system help in regulating the temperature, and sometimes also humidity, lowering its energy consumption.

1.3.4 Lighting system and electrical appliances

A good design of building daylighting, controlling admission of natural light into a building, including direct sunlight and diffused-skylight, reduces electric lighting and generates energy gains. The overall objective of daylighting is to improve visual comfort in buildings, while minimizing the amount of artificial light and reducing electricity costs, but it can also lower HVAC costs as well. Natural lighting offers a large number of benefits for human health: reduction of bacteria growing in buildings, increase of red blood cells and vitamin D in the human body, strengthening of its immune system, psychological benefits, etc. But it is still necessary to install an **artificial lighting system** in each building, in addition to its daylighting.

A choice of judicious lamps and lighting devices, in compliance with lighting standards, may improve visual comfort and building energy performance. LEDs, compact fluorescent lamps or other energy-efficient lamps will be preferred. Using some lighting management devices is also useful to reduce lighting energy consumption (Reiter and De Herde 2004, 265). These are some energy-efficient lighting management devices and the percentage of energy consumption reduction that they allow compared to traditional artificial lighting systems:

- Lighting device with electronic power supply: 25% reduction in energy consumption,
- Lighting device (with an electronic power supply) with manual dimmer or with a clock programming hourly: 35% reduction in energy consumption,
- Lighting device (with electronic power supply) with dimming based on daylight management cell or presence detector: 50% reduction in energy consumption,
- Lighting device (with electronic power supply) with dimming based on daylight management cell and presence detector: 70% reduction in energy consumption.

In terms of artificial lighting management systems, the best system for rooms with highly variable occupancy is a presence detector, in order to switch off the lights in occupied rooms. In rooms with high daily occupancy, the most energy-efficient lighting management system is a dimming system based on the available daylighting. In all cases, it is useful to design carefully electrical circuits of the lighting installation. For example, it is advisable to provide the possibility of separately switching on lamps located closest to windows.

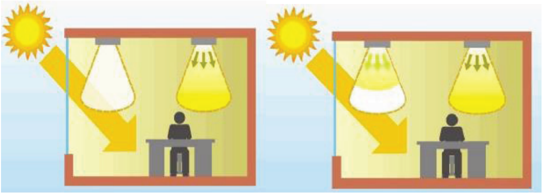

Figure 1.8: Lighting dimming system based on daylight management cell (Reiter and De Herde 2004, 265).

In addition to lighting consumption, **electrical appliances** generate also significant energy consumption in buildings. It is therefore recommended to use the most energy-efficient appliances (for example with labels A and A +) and to limit consumption linked to the standby mode of some appliances.

1.4 Renewable energy production systems

The use of fossil fuel resources in buildings is a solution with no long-term future. Coal, oil, and gas are becoming increasingly scarce. Moreover, using coal, oil, or gas seriously accelerates climate changes and all fossil fuels generate significant environmental costs. The current energy mix of electricity grids also has significant environmental consequences. Fortunately, a wide range of climate-friendly and renewable energy sources (solar, wind, geothermal, etc.) exist.

A zero-energy building produces annually at least a quantity of local renewable energy equal to the amount of non-renewable energy consumed in its heating, cooling, ventilation, and lighting systems as well as through electrical appliances. The main systems of renewable energy production at the building scale are:

1/ for heating consumption:

- Heat pump, powered with photovoltaic panels, wind turbine, geothermal energy, or renewable electricity grid,
- Solar thermal panels,
- Wood or pellets condensing boiler, provided that wood or its derivatives (pellets, etc.) are managed in a sustainable way,
- Biomass cogeneration, provided that biomass is managed in a sustainable way,

- Gas burner or hybrid heat pump-gas system, using zero-carbon gas (hydrogen or biomethane),
- Electrical heating system powered with photovoltaic panels, wind turbine, or renewable electricity grid,
- Heat exchanger on a district heating network powered with 100% renewable sources or waste heat,

2/ for cooling consumption:

- Reversible heat pump, powered with photovoltaic panels, wind turbine, geothermal energy, or renewable electricity grid,
- Cooling system powered with photovoltaic panels, wind turbine, or renewable electricity grid,
- Urban cooling network, powered with reversible heat pumps, or renewable electricity grid,

3/ for lighting and electrical consumption (including ventilation and electrical appliances):

- Photovoltaic panels (PV),
- Wind turbine,
- Renewable electricity grid.

The most common sources of renewable energy production at the building scale are heat pumps and solar panels, which produce hot water through thermal solar panels or electricity through solar photovoltaic panels. Wind energy can also be harnessed on a building by a small wind turbine. However, it is more interesting to participate collectively in the operation of a larger wind turbine, since the efficiency of the latter will be more attractive and its financial profitability faster.

For a passive semi-detached residential building with a footprint of 55m², including apartments with a total living area of 210m², located in Brussels (Belgium) under a cold temperate climate, the total energy needs for heating, domestic hot water and electricity are 40kWh/m².an, which represents 60 kWh/m².an of primary energy consumption with a condensing gas boiler and the Belgian energy mix, and therefore requires 40m² of photovoltaic panels to reach the zero-energy goal in this climate (Maerckx 2016, 65). If thermal solar panels are added to cover 50% of energy consumption due to domestic hot water, the surface area of PV required decreases to 32m². If a pellet boiler is used for heating and domestic hot water (without solar thermal panels), the PV surface is reduced to 24 m². The same PV surface (24m²) is achieved thanks to a renewable electricity grid. If these last two strategies are combined, the surface of PV needed is only 7 m². This example, presented by Maerckx (2016, 65), shows the importance for highly insulated buildings to take into account both renewable energy sources for heat needs and for electricity demands.

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Chapter 2: Strategies to reach low-carbon targets for buildings

Carbon Neutral Laboratory, designed by Fairhursts Design Group, in Nottingham (UK)

2.1 Zero-carbon buildings

The Paris Agreement commits countries around the world to limit global warming to well below 2°C compared with pre-industrial levels, with an aspirational target of limiting the temperature increase to 1.5°C (EC 2018, 1). In its long-term strategy for 2050, the European Commission claims the need for a near-complete decarbonisation of the EU's building sector to meet its climate goals (CE Delft and Climact 2020, 1). GHG emissions cannot be reduced sufficiently to meet this target based only on energy-efficiency solutions. Renewable energy systems, carbon-neutral materials and green processes will be necessary to support this effort. In 2006, the world production of renewable energy from all sources (solar, wind, geothermal and biomass) contributed only 2% of global production (Socolow and Pacala 2006, 50-57).

A zero-carbon objective aims to eliminate all the GHGs – including carbon dioxide, methane, ozone, black carbon and fluorocarbon compounds – involved in a product's life cycle, to generate zero impact on climate change. A **zero-carbon building (ZCB)** is one that, over its entire life cycle, generates only as much GHG emissions as it can offset. The carbon footprint of a building is the total amount of GHGs emitted to supply, build, operate, maintain and deconstruct it. A ZCB is thus a carbon-neutral building, characterised by the demonstration of a zero-carbon balance over its whole life cycle (Emerson 2020,15; Moncaster 2015, 751-758).

Design strategies for ZCBs include all solutions for reducing energy demand and GHG emissions. A ZCB is defined as a very energy-efficient building, using low-carbon materials and systems, combined with carbon offsetting strategies, in sufficient quantity to offset the carbon emissions of the building. Carbon offsetting strategies may include solutions such as reforestation, producing carbon-free renewable energy and using materials that are able to store carbon (wood, innovative carbon sequestering concrete products, etc.).

The five main objectives to reach the zero-carbon goal in the building sector are (CE Delft and Climact 2020, 31):

- Improvement of the building envelope of existing and new buildings, to reduce their energy demand for heating and cooling. In existing buildings, high energy consumption is associated with significant GHG emissions, so that a drastic reduction in energy consumption of the existing building stock constitutes a major challenge for a low-carbon policy in the building sector. The net reduction potential of CO_2 emissions in Europe, based on improvement of the envelope of existing buildings thanks to a renovation rate of 3% of the building stock and an average energy saving of 55%, constitutes a contribution of 19% to the decarbonisation goal of the European building sector by 2050.

- Replacement of existing systems for heating, cooling, ventilation, lighting and other electrical appliances with more efficient ones. Improving the efficiency of electrical appliances represents a contribution of 11% to the decarbonisation goal of the European building sector by 2050.
- Decarbonisation of the remaining heating demand, by switching to (or using) zero-carbon energy sources (such as renewable electricity, zero-carbon district heating, zero-carbon gas or sustainable biomass). This strategy has the potential to contribute 39% to the decarbonisation goal of the European building sector by 2050.
- Decarbonisation of the remaining electricity use by switching to 100% renewable power. This strategy has the potential to contribute 11% towards the targeted reduction of CO_2 emissions of the European building sector by 2050.
- The reuse of on-site materials and use of reused, recycled and zero-carbon materials in construction and renovation, while promoting a 100% carbon-free materials industry. Applying the principles of circularity to the building supply chain and using reused, recycled and zero-carbon materials in construction and renovation can contribute up to 19% towards the decarbonisation of the European building sector by 2050.

Switching to zero-carbon heating fuels will contribute the most to the full decarbonisation of the building sector in Europe. Indeed, based on Eurostat data, 75% of heating consumption of the built environment in Europe in 2018 was based on fossil fuels (gas, oil and coal). Switching to decarbonised energy carriers for heating is therefore essential to reduce GHG emissions in the European building sector. In hot climates where cooling consumption is greater than that for heating, switching to decarbonised electricity may be more efficient.

The first two objectives listed above have already been developed for zero-energy buildings in Chapter 1. The design of a ZCB requires taking into account passive and active strategies to reach a zero-energy building (see Chapter 1), and in addition it also requires carbon offsetting strategies, including the production of carbon-free renewable energy, the reduction of a building's embodied carbon and promoting solutions that store carbon (reforestation, innovative carbon sequestering materials, etc.). The zero-energy objective is much easier to achieve in a building than the zero-carbon objective, because the former only takes into account operational energy while the latter is calculated over its lifetime.

An intermediate step, chosen by various researchers and associations, consists of targeting a ZCB in its operational phase only (calculated annually). Indeed, for buildings, the use phase is predominant and accounts for 80–98% of CO_2 emissions over the entire life cycle, whereas the construction phase (including embodied carbon of materials) accounts for 1–19.8% and the deconstruction and recycling phase accounts for 0.2–5% (Rossi et al. 2012, 402-407).The Net Zero Carbon Buildings Commitment challenges companies, cities, states and regions to reach net-zero operating emissions in their portfolios by 2030, and to advocate for all buildings to be net zero in operation by 2050. By setting ambitious targets, the Commitment aims to maximise the chances of reaching the Paris Agreement targets, by drastically reducing operating emissions from buildings (Kalz et al. 2010, 632-646). In its new strategy towards sustainable development, the EU has suggested that 100% of all new constructions must be low-carbon buildings from 2030 onwards (EU 2010, 13-35).

Some studies have mentioned support tools for facilitating different stages of low-carbon design applied to construction supply chains and buildings (Burrows and Adams 2019, 49; Karlsson et al. 2020, 120), or evaluating the calculation approaches for low-carbon buildings (Becqué et al. 2019, 84; Janda et al. 2014, 911-936). Zero-carbon designs are always created with significant energy-saving features. Most ZCBs use the electricity grid for carbon storage, but some are independent of the grid.

This chapter presents **the calculation method for a zero-carbon operational balance sheet**, and **a design strategy for ZCBs**, based on zero-energy building design and three complementary steps, including (1) zero-carbon energy production, (2) reduction of a building's embodied carbon, and (3) carbon sequestering strategies. These four types of complementary solutions, which have to be combined to reach the zero-carbon level, are developed below. Moreover, this chapter summarises the most common low-carbon strategies and innovative technologies for ZCBs.

2.2 Zero-carbon operational balance sheet

The zero-carbon operational balance sheet means that there are no net GHG emissions associated with the operation of the building. GHG emissions are offset by the production of clean and renewable energy on- or off-site. The zero-carbon operational balance is established by achieving a net emissions balance of zero or less, with net emissions being defined as follows:

Net Emissions = Direct Emissions + Indirect Emissions + Biomass Emissions − Avoided Emissions of Green Energy Produced Off-site – Avoided Emissions of Exported Green Energy

Direct emissions are associated with on-site combustion, with the exception of biomass combustion. Indirect emissions are associated with purchased energy, such as emissions related to electricity drawn from the electricity grid and emissions related to thermal energy generated by urban heating networks at the neighbourhood scale.

Biomass emissions are related to the use of biomass resources on-site. However, there is biomass that can be considered as zero-emission biofuel: whole plants, parts of plants, and residues of harvested or industrial by-products from the harvesting and processing of agricultural or forestry products. But there is also biomass ineligible to be considered as zero-emission biofuel: wood covered with paint, plastic or Formica; wood treated with preservatives that contain halogens, chlorine or halide compounds, such as chromated copper arsenate or arsenic; wood treated with adhesive products; railway sleepers; etc.

Avoided emissions of green energy produced off-site and exported green energy mean that these can be used to offset direct, indirect and biomass emissions. These avoided emissions are related to the production of renewable zero-carbon energy (solar energy, wind power, hydroelectric power, etc.), for example.

2.3 Zero-carbon energy production

The amount of GHGs emitted for each kWh of useful energy varies greatly between energy sources. The combustion of gas produces much less CO_2 than from fuel or coal. Nowadays, it is possible to choose between many different hybrid systems combining renewable and non-renewable energies. It is therefore necessary to have emission factors corresponding to each of these systems. For example, a hybrid heat pump associating an electric heat pump operating on base and a fuel generator operating on the coldest days and avoiding the consumption of electricity at the time when it is the most polluting will have to see the benefit on its emission factor. These factors will have to be calculated through a life cycle assessment (LCA) to allow a fair comparison between each solution. However, the long-term goal is to achieve 100% zero-carbon energy use. This objective can only be achieved if regulations, CO_2 pricing and subsidies are used effectively.

There are four main types of **zero-carbon energy carriers**: renewable electricity production, sustainable heat sources, zero-carbon gas production and sustainable biomass production. The last three items in this list are heating options. A combination of these solutions in the building stock, based on local factors, will generate the lowest overall cost to society. There is no one single solution, such as electric heat pumps, that will be best for all buildings (CE Delft and Climact 2020, 31). To stimulate a switch to zero-carbon energy production, a combination of these four zero-carbon energy carriers will be needed. This will include, in particular, renewable electricity production, electrification of heating systems, development of district heating systems, adaptation of existing gas networks to zero-carbon gas and use of sustainable biomass resources.

The use of electricity is non-polluting in itself, with the associated pollution being concentrated at its place of production instead. But its primary energy consumption is generally high in relation to current electricity mixes, power plant yields, energy losses due to transport via power lines, etc. **Renewable electricity** produced on-site, mainly based on photovoltaic panels, is increasingly being integrated into new construction projects to minimise their environmental impacts. The development of electricity networks totally powered by renewable energies (solar, wind and hydropower) at local, regional and national levels are also likely to appear more frequently in the future. Renewable electricity sources are perfect for meeting the electricity needs of a building for cooling, ventilation, lighting and electrical appliances.

However, heat pumps, and electrical resistances supplied by photovoltaic panels or a renewable electricity network are only suitable for buildings with high energy performance (or at least low energy buildings). They cannot be applied to old buildings without carrying out heavy renovation works. Moreover, these electrical heating solutions generate increased electricity demand with high peak demand, which has a negative impact on the electricity grid and renewable production. The use of photovoltaic panels to supply a heating system also competes with its potential contribution to cover other building energy consumption (lighting, IT, electric car, etc.).

Regarding heat pumps, there might also be resistance from inhabitants due to noise, disruption and aesthetics. Despite these limitations, heat pumps and renewable electricity heating are interesting solutions for passive and zero-energy buildings.

District heating networks, using sustainable heat sources such as waste heat, geothermal heat, cogeneration powered by vegetable oil, or collective solar thermal production, are suited to urbanised areas with concentrated heating demand (at least 1000 kWh/m but ideally 2000 kWh/m). Heating networks distribute thermal energy in the form of steam or hot water, from a central production installation and through a network to heat several buildings or industrial sites. Then, a heat exchanger supplies energy to each building connected to the network. For large networks, substations have to be provided.

The main benefits of district heating networks using sustainable heat sources are the potential for using a diverse range of energy sources, flexibility in changing energy sources and centralisation of maintenance. However, collective investment is generally needed to build or renovate the district heating network and to develop the use of sustainable energy sources. These projects are complex to implement because of the multiplicity of urban constraints (existing roads, etc.) and actors involved. In addition, this solution creates inhabitants' resistance to the monopoly of heat companies, high perceived costs, thermal load losses in the network (10% on average in new networks), nuisance during construction and lack of control over comfort. A heat exchanger on an energy-efficient urban heating network is nevertheless a practical and environmentally friendly heating system, which may be particularly suitable for low temperature radiators. This solution is especially recommended for new neighbourhoods or where there is a reliable source of fatal energy over the long term.

Zero-carbon gas (such as biomethane or green hydrogen) offers the great advantage of using existing gas networks. It is used with a gas burner or hybrid heat pump–gas system. But there are not enough resources to allow the replacement of all existing gas boilers. Biomethane is produced from biomass; however, the availability of sustainable biomass is highly limited. Estimates for the total potential sustainable biomethane production vary from 7% to 18% of the current natural gas demand (CE Delft and Climact 2020, 31). Moreover, demand for the use of biomethane also exists in other sectors, such as industry, power and transport. Green hydrogen, which is hydrogen produced from renewable electricity, is not yet available at a reasonable cost. Future developments remain uncertain and sectors like industry and shipping, with fewer decarbonisation alternatives, will want to use green hydrogen. Zero-carbon gas is suitable for buildings with high heating demand, such as poorly insulated buildings. Biomethane should thus be reserved for buildings connected to existing gas infrastructure and that are not adequately insulated, such as historic buildings.

Sustainable biomass for zero-carbon heating systems – for example, a pellet stove, wood boiler, or wood-fired cogeneration – has significant limitations. First, there is a limited availability of sustainable biomass and competing demands for it from other sectors. Moreover, the smoke emissions should be via a chimney equipped with good quality filters. However, the high price of filters limits their use for small buildings such as individual residential houses. Smoke emissions without adequate filters generate significant air pollution (fine particles, etc), which can be extremely harmful for the environment and human health. On the other hand, in Europe, cogeneration and pellet boilers used in district heating networks or industrial installations are compulsorily equipped with high performance filters, making them eco-friendly heating systems. Another limitation is that biomass heating requires large storage areas, which is problematic in dense urban environments. The road transport of biomass to the site of its use can also be problematic and therefore should be reduced as much as possible. In view of this, it is preferable to use biomass heating in rural areas, near sustainable biomass production sites.

The University of Liège in Belgium, which has building stock including educational buildings, offices, residential buildings, a hospital and sports facilities, is a good example of a community investing to reduce its annual CO_2 emissions. The university applies energy renovations to 3% of its building stock each year (approximately 17,000 m²). The heating demand of the university (all sites combined) has decreased in recent years (−24%) and so has electricity demand (−10%) thanks to the renovation programme and better management of energy systems.

In 2012, the University of Liege installed a biomass cogeneration unit (see Figure 2.1) supplying a heating network at the Sart-Tilman university campus. In addition, the university has seven photovoltaic installations (with an installed capacity of 2–466 kWp) to reduce its environmental footprint by self-consuming nearly 100% of its production. These facilities allow the university to produce approximately 40% of its thermal energy demand as well as 25% of its electricity demand in a renewable manner. Coupled with better management of production systems, these facilities have enabled the university to reduce its CO_2 emissions by 42% in 2018 compared with the 2005 level, i.e. a reduction of 50 kg of CO_2/m^2 per year.

Figure 2.1: Biomass cogeneration unit of a district heating network (left) and renewable photovoltaic electricity production (right) at the Sart-Tilman campus of the University of Liège, Belgium.

2.4 Reduction of a building's embodied carbon

Embodied carbon emissions are associated with the materials and processes used throughout the whole life cycle of a building or infrastructure. About 11% of global GHG emissions come from the embodied carbon in buildings (Emerson 2020, 1). They currently contribute 8% of total emissions from the residential building sector in Europe and this share will increase over time (CE Delft and Climact 2020, 31). Current industry policies, such as the EU ETS, regulating the production of construction materials have not yet managed to reduce embodied emissions. Promoting a circular economy and reducing carbon emissions in the materials industry are key targets, but introducing requirements for the construction sector that create a market for reused, recycled, and low-carbon materials and products is also needed. These requirements should target operational and embodied emissions ("whole life carbon") in an integrated manner to avoid a situation where requirements to reduce embodied emissions reduce efforts to tackle operational emissions. Figure 2.2 gives an estimation of GHG emissions per material related to the construction of a road (Karlsson et al. 2020, 120).

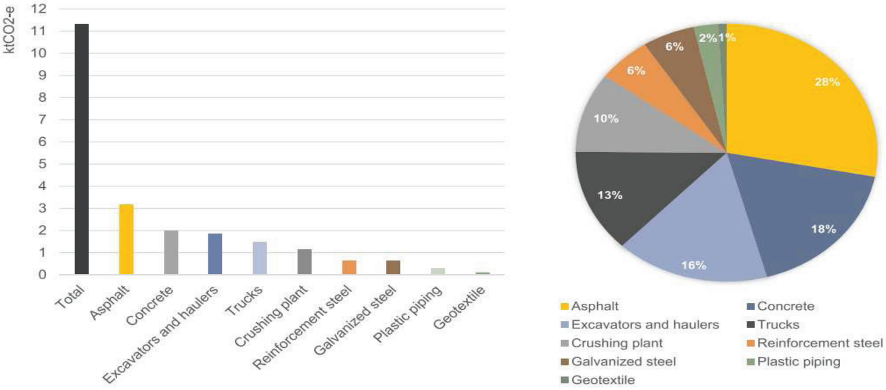

Figure 2.2: Estimated GHG emissions by category for the construction of a road in Sweden (Karlsson et al. 2020, 120).

An LCA helps to develop new eco-designs that affect all stakeholders: optimisation of architectural design and choice of construction systems reducing the volume of materials used, selection of low-carbon materials, well-sized technical installations, etc. Assessing environmental impacts through LCA allows arbitration between various solutions. A list of building materials and their embodied carbon is shown in Table 2.1.

Table 2.1: Embodied carbon of building materials.

Building material	**Thickness (m)**	**Thermal conductivity (W/mK)**	**Density (kg/m^3)**	**Specific heat capacity (J/kg K)**	**Embodied carbon (kgCO$_2$)**	**Cost (\$/m^2)**
Ceiling	0.015	0.056	380	1000	1.2	6.6
Hemp	0.150	0.04	25	1000	0.0	27.5
Limestone silicon	0.150	0.136	270	880	0.0	16.5
Polyurethane	0.02	0.028	30	1470	3.0	5.1
Roof tiles	0.030	0.08	530	1800	0.19	30
Wood	0.02	0.120	510	1380	0.00	15
Extruded polystyrene	0.02	0.034	35	1400	2.88	6.3
Expanded polystyrene	0.05	0.04	15	1400	2.5	8.8
Mortar	0.02	0.88	2800	896	0.19	25
Concrete slab	0.15	0.16	840	500	0.33	17.0
Copper	0.02	300	8900	380	3.1	94.0
Aluminium	0.02	160	2800	880	8.55	100.3
Steel	0.02	50	7800	450	1.77	94.1
Stone	0.02	1.2	2000	840	0.46	56.4
Plastic tiles	0.02	0.2	1000	1000	2.53	31.3
Cork	0.02	0.08	530	1800	0.19	37.6
Earth brick	0.10	0.80	1890	880	0.46	94.0
Plasterboard	0.02	0.25	2800	896	0.38	37.6
Wood-wool	0.02	0.1	500	1000	0.98	37.6
Rubber	0.02	0.17	1500	1470	3.5	37.5
Cast concrete	0.10	1.1	2000	1000	0.08	1254
Brick reinforced	0.10	1.1	1920	840	0.22	94.0

However, it should be noted that there are several calculation assumptions for GHG emissions related to bio-based materials, depending on the choices made for the calculation of carbon storage. These various calculation methods give different results.

2.4.1 Renovation of existing buildings

Very often, the choice between renovation of an existing building or demolition with rebuilding of a new building is based on cost, heritage and insalubrity constraints. The prism of GHG emissions provides a particular light that can complement the others. From the point of view of GHG emissions, reusing an existing building will save around 300 kgeq CO_2/m^2, which leads to several tens of years of having a better performance than a new building, even if the latter consumes less energy than a well-renovated building. During deep renovation of a building that is keeping its structure, half of the emissions related to materials are saved compared with a new construction. This example shows the importance of studying on a case-by-case basis, as part of an LCA, the respective environmental impacts of each project. In construction nowadays, the analysis is generally undertaken on the emissions during the phase of exploitation, which are very strongly reduced by a new construction. It is therefore necessary to analyse the whole life cycle of buildings.

2.4.2 Sustainable construction methods

The **choice of a material** from an environmental point of view should ideally integrate the following criteria:

- Origin of the materials. Care should be taken to select materials of local origin. Local materials generally fit well into the landscape and existing built environments, while enhancing local resources and the economy (wood industry, quarries, etc.) and limiting transport distances.
- Reused, recycled or renewable materials should be chosen first, or at least materials with existing abundant stocks of raw materials.
- Embodied energy and GHG emissions should be minimised on the basis of a comparison of solutions with the same thermal conductivity.

- Choosing a material that generates the least pollution by its manufacture, implementation, use and disposal, by minimising the emissions of dust, solvents, volatile organic compounds (VOCs), formaldehyde, heavy metals, etc.
- A long lifespan and good conservation of its performance over time are interesting criteria.
- The potential to reuse or recycle the material at the end of its life will limit waste products and raw material consumption in the future.

Certain constructive rules should also be respected. For fixing materials, we will favour assemblies by **mechanical fastening** (screws or interlocking) over assemblies by gluing, because the former facilitate dismantling work and are not polluting. An environmental choice also favours resistant materials that require little treatment (antifungals, insect repellents, etc.), varnishes and paints.

Prefabrication and **standardisation** are constructive choices that reduce the amount of waste generated and therefore also help to reduce CO_2 emissions. These two construction methods will also facilitate deconstruction and reuse of materials at the end of their life and better sorting of waste to increase its recyclability. Taking into account the reversibility and adaptability of buildings, from their design phase, is also part of a sustainable and low-carbon design.

2.4.3 Reused and recycled materials

All materials are a source of waste production, whether during their production, operation or demolition phases. Building designers should try to minimise waste production by choosing reused materials as a priority, then recycled materials.

To facilitate the use of reused materials in construction and renovation projects, it is necessary to develop directories of professional operators who sell construction materials arising from the demolition of old buildings, as well as those who offer services such as demolition, cleaning and resizing of recovered materials, and advice about the reuse of materials.

It is also necessary to identify the most efficient recycling channels locally for construction materials, from an environmental point of view. The recycling market is constantly evolving; it is not always easy for building designers to identify the potential for recycled materials and recycling channels, depending on geographic location. Building materials companies and public authorities should participate in the dissemination of this information to encourage a local circular economy.

Figure 2.3: Institute of Botany at the University of Liège (Belgium) – facade renovation with reused wood (initial building: Roger Bastin, 1970; renovation: ULIEGE-ARI, 2018).

The Institute of Botany at the University of Liège in Belgium is an excellent example of a building renovation with reused materials (see Figure 2.3). An old raw concrete facade has been replaced by a reused wooden facade. During the renovation, three forms of reused materials were applied in this building: reused materials from another demolition site, reused materials from in-situ deconstruction and rehabilitation of existing infrastructure (including the renovation of an old ventilation system).

2.4.4 Low-carbon materials for a greener future

Concrete is often used as a core component in constructions. Although it represents an attractive choice in terms of thermal inertia, acoustic qualities and reasonable price, its environmental impacts cannot be neglected. This is why in recent years much research has focused on the development or rediscovery of bio-sourced, or other more ecologically sound, materials.

The following sustainable construction materials could represent greener alternatives to concrete in both residential and commercial projects in the future, due to their lower GHG emissions (CRL 2018, Chapter 1). However, the choice of a specific material must always take into account various design criteria: aesthetics, structural performance, fire resistance, thermal conductivity, thermal inertia, acoustic insulation, service life, environmental impacts, integration into the local context, adaptation to the climate, etc. No material should therefore be considered as the best solution for all situations.

Moreover, it is important to remember that one of the most vital criteria for a material to be considered low carbon is that it comes from a local resource. A bio-sourced and sustainable material from a distant country will generate significant impacts in connection with its transport to the construction site. In terms of constructive choices, it is therefore always necessary to analyse local resources.

Straw bales

Straw bale buildings date back to when homes were built from natural and local materials (Construction Supply Magazine 2020, 1). Straw is a renewable, sustainable and affordable resource. Straw bales are useful for replacing various materials, such as concrete, plaster, gypsum and other building materials in walls. When sealed properly, they have a high insulating ability. Straw bales are made from the waste of the agricultural industry. They are a substitute for lumber and sequester carbon. Contrary to what might be believed, straw bale homes are resistant to fire and can generate a specific aesthetic.

Figure 2.4: Examples of straw bales used in buildings.

Bamboo

Bamboo is a sustainable alternative to various traditional building materials. Although it resembles wood aesthetically, bamboo is actually a member of the grass family, meaning that bamboo regenerates extremely quickly compared with trees. In fact, bamboo is one of the fastest-growing plants on the planet: depending on the type of bamboo and the region, it can sometimes grow up to 3 feet per day (Elemental Green 2019, 1). Bamboo might seem fashionable and up to date (see Figure 2.5), but it has actually been a locally sourced building material in some regions for millennia.

Figure 2.5: Examples of buildings using bamboo.

What makes bamboo such a promising material for modern buildings is its combination of tensile strength, light weight and fast-growing renewable nature. Used for framing buildings and shelters, bamboo can replace expensive and heavy imported materials, and provide an alternative to concrete and rebar construction, especially in difficult-to-reach areas, post-disaster rebuilding and low-income areas with access to natural locally sourced bamboo (In Habitat 2016, 1). Finally, bamboo, used on the facade, allows a building to be well integrated into the natural environment.

Wood

Wood, a proven pillar of construction, retains many advantages over concrete, steel and other industrial building materials from the carbon emission point of view (Shafique et al. 2020, 47). Trees absorb CO_2 as they grow and do not need to undergo energy-intensive procedures to be converted into a construction product (CRL 2018, 1). When a forest is properly managed, it is also renewable and it participates in the preservation of biodiversity.

Rammed earth

Rammed earth has been used by human civilisation for thousands of years. It lasts a long time and, thanks to their excellent thermal mass, rammed earth walls (or even floors) may be used to store warmth in the cold season and keep the building cool in the hot season. No painting or maintenance is required with rammed earth surfaces. Moreover, humidity is controlled through the natural ability of the material to absorb and release moisture vapour. Rammed earth is also easily recyclable. Mechanical tampers are used to reduce the labour needed to produce sturdy rammed earth walls (Shafique et al. 2020, 47). Finally, rammed earth buildings can be fortified by bamboo or rebar for added safety.

Figure 2.6: Buildings using rammed earth.

Timbercrete

Timbercrete (conductivity ranging from 0.234 to 0.391 W/mK) is an interesting building material made of sawdust and concrete mixed together. Since it is lighter than concrete, it reduces transportation emissions, and the sawdust both reuses a waste product and replaces some of the energy-intensive components of traditional concrete. Timbercrete can be formed into traditional shapes such as blocks, bricks and pavers.

Figure 2.7: Buildings using Timbercrete blocks.

Ferrock

Ferrock is a new material being researched that uses recycled materials, including steel dust from the steel industry, to create a concrete-like building material that is even stronger than concrete. Moreover, this unique material absorbs and traps CO_2 as part of its drying and hardening process, making it not only less CO_2 intensive than traditional concrete but also carbon neutral (Elemental Green 2019, 1).

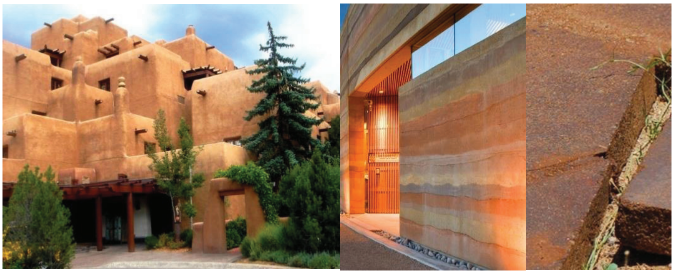

Figure 2.8: Buildings using Ferrock.

Hempcrete

Hempcrete is a concrete-like material that weighs only about an eighth of the weight of regular concrete. Using the woody inner fibres of the hemp plant, Hempcrete is made by mixing the woody core of the hemp plant with lime and water. Its conductivity ranges from 0.06 to 0.07 W/mK. Hemp is a fast-growing renewable resource. Hempcrete blocks are super-lightweight, which reduces the energy used to transport them.

Figure 2.9: Buildings using Hempcrete.

Ashcrete

Ashcrete is a concrete alternative that uses fly ash, a by-product of burning coal, instead of traditional cement. By using fly ash, 97% of the traditional components in concrete can be replaced with recycled materials (Elemental Green 2019, 1; In Habitat 2016, Chapter 1).

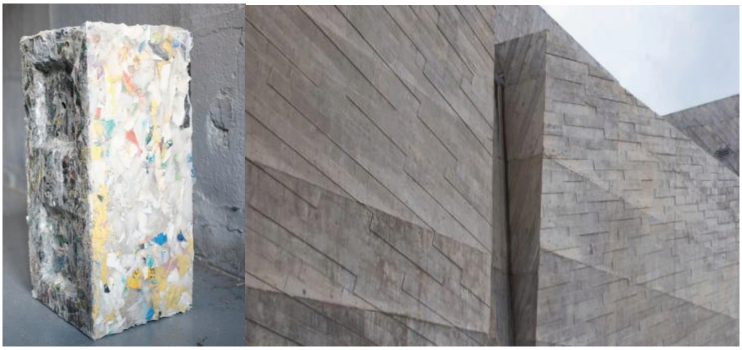

Figure 2.10: Building using Ashcrete.

Mycelium

Mycelium is a futuristic building material, which is totally natural and based on the root structure of fungi and mushrooms. Mycelium can be encouraged to grow around a composite of other natural materials, like ground-up straw, and in moulds or forms, then air dried to create lightweight and strong bricks or other shapes. The conductivity of mycelium varies between 0.04 and 0.07 W/mK.

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Figure 2.11: Mycelium used in a built structure.

Recycled plastic

Plastic is emerging as a potential sustainable construction material. Instead of sourcing, mining and milling new components, researchers are producing concrete made from ground-up waste and recycled plastics. This practice reduces GHG emissions and provides a positive new use for plastic waste that would otherwise be clogging landfills. Plastics that can sequester carbon are even being studied in research laboratories.

2.5 Carbon sequestering strategies

Zero-operational-carbon industrial equipment and processes, as well as carbon sequestering materials, such as concrete and plastics, have already been developed. But until they are readily available, building designers will need to compensate for the embodied GHG emissions of buildings by exporting the surplus generation of on-site renewable energy or through other carbon offsets (for example, reforestation) (Emerson 2020, 1).

Carbon sequestration is the process of capturing CO_2 from the air and storing it for long periods so that it lowers the level of atmospheric GHGs. In buildings, it can be achieved by using materials such as wood that capture and hold significant amounts of carbon while growing, compared with concrete and steel that emit significant amounts of carbon during manufacture. However, concrete and plastic products that sequester carbon are currently being developed and can be used in low-carbon constructions (Emerson 2020, 1).

2.5.1 Green roofs

In urban areas, one way of mitigating the adverse effects of air pollution and reducing carbon emissions is the sustainable rooftop greening practice known as green roofs (Kuronuma et al. 2018, 10). A **green roof** is one that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane. Carbon sequestration of green roofs involves vegetation and soil media, which can capture and store air pollutants on a building scale. Carbon is the main component of plant matter and is naturally absorbed by plant tissue. The carbon is stored in the plant tissue and the soil substrate through plant litter and root exudates. Greening existing roofs reduces the energy consumption of buildings and their related CO_2 emissions. Extensive green roofs contribute to CO_2 reduction within their lifespan.

Figure 2.12: The green roofs at the School of Art, Design and Media, at the NanYang Technical University in Singapore.

Based on a literature review (Kuronuma et al. 2018, 10; Shafique et al. 2020, 47), green roofs in building construction projects are a useful climate mitigation strategy. They store on average between 107 g/cm^2 and 168 g/cm^2. Variations occurred among the different species of plant used. The sequestration can be improved by changing plant species, increasing substrate depth, developing the substrate composition and management practices.

In addition, green roofs are one of the most effective methods for re-greening cities and participating in the return of biodiversity to urban areas. Other benefits of green roofs relate to their positive impacts on the urban microclimate, thanks to their limitation of the urban heat island effect, as well as to their help in the management of rainwater.

Some cities are starting to mandate the use of green roofs – for example, in Linz, Austria, where any building with a roof area of more than 100m² must install a green roof. This policy makes it possible to create urban green networks, which are useful for biodiversity, even in industrial zones, densely built urban areas or parking areas.

Figure 2.13: A green roof installed on a parking area in Linz (Austria).

2.5.2 Reforestation and greening of cities

Preserving and developing green spaces in urban areas and forests in rural areas are important strategies for carbon sequestration. Moreover, these solutions have many other benefits: reducing the urban heat island, satisfying the human need for contact with nature, preservation of biodiversity, etc. So, green surfaces should occupy the largest possible area in future cities. Public and private green spaces developed in new districts should always represent at least 30% of the total surface of each district.

Figure 2.14: Balance between built density and natural spaces in Brussels (Belgium).

It is also important to green existing neighbourhoods. The Bastille viaduct in Paris is a project that reused an existing urban structure to generate a new green space and new activities. This project, led by architect Patrick Berger, includes 13 hectares of parkland above the viaduct, as well as shops and restaurants in the arches of the viaduct at ground level.

Figure 2.15: Urban renovation of the Bastille viaduct in Paris (France).

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Chapter 3: Strategies to reach zero-energy and low-carbon targets in the transportation sector

Electric bus in Brighton (UK).

3.1 Transportation sector emissions

The globalisation of economies, the rise in living standards and the development of tourism have contributed for decades to increasing the volume of transport, for passengers and goods. Global transport involves different modes (road, rail, air, sea, etc.) operating in two main areas: passenger and commercial freight transport (Planète Energies 2020, 1). In 2018, transportation was responsible for 24% of direct CO_2 emissions from fuel combustion in the world. These emissions increased on average by 1.9% per year between 2000 and 2018. However, this increase in global transport emissions has been reduced in 2019, thanks to efficiency improvements, electrification and greater use of biofuels (IEA 2019, Chapter 1). However, global population growth remains a major threat to the rapid increase in carbon emissions for the transportation sector.

In 2018, global transportation CO_2 emissions were 3.6 Gt for passenger road vehicles, 2.4 Gt for road freight vehicles, 0.9 Gt for aviation, 0.9 Gt for shipping, 0.1 Gt for rail transport and 0.2 Gt for other transport emissions (IEA 2019, Chapter 1). Road transport (cars, lorries, buses, two-wheelers), taking into account passenger transport and freight, is by far the primary contributor, producing nearly three quarters of global transport CO_2 emissions. Analysing the situation in more detail, the most significant emissions come from passenger transport and more specifically from passenger road transport. Mobility consists in 57% of global oil demand. But global commercial freight is increasing sharply, due to the increase in trade. Consumer goods are no longer produced at a single point, but generally consist of elements from different factories around the world. About 70% of their transport is conducted by sea, 18% by road, 9% by rail, 2% by canals and less than 0.25% by air (Planète Energies 2020, 1).

The same trends are found in developed countries. In the US in 2018, GHG emissions from transportation accounted for about 28.2% of total GHG emissions. The number of vehicle miles travelled by light-duty motor vehicles (passenger cars and light-duty lorries) increased by 46% from 1990 to 2018, as a result of a confluence of factors including population growth, economic growth, urban sprawl and periods of low fuel prices (US EPA 2019, 1). In Europe since 2014, GHG emissions from the EU-27 transport sector (including international aviation but excluding international shipping) have also increased. In comparison with 2016, emissions during 2017 increased by 2.2%, mainly due to greater emissions from road transport, followed by aviation. In 2017, transport (including aviation and shipping) was responsible for 27% of total GHG emissions in the EU-28. In 2017, road transport was responsible for almost 72% of total GHG emissions from transport (including international aviation and shipping) in the EU-28, with 44% due to passenger cars, 9% due to light commercial vehicles and 19% due to heavy-duty vehicles.

Over the last decade, the GHG emissions and energy demand from the transportation sector have increased faster than in any other sector. Based on current policies, it is estimated that global transport emissions will increase by 60% between 2015 and 2050; however, to achieve the objectives of the Paris Universal Agreement, commercial transport emissions will have to drop by 45% and those of passenger transport by 70%. It is therefore urgent to take measures in order to change our mobility behaviours. In addition, traffic congestion increased worldwide by 13% between 2008 and 2015. Other harmful consequences of individual car use include road accidents, health problems related to pollution, noise nuisance, a lack of physical activity of the passengers, generation of social inequalities, and excessive consumption of public spaces for its use and parking (Nematchoua et al. 2020, 3).

There are a variety of opportunities to reduce GHG emissions associated with transportation (IPCC 2014, Chapter 2), especially in terms of reducing travel demand and improving fuel efficiency. This chapter presents a strategy to mitigate GHG emissions from transportation, based on the reduction of travel demand as well as fuel switching and improving the efficiency of vehicles. This study is completed by the description of forecast scenarios to analyse potential mobility trends and their energy consumption by 2050.

3.2 Mitigating GHG emissions from transportation

In terms of CO_2 emissions, driving 13 km by car every day over a year pollutes as much as heating a 190m² passive house equipped with a natural gas condensing boiler. Various strategies exist to trigger a sustainable mobility transition (Marique and Reiter 2012, 1-6): (i) reducing the length of journeys – for example, by reasonably increasing the densification of built environments, (ii) improving public spaces and supporting the health of inhabitants by favouring active modes of transportation, such as walking and cycling, and also, to a lesser extent, collective modes of transport (bus, train, carpooling), and (iii) reducing the pollution from, and dependence on, fossil fuels thanks to the use of renewable energies.

3.2.1 Reducing travel demand

Reducing travel demand may be achieved through various solutions, such as increasing the built density, improving the localisation of activities, teleworking or promoting changes in mobility behaviours. Employing urban planning to reduce the distance that people drive each day is an efficient solution. Newman and Kenworthy (1989, 24-37) proved that the growth of transport energy consumption per person is a function of urban density (see Figure 3.1). As a result, there is a very large increase in car use when the density drops below 30 inhabitants per hectare. A high density brings environmental benefits at the global level but also creates significant constraints at the local level and for the health of inhabitants. **Reasonable urban densities** should therefore be promoted, in parallel with attractive and comfortable public spaces.

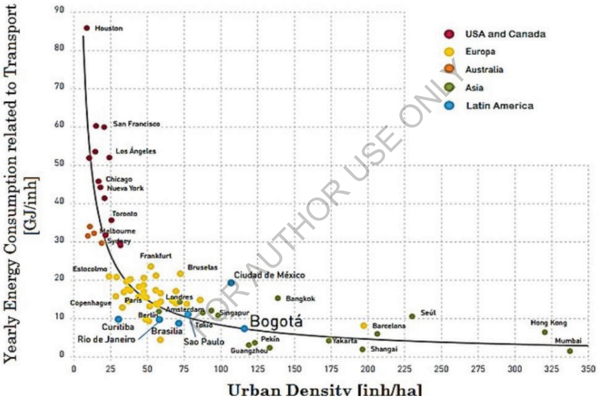

Figure 3.1: Relationship between urban density and energy consumption in the transportation sector, according to Newman and Kenworthy (1989, 24-37).

Better localisation of activities, promoting mixed-use areas, so that residences, schools, shops and businesses are close together reduces travel demand, in particular due to a modal shift towards walking and cycling. Functional diversity allows a reduction in the distances to be travelled and the related energy consumption, facilitates the use of soft modes, and increases attendance in public spaces. On the other hand, polluting activities, such as industries, must be built away from residential areas.

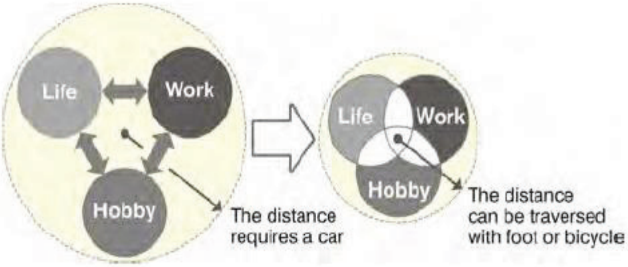

Figure 3.2: Influence of functional diversity at the local scale on mobility behaviours.

Teleworking is another solution to reduce commuting journeys (Marique and Reiter 2012, 1-6). As a consequence of the Covid-19 crisis, road transport in regions experiencing lockdowns in 2020 dropped by between 50% and 75% compared with 2019 levels.

Reducing the need for driving can also be achieved through cycling and pedestrian programs (Nematchoua et al. 2020, 2), and the development of efficient public transport infrastructure or car-sharing and carpooling systems. A modal shift from the car to soft transport modes (cycling or walking) requires investment in good quality pavements and bicycle paths. One of the main obstacles for these sustainable modes of transport is the lack of continuous and secure networks for their users. Care should also be taken to create, secure and enhance the **attractiveness of pedestrian and bicycle paths** – for example, by developing attractive and secure public spaces, and continuous networks dedicated to soft modes of transport, in particular near to shops, places of work, parks and playgrounds.

Figure 3.3: Footbridge for pedestrians and cyclists ensuring the continuity of their paths.

The energy consumption of the transportation sector can be decreased by up to 19% through reducing car journeys by between 10% and 20%, and increasing up to 60% displacements by bicycle (for distances less than 12 km) and walking (for distances less than 1 km). Concerning the share of cycling as the main mode of transport, the European Cyclists' Federation reported an average share of 8% of all trips travelled by bicycle for the EU-27 in 2014, varying from 0% in Malta, to 23% in Denmark and 36% in the Netherlands (Nematchoua et al. 2020, 5). At the local level, the share of cycling can be as high as 60% – for example, in the Dutch city of Groningen. In Paris, 46% of trips are made by walking, 25% by car and 25% by public transport.

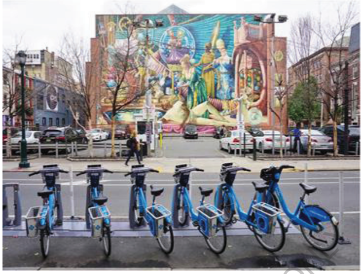

Figure 3.4: The Indego bike share system in Philadelphia (US).

3.2.2 Fuel switching and improving the efficiency of vehicles

Fuel switching can be a strategy to reduce GHG emissions in the transport sector, by using fuels that emit less carbon than those currently being used. Alternative sources can include electricity from renewable sources (such as wind and solar), hydrogen, or fossil fuels that are less CO_2-intensive than those they replace. A recent meta-analysis of 11 independent LCA studies concluded that a **battery-powered electric car** (see Figure 3.5) over its entire lifetime produces 50% fewer CO_2 emissions than an average new car in the EU in 2020.

Figure 3.5: Battery-powered electric car.

For **hydrogen-powered vehicles**, a fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is one that uses a fuel cell to power its on-board electric motor. Fuel cells in vehicles usually generate electricity using oxygen from the air and compressed hydrogen. Most FCVs are classified as zero-emission vehicles that only emit water and heat. The engine of a hydrogen vehicle is said to be carbon free, as it does not directly emit GHGs. However, the prior production of the hydrogen consumed and the embodied energy necessary for the manufacture of the vehicle strongly modify this qualification. Hydrogen is an energy carrier that can be produced from various feedstocks, influencing GHG emissions of hydrogen-powered vehicles with varied environmental impacts. Finally, the cost of manufacturing hydrogen-powered cars in 2018 was about three times that of petrol cars. FCEVs and the hydrogen infrastructure to fuel them are in the early stages of implementation.

Shown below are some examples of the application of low CO_2 emission fuels:

- public buses that are fuelled by compressed natural gas rather than petrol or diesel,
- electric or hybrid automobiles, provided that the electricity is generated from low-carbon or non-fossil fuels,
- renewable fuels such as low-carbon biofuels.

Using **advanced technologies, design and materials**, as well as operating practices, may help to develop more fuel-efficient vehicles. For example, the following technological and vehicle design improvements could have a favourable impact on GHG emissions:

- Using electric vehicles fitted with a battery, powered by renewable solar energy, in order to store the electricity and use it for power later. Indeed, electric vehicles can be effectively used as smart-charging batteries to help balance the electricity grid.
- Reducing the aerodynamic resistance of vehicles through better shape design.
- Reducing the weight of materials used to build vehicles.

The broad implementation of **autonomous vehicles (AVs)** can be a turning point in terms of reducing emissions of GHGs. It may be expected that in total the reduction will be by approximately 40–60% (Iglinski and Babiak 2017, 353-358). The greatest reduction in emissions may be brought about by a change in the mobility model and the transition from the currently common practice of owning private cars to car-sharing and ride-sharing. Fully autonomous cars should also reduce the number of parking spaces that are needed in public spaces.

Figure 3.6: Autonomous, electric-powered bus, Olli, in 2016 in the US.

Practices that minimise fuel use in vehicles include strategies to **improve driving practices** and **vehicle maintenance**, such as:

- Making the population aware of the impact of driving style on vehicle emissions (e.g. avoiding rapid acceleration and braking, observing the speed limit).
- Reducing the average taxi time for aircraft.
- Improved planning of journeys by ships due to better weather routing, for increased fuel efficiency.

3.3 Forecast scenarios to analyse potential mobility trends by 2050

This section analyses forecast scenarios of energy consumption related to the mobility of inhabitants in the city of Liège (Belgium) by 2050 (Nematchoua et al. 2019, 523-534). This study is based on provisional mobility scenarios developed by ADEME in France (Theys and Vidalenc 2014, 305).

3.3.1 Scenario 1: Passive behaviour, wait-and-see

In this scenario, it is assumed that nothing different will be done in the future: no new political decisions, and no advances or technological innovations in the area of mobility. As a consequence, we observe that energy consumption increases linearly with population growth.

3.3.2 Scenario 2: Smart wait-and-see

In the second scenario, society applies a strategy of smart wait-and-see. Communities do not make long-term decisions because of the uncertainty in which change agents live. Renewable energies are developing slowly. New green technologies (including vehicles) do not find a sufficient market and are therefore underdeveloped. This scenario is focused on “no regrets” policies, which allow the society to obtain benefits in terms of employment and urban attractiveness, as well as poverty reduction.

No long-term policy is carried out. Local policies evolve according to fluctuations in the context, and seek to both absorb shocks and exploit opportunities. They are hit by a stagnant economy, and an explosion in unemployment and social spending. Then, a “window of opportunity” opens, marked by a remobilisation on climate or energy issues, and a more favourable economic context. This scenario allows pursuing for a second time environmental policies, but it is too late: they do not prevent a new oil shock of much greater magnitude than previous ones. In this scenario, the event affecting transport energy consumption the most is the oil shock of 2035. People face a radical breakup.

3.3.3 Scenario 3: Carbon creativity

Carbon creativity is a forecast scenario based on the fact that energy and climate actions can only be effective if appropriate price or tax signals are put in place. This is an industrial policy scenario, based on the expectation that domestic companies will be able to take advantage of a high carbon price. The engine of the scenario is interest, in the sense of economic rationality. Cities follow the technological movement and invest in local innovation, while setting up the essential networks (e.g. for electric cars), encouraging experimentation, and supporting new services and training in new trades by multiplying public–private partnerships.

The choice is made to develop electric vehicles and to increase the share of electric cars to 40% by 2050. The principle of “yield management” is developing for all modes of transport. We are in a state of generalised urban optimisation. Teleworking and teleconferencing are very strongly extended or encouraged. Some companies go so far as to set up annual travel quotas. All of this opens up much greater opportunities for working from home. We are entering an economy of functionality. In the area of mobility, manufacturers could sell their vehicles to private mobility operators, who offer monthly packages to their customers.

3.3.4 Scenario 4: New climate and energy infrastructure

The fourth scenario places investment in cities at the heart of the energy and climate transition. As far as mobility is concerned, the aim is to invest widely in public transport and infrastructure for soft modes, wherever it pays off in the long term. The goal is to obtain, in each city centre, the objective of "three thirds" – a third of cars, a third of public transport and a third of soft modes – by constructing new infrastructure and asking for large investments. The assumption is that this will be offset by future savings and a better quality of life. This scenario shows increased attention to social aspects. However, new public or private resources must be able to finance investments.

In this scenario, communities plan to invest massively in new public transport infrastructure as an alternative to the car, generating an urban renaissance. Network creation and extension projects should begin in the decade 2025–2035. In this scenario, let us assume that the total distance travelled by car each year will not change straight away, but it will reduce by 10% in 2030 and by 40% in 2050, being replaced by use of the train, tram, metro, etc. Moreover, the energy consumption of various vehicles will decrease by 10% in 2030 and by 20% in 2050. This scenario, in addition to offering a massive investment strategy, carries the highest ambition for the modernisation of cities. This is arguably the most obvious path to the post-carbon city. However, there will be urban sprawl and uncontrolled localisation dynamics, and below a certain density, public transport infrastructure is not profitable. It also risks creating large inequalities between cities and rural areas.

3.3.5 Scenario 5: Biopolis

The biopolis offers a hybrid of nature, city and countryside. It is the design of a new form of integration between the city and nature, which is more attractive for those who live there and productive of more effective solutions to energy issues and climate risks. In this fifth scenario, rather than making cities even more crowded, they will be expanded and made sustainable. We are talking about green medium-density neighbourhoods, offering large green areas. The trigger for this scenario is energy decentralisation, through a rapid development of renewable energy sources and improved energy stockage, combined with large green public spaces, such as parks, urban forests, etc. Biochemistry, recovery of biomass waste and recycling are the pillars of the circular economy. This scenario favours the quality of life of the inhabitants throughout the national territory. Given the size of urban areas, many cars continue to circulate but 20% run on biofuel and 60% are electric in 2050.

3.3.6 Scenario 6: Mixed uses and density

Here, local and regional authorities engage in policies for the organisation of their space and mobility, which should make it possible to relocate activities and housing in order to design a denser, and more structured and accessible city. This scenario strongly links local climate policy tools with those of urban planning. It also introduces into local taxation an explicit consideration of localisation, which allows housing and employment to be brought closer together and to contain urban sprawl. Traffic in the city centre is limited and the nearby suburbs are the privileged places for building densification (through plot division, roof stacking, etc.). In this scenario, the total distance travelled each year will be reduced by 10% in 2030 and by 20% in 2050. There is also a reduction in car use of 10% in 2030 and 40% in 2050, with people transferring to modes of public transport; plus, 5% of cars will be electric in 2030 and the figure will be 15% in 2050.

This scenario is only possible on three conditions: greater sensitivity to climate risks, institutional and land policy reforms, and infrastructure development. Thanks to the compactness of the city, it is possible to effectively reduce GHG emissions and oil consumption, especially in transport. But these results require a long process of transformation of urban forms, and a major reform of the territorial organisation and local taxation. But is the time required for this process compatible with the challenges of the post-carbon city? In addition, this territorial transformation is irreversible; there is the risk of a lack of resilience (epidemics, etc.). However, the emphasis is on anticipation and, therefore, in the long term this scenario provides operational savings.

3.3.7 Comparison of scenarios

A comparison of the results shows the influence of these forecast scenarios on city transport energy consumption for an average working day in 2010, 2030 and 2050 (see Figure 3.7). The best option seems to be the smart attendance scenario, which gives the lowest levels of energy consumption in 2030 and 2050. However, this result is caused by the biggest oil crisis ever encountered, and is related to a catastrophic economic and social context. The most interesting scenarios are "Biopolis" and "Carbon creativity", but "New climate and energy infrastructure" and "Mixed uses and density" also lead to reduced consumption compared with 2010 values. An analysis of these scenarios shows the need to act now, and to think of long-term solutions and policies. Most sustainable scenarios require very strong political decisions and a social acceptance that is far from being obvious in the current context. Finally, a combination of several of these scenarios is also possible.

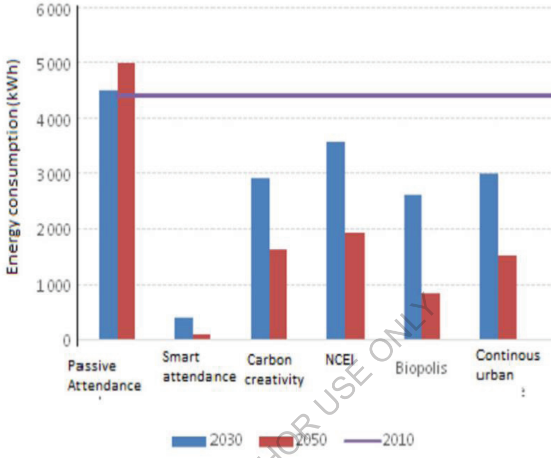

Figure 3.7: Influence of forecast scenarios on city transport energy consumption for an average working day in 2010, 2030 and 2050 (Nematchoua et al. 2019, 523-534).

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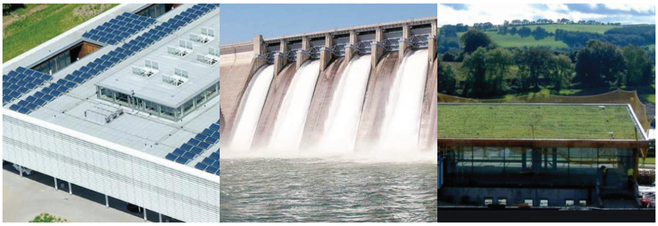
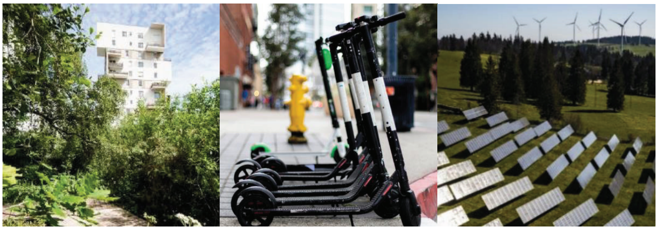
Part 2: Complementary challenges for sustainable cities

Chapter 4: Strategies to reach zero-energy and low-carbon targets in the industrial sector and energy production



Chapter 5: Strategies to reach zero-energy and low-carbon targets in waste treatments

Chapter 6: Strategies to reach zero-energy and low-carbon targets in cities – 20 summary questions



Chapter 4: Strategies to reach zero-energy and low-carbon targets in the industrial sector and energy production

All roofs on the 4120m² of this warehouse complex, built by Mattig & Lindner in Germany, are entirely covered by photovoltaic solar panels.

4.1 Industrial sector emissions

The solution to human-made climate change is finally in full view. Thanks to rapid advances in zero-carbon technologies in industries, including energy production, the world can truly reduce GHG emissions by the middle of the century, with decisive safety and security benefits to health. The main obstacle is inertia: politicians continue to favour the fossil fuel industry. Most of climate change – as well as the huge burden of air pollution – is the result of the use of fossil fuels: coal, oil and gas.

A report by the NGO Carbon Disclosure Project (CDP) produced in collaboration with the Climate Accountability Institute reveals that fossil fuels are the largest source of anthropogenic GHG emissions in the world: the fossil fuel industry and its products accounted for 91% of global industrial GHGs in 2015 (Griffin 2017, 14).

Reaching zero-carbon emissions by the middle of the century would probably guarantee the objective of limiting global warming to 1.5°C compared with the pre-industrial temperature. But, despite an increase in the share of gas (a less carbon-intensive fuel), coal production has caused an increase in the overall emissions intensity of fossil fuels since 1988 (by 2.4%) (Griffin 2017, 14).

An industrial strategy aiming at reducing the carbon rate requires the implementation of a set of political objectives. The different climate change mitigation targets specify the extent of the transformation requested; the different strategic objectives should be compatible with the achievement of this transformation in the most beneficial economic and social ways (Busch et al. 2018, 114-125).

The power industry produces 43.75% of the world’s total CO_2 emissions, through electricity and heat generation. But if electricity and heat generation are reallocated to the sectors that use them, 38.84% of the world’s total CO_2 emissions will still be generated by industry. The mains types of industries are: energy production, food, construction, military defence, distribution, electronics, equipment, mechanics, machining and metal, printing and paper, furniture and wood components, pharmaceuticals and natural products, plastics, doors and windows, mineral products, health and paramedical, sawmills, textiles and shoes, transport, and aerospace. These industries can be classified into several categories.

The 10 most polluting industries in the world are related to energy production and are listed below (Business AM 2018, 1):

- China National Coal Group – China is considered the largest producer of coal in the world. The China National Coal Group alone is responsible for 14.32% of GHG emissions in the world. It is a major national industry, which combines coal production and trade, integrated utilisation of coal, and the manufacture of coal mining machinery.

- Saudi Arabian Oil Company (Amarco) – This is the Saudi national oil company. It owns all of the country's hydrocarbon resources and is by far the largest oil company in the world. Indeed, it produces 10.5 million barrels of oil per day. On the gas side, it produces an average of 260.8 billion barrels per day. As a result, it achieved a turnover of 318 billion in 2015. Also, Amarco is responsible for 4.50% of global CO_2 emissions.

- Gazprom – This company is responsible for 3.91% of global CO_2 emissions. It was the first stock market valuation on the European continent. In 2004, Gazprom produced 93% of Russia's natural gas, while controlling 16% of the world's production. Gazprom alone contributed 20% to the budget of the Russian state. It employs over 400,000 people. In addition to immense gas reserves, the company has the largest network of gas pipelines in the world.

- National Iranian Oil – This is a public company that produces and distributes oil and gas across the country. On its own, it accounts for 2.28% of global CO_2 emissions. The industry is all-powerful in the country since it holds all of Iran's hydrocarbon reserves. What this represents is simply breathtaking: the oil reserves stand at 561.9 billion barrels and 41.14 trillion m^3. Production on such a scale directly implies high pollution.

- ExxonMobil Corp. – The company's oil fields are estimated to hold the equivalent of 22.4 billion barrels of oil. As a result, it emits 1.98% of global GHGs.

- Coal India – This is the leading producer of coal in India. It is responsible for 1.87% of global CO_2 emissions. In 2017, the company produced more than 550 million tons of coal from its 471 mines spread across the territory.

- Petroléos Mexicanos (PEMEX) – This company produces 1.87% of global CO_2 emissions.
- Russian Coal Company – This company is in 8th position in the ranking of the most polluting industries in the world, being responsible for 1.86% of global CO_2 emissions. A total of 14.4% of Russian electricity is produced by coal. Total reserves owned by the company are estimated at 173 billion tons.
- Royal Dutch Shell PLC – Shell is one of the largest oil companies in the world, with 94,000 employees. The company is involved in all aspects of the energy sector: prospecting for deposits, extraction of oil and natural gas, refining, petrochemicals and sales.
- China National Petroleum Corp. – On its own, this company accounts for 1.56% of global CO_2 emissions.

4.2 Low-carbon emissions in industry

Generally, two main perspectives concern the different social and economic benefits of a low-carbon transformation due to low-carbon industries (Perez 2002, 1; Ockwell and Byrne 2017, 230; Stern 2007, 712; Fouquet 2016, 16,098-16,105):

- The possibility that the adoption of low-carbon technology could stimulate economic development. Thus, this perspective identifies innovation as the main engine of economic dynamics and development.
- The low-carbon transformation of industries is important for the strategic objectives of a global carbon transformation, by focusing on competition for innovation rather than price competition as the main mechanism for co-ordinating the economy.

Moreover, low-carbon industries present multiple benefits to ecosystem resilience, trade, employment, health, energy security and competitiveness (Clapp et al. 2010, 56). Low-emission development strategies for the industrial sector can prioritise the protection of carbon-rich ecosystems, to not only reduce emissions but also protect biodiversity and safeguard local livelihoods, and to reduce rural poverty – all of which can lead to more climate-resilient systems, according to the Low Emission Development Strategies Global Partnership (Raghav 2016, 1-6).

Achieving low-carbon emissions in the industrial sector is not easy. The following rules should be adopted to reduce industrial CO_2 emissions:

- Increase the efficiency of materials across the value chain**.** This could reduce between 58 and 171 Mt of CO_2 per year until 2050 in the case of heavy industries in the EU.
- Improve co-ordination throughout the value chain for eco-design and increased product lifespan.
- Introduce new production methods and techniques to reduce the waste produced by industry.
- Ensure greater efficiency in the use of materials and technologies for capturing and storing CO_2.
- Improve industrial buildings by the strategies explained in chapters 1 and 2.

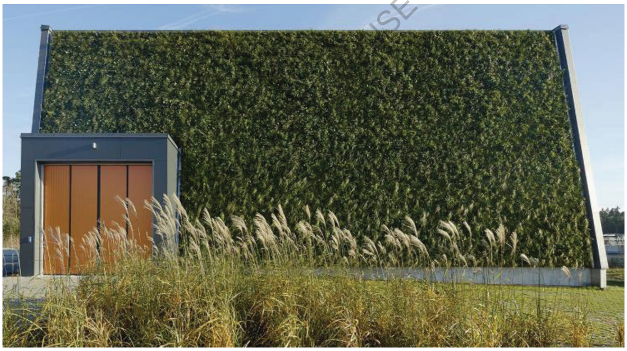


Figure 4.1: The new waste Envac vacuum system terminal in Stora Ursvik (Sweden), designed by Tengbom, is a BREEAM-certified industrial building. The collection station building is covered by a 250 m^2 green wall containing 2000 plants and over 20 varieties of grasses and herbs.

As one of the three major sectors of energy consumption, industrial enterprises are under pressure regarding energy saving and emission reduction; industrial building energy consumption represents more than 50% of their total consumption (Wang et al. 2019, 370-385). Therefore, it is essential to develop green industrial buildings to achieve targets for reducing CO_2 emissions. Energy efficiency recommendations involve energy savings by insulating industrial buildings and eliminating energy waste (heat recycling, etc.) – for example, through heating networks – while improving combustion plants and processes. Using renewable energy sources, bio-based materials, growing plants (green roofs, etc.) and CO_2 sequestration techniques should make it possible to develop zero-carbon industrial buildings. In most cases, the shape of industrial buildings and their flat roofs make them an ideal application for large-scale installation of solar panels and/or green roofs.

Industry wastes potentially recoverable heat equal to around 36% of its fuel consumption, half of which is lost at a temperature of more than 100°C. Industry therefore represents enormous potential for supplying zero-carbon urban heating networks. In addition to the recoverable heat from industry, there is a large amount of heat lost at waste incineration units, water purification stations and data centres. Waste incineration now provides 28% of all the energy distributed by French heating networks, which is much greater than geothermal energy and biomass (14%). Biogas and industrial heat recovery represent only around 2.5% of the total. However, their location is sometimes too peripheral to be significantly useful. But it is certain that this industrial heat recovery is currently underutilised. An example of recovering industrial heat is the Dunkerque heating network, in France, which takes advantage of industrial waste heat from the Arcelor industrial site. This network heats buildings equivalent to 16,000 houses and avoids the emission of 30,000 tons of CO_2 each year.

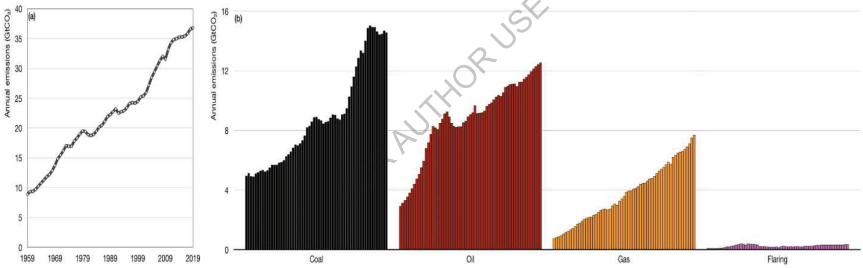
Busch et al. (2018, 114-125) identified five elements for a low-carbon industrial strategy, which show how political interventions are necessary. These different elements are drawn from the synthesis of neo-Schumpeterian and ecological-economic theories of industrial evolution. They represent the framework of a low-carbon industrial strategy, as follows: (1) define and enable a low-carbon industrial mission – for example, favouring a circular economy, (2) create markets through demand, (3) shape markets by identifying opportunities and rewarding successes, (4) stimulate investment, and (5) integrate learning approaches into governance. A low-carbon industrial strategy needs to focus on creating the systems to support low-carbon activities. A strategic and systemic policy process should recognise these industries as part of indispensable supply chains, and reimagine their role in future low-carbon and circular economies.

In the 27 countries that make up the EU, the following rules have been set to facilitate industries to reduce their CO_2 emissions:

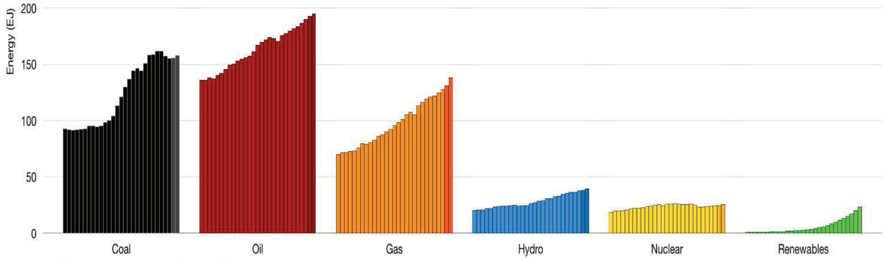
- Offering a bonus to further support green business investments.
- Imposing a carbon tax at the borders of the EU to reduce the carbon footprint generated by industries.
- Using public contracts so that the clauses better integrate environmental issues.
- Setting up tax assistance for business investments to decarbonise their production.
- Obliging and supporting industries to adapt their production tools to reduce their emissions by providing them with capital at negative interest.

4.3 Emissions related to energy production

Low-carbon power comes from processes or technologies that produce power with substantially lower amounts of CO_2 emissions than are emitted from conventional fossil fuel power generation. It includes low-carbon power generation sources such as wind, solar, hydro and nuclear.



(a) World fossil fuel and cement CO2 emissions, 1959-2019.



(b) World primary energy supply, 1990 to 2018

Figure 4.2: CO_2 emissions (1959–2019) and world primary energy supply (1990–2018) (The World Energy System 2019, 2).

For many decades, world energy use and CO_2 emissions have been increasing. Figure 4.2 shows CO_2 emissions generated by various energy sources from 1959 to 2019, and the world's primary energy supply between 1990 and 2018 (The World Energy System 2019, 2). Fossil fuels accounted for 65% of electricity generation, and the annual increase in fossil-fuelled electricity generation was 9% greater than the combination of hydro and renewables.

Even when electricity and heat generation are reallocated to the sectors that use them, energy production accounts for over 12% of global GHG emissions. The emission concentration was estimated to be around 37 $GtCO_2$ in 2019, with over 45% coming from coal and 35% from oil.

According to the International Energy Agency (IEA 2020, 1), for the first time in more than 30 years, CO_2 emissions from the electricity sector decreased by 2% worldwide in 2019. This result is largely explained by the 3% drop in emissions linked to the production of electricity from coal. In 2019, the average carbon intensity of electricity produced by advanced economies was 340 gCO_2/kWh, which corresponds to a reduction of almost 6.5% compared with 2018.

The two main strategies to reduce CO_2 emissions during energy production are: (1) a radical decarbonisation of the energy mix by 2050, and (2) accelerated energy efficiency gains.

4.3.1 A radical decarbonisation of the energy mix by 2050

Achieving the goal of a radical decarbonisation of the energy mix by 2050 will require a massive reduction of emissions generated by the production of electricity and heating networks. This scenario is based on an assumption of significant deployment of carbon capture and storage technology by 2050. This strategy aims to:

- Avoid investments in new fossil fuel thermal production as much as possible. In fact, the IEA and other international organisations will have to control precisely the demand for new thermal production, according to the orientations taken on the other sectors, security of supply objectives and the need for flexibility of the electricity system, in compliance with carbon budgets and long-term decarbonisation targets for the system.

- Reduce emissions from existing energy production facilities, by the use of a sufficiently high carbon price.

- Provide possibilities for deploying carbon capture and storage systems or the use of carbon for fossil-fired power plants that will operate by 2050, taking particular account of storage possibilities when choosing the location of energy production facilities.

- Improve the flexibility of the system without increasing emissions; integrating renewable energies will ultimately require increased flexibility. This means, in particular: developing the flexibility capacity of the hydroelectric power sector, because this renewable energy sector allows a significant peak production; developing smart grids and storage adapted to needs – weekly storage to cope with the intermittency of wind power by 2030, and daily storage to manage photovoltaic production after 2030 when it reaches significant levels; developing transfers between energy systems (power to gas, power to heat); and developing interconnections with neighbouring countries to maximise the production of renewable energy.

4.3.2 Accelerated energy efficiency gains

Energy efficiency can be improved at the level of centralised production methods and in the energy choices of each country. This energy efficiency related to energy production can be achieved by the following solutions:

- By increasing the energy efficiency of the installations and limiting losses during energy production, transport and distribution, through the use of more efficient technologies. For example, this could include the replacement of old coal-fired power stations by supercritical-steam-powered stations or by combined gas cycles, using the combined production of heat and electricity (cogeneration). The electricity network supplies buildings, transport and heavy industries. Optimising the electricity network helps to limit energy losses during the transport and distribution of electricity. As electricity can be produced from renewable sources, it may be necessary to electrify future uses as much as possible, in order to reduce GHG emissions. The climate emergency is imposing important changes on energy production to achieve carbon neutrality and the electrification of new activities seems likely to happen. Reducing electricity losses through the network will therefore be a priority.

- By using low-CO_2 emitting sources as a means of energy production, such as nuclear energy (non-renewable) or renewable energies. Six examples of low-CO_2 emitting energy production modes are: hydroelectric power, nuclear power, wind turbines, solar photovoltaic panels, solar thermal panels and bioenergy – these modes are described in more detail below.

Hydroelectric power

Hydroelectricity is electricity produced from hydropower. In 2018, hydropower generated over 16.6% of the world's total electricity and around 70% of all renewable electricity, and was expected to increase by about 3.1% each year for the next 25 years (IEA 2020, 1).

Hydroelectric plants have the advantage of being long-lived and many existing plants have operated for more than 100 years. Hydropower is also an extremely flexible technology from the perspective of power grid operation. Large hydroelectric plants provide one of the lowest cost options in today's energy market, even compared with fossil fuels, and there are no harmful emissions associated with their operation (IAEA 2020, 1). Typically, there are low GHG emissions associated with the use of reservoirs.

Nuclear power

Nuclear power involves the use of nuclear reactions that release energy to generate heat, which most frequently is then used in steam turbines to produce electricity. Nuclear power can be obtained from nuclear fission, nuclear decay and nuclear fusion reactions. Currently, the vast majority of electricity from nuclear power is produced by nuclear fission of uranium and plutonium. Nuclear decay processes are used in niche applications such as radioisotope thermoelectric generators. Generating electricity from fusion power remains at the focus of international research (IEA 2019, 1).

Civilian nuclear power supplied 2563 TWh of electricity in 2018, equivalent to about 10% of global electricity generation, and was the second largest low-carbon power source after hydroelectricity (IEA 2019, 1). In December 2019, there were 443 civilian fission reactors in the world, with a combined electricity capacity of 395 GW. There are also 56 nuclear power reactors under construction and 109 more reactors planned, with a combined capacity of 60 GW and 120 GW, respectively (World Nuclear Association 2020, 2). The US has the largest fleet of nuclear reactors, generating over 800 TWh of electricity per year, with an average capacity factor of 92% (Office of Nuclear Energy 2020, 1).

Nuclear power has one of the lowest levels of fatalities per unit of energy generated compared with other energy sources. Coal, petroleum, natural gas and hydroelectricity each have caused more fatalities per unit of energy due to air pollution and accidents (Markandya and Wilkinson 2007, 979-990). Since its commercialisation in the 1970s, nuclear power has prevented about 1.84 million air-pollution-related deaths and the emission of about 64 billion tons of CO_2 equivalent that would have otherwise resulted from the burning of fossil fuels (Kharecha and Hansen 2013, 4889-4895). However, accidents do occur at nuclear power plants and include the Chernobyl disaster in the Soviet Union in 1986, the Fukushima Daiichi disaster in Japan in 2011, and the (more contained) Three Mile Island accident in the US in 1979.

There is, of course, a debate about nuclear power. Proponents, such as the World Nuclear Association and Environmentalists for Nuclear Energy, contend that nuclear power is a safe, sustainable energy source that reduces carbon emissions. Nuclear power opponents, such as Greenpeace and NIRS, contend that it poses many threats to people and the environment, in particular in relation to the risk of accidents and the difficult management of nuclear waste. Collaboration on research and development towards greater efficiency, safety and recycling of spent fuel in future generation IV reactors currently involves Euratom and the co-operation of more than 10 permanent member countries globally.

Wind turbines

Wind energy can be used to generate electricity via a turbine, an example of which is shown in Figure 4.3. From an operational point of view, a wind turbine consists of a mast, a rotor or propeller composed of several blades with a vertical or horizontal axis, and a generator which transforms mechanical energy into electrical energy. The energy produced can be used on-site or connected to the grid.

Figure 4.3: Wind turbine.

With the ability to supply individual buildings, the micro wind turbine (with a power less than 1 kW) and the small wind turbine (with a power between 1 and 20 kW) can represent, in regions with regular and frequent winds, an alternative to fossil-fuel energy. Depending on the power and regularity of the wind, a 5 kW wind turbine that rotates for 2000 hours per year at its nominal power can produce the equivalent of the annual consumption of a household of five people. Nevertheless, it is often logical to group together the needs of various buildings in order to benefit from larger wind turbines, which have a better performance. Over the past 40 years, the size of the largest wind turbine has increased from 75 kW to 5000 kW.

<u>Solar photovoltaic panels</u>

Solar energy is available everywhere on Earth and theoretically represents 900 times the global energy demand. Photovoltaic solar energy is the electricity produced by transforming part of the solar radiation using a photovoltaic cell. Schematically, a photon of incident light makes it possible under certain circumstances to set in motion an electron and thus produces an electric current. Two technologies are mainly used today:

- First-generation panels that use silicon. These panels represent 85% of the global photovoltaic market.

- A second generation of panels, known as thin layers, have also developed on the market. They are more efficient but also more expensive because they use rarer minerals (indium and telluride). They represent 15% of the world market.

An area of 25 m^2 of photovoltaic panels, located in the north of France, can produce in one year as much green electricity as the annual consumption of a family of four (excluding heating, cooking and hot water), or approximately 2500 kWh. It is preferable to orient the photovoltaic panels to the south in the case of countries located in the northern hemisphere, with an inclination of 37° with respect to the horizontal; and towards the north with an inclination close to 45° for countries located in the southern hemisphere. Solar panels have a lifespan of over 30 years and are largely recyclable. The challenge of current research is to improve yields and reduce the costs of photovoltaic cells.

Solar thermal panels

Solar thermal panels are often used to provide partial or total domestic hot water (DHW), and, more rarely, to provide building heating. They are also very useful for producing hot water for laundries, swimming pools, hotels, restaurants, hospitals, etc. This practice effectively limits GHG emissions, which is why this system is strongly encouraged by many states and local authorities via taxation and bonuses (ecological bonus, tax credits). In a temperate climate, a solar water heater provides 40–80% of a family's hot water needs. There are three types of solar thermal panels:

- flat non-glazed collectors: water circulates in a generally black absorber open to the air,
- flat glass collectors (most common),
- vacuum tube collectors, composed of solar collectors primed to a heat collector on which vacuum glass solar tubes are fixed.

Bioenergy

Bioenergy is renewable and made from materials derived from biological sources. Biomass is any organic material that has stored sunlight in the form of chemical energy. As a fuel, it includes wood, wood waste, straw and other crop residues, manure, sugarcane, and many other by-products from a variety of agricultural processes.

In its narrowest sense, bioenergy is a synonym to biofuel, which is fuel derived from biological sources. In its broader sense, it includes biomass, the biological material used as a biofuel, as well as the social, economic, scientific and technical fields associated with using biological sources for energy. From a scientific point of view, bioenergy is the energy extracted from the biomass, and the biomass is the fuel.

Biomass is the material derived from recently living organisms, which includes plants, animals and their by-products (US Department of Energy 2020, 1). Manure, garden waste and crop residues are all sources of biomass. It is a renewable energy source based on the carbon cycle, unlike other natural resources such as petroleum, coal and nuclear fuels. Another source of biomass includes animal waste, which is a persistent and unavoidable pollutant produced primarily by the animals housed in industrial-sized farms.

One of the advantages of biomass fuel is that it is often a by-product, residue or waste-product of other processes, such as farming, animal husbandry and forestry. In 2019, using biomass for energy prevented more than 30 million tons of organic waste – from construction and demolition activities, used tires, and papermaking by-products, for instance – from being landfilled in the US. Moreover, sustainable forest waste recovery allows a healthy forest to grow and reduces the threat of forest fires.

Bioenergy from sustainable biomass production (for example, coming from sustainably managed forests) is carbon neutral because plants and trees re-absorb CO_2 as they grow. However, burning plant-derived biomass releases CO_2, VOCs, particulates and other pollutants, but it has been classified as a renewable energy source in EU and UN legal frameworks, considering the sustainable management of biomass production. In practice, for a particular bioenergy project to be carbon neutral, the total carbon sequestered by a bioenergy crop's root system must compensate for all the emissions from the related above-ground bioenergy project. This includes any emissions caused by direct or indirect land use change and by biomass transport.

To bring climate benefits, wood biomass also needs to come from a working forest that is returned to a forest after harvest, not from a forest that is converted to agriculture or another use after trees are felled. It should also come from low-value wood residues or smaller trees coming from timber harvests, not from high-value trees that could be used in products like furniture or construction material. It is necessary to protect primary and old-growth forests, which have significant impacts on the world's biodiversity and keep removing carbon from the atmosphere. Biomass should always come from sustainable production, with stable or increasing tree stocks.

Another advantage of bioenergy as a renewable power source is that it can operate 24/7. It is thus a consistent and reliable source of energy. As of 2020, biomass produced 60% of the EU's renewable energy, which is more than solar and wind power combined, according to the EU's statistical office (Eurostat).

Biomass can be used for heat or electricity production. With intermittent wind and solar energy providing the electricity base load, biomass is well positioned to provide the peak load. Biomass can help the electricity grid to become greener, especially in countries where the sun produces less energy during some seasons.

In biomass power plants, wood waste or other biomass is burned to produce steam that runs a turbine to make electricity, or to provide heat to industries and heating networks. Due to new technologies for pollution control, emissions from burning biomass in industrial facilities are generally lower than emissions produced when using fossil fuels. It is essential to use performant cleaning processes that keep emissions low and to reuse the produced ash.

But when biomass is used for low-temperature heating – for heating individual houses, for example – it is not the most efficient solution at this scale, and it also generates pollutants and particulates which are not sufficiently well filtered on small installations. Instead, biomass should be used as a priority for industrial purposes, heavy-duty road transport, shipping and aviation, where biofuels can provide an alternative to hydrocarbon-based fossil fuels. For buildings, biomass should preferably be used in industrial settings or urban heating networks that supply heat to an entire district or even a city.

Finally, there is sometimes competition between the production of fuel, food and wood, although this is not always the case. Land use, existing biomass industries, relevant conversion technologies and pollution control technologies must be considered when evaluating the suitability of developing biomass as a feedstock for energy (Kosinkova et al. 2015, 1271-1285). Transporting biomass over large distances should also be avoided.

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Chapter 5: Strategies to reach zero-energy and low-carbon targets in waste treatments

High-grade compost produced from bio-organic waste.

5.1 Environmental impacts of waste management

One of the most significant global environmental agendas in the 21st century is sustainable waste management (UNEP 2012, 21). The emission of waste produced by humans has a significant impact on environmental degradation. The strong population growth expected by 2050 could accelerate the production of urban waste. Increased generation of waste is also causing greater environmental degradation: in particular, pollution of land, water and air due to unsustainable waste disposal and management methods. However, according to an Intergovernmental Panel on Climate Change (IPCC) report, the waste sector only contributes less than 5% of global GHG emissions, which is very low compared with the energy production and industrial sectors (Bogner et al. 2007, Chapter 2). As a result, the waste sector has been given lower priority in terms of climatic adaptation and problem mitigation.

However, cities are currently responsible for 70% of the waste produced globally in the world. Nowadays, waste management in cities is becoming a major concern for both city officials and inhabitants. The potential for recovery or processing of any product and material must be valued. Waste released in a neighbourhood can be a resource in agriculture (Najih et al. 2014, 1). Waste management is done by chain: first, inside houses, followed by neighbourhoods and cities (Mickaël 2013, 173-209). Overall, the economic impact of waste is mainly influenced by food losses (Wang et al. 2012, 89-98). Food waste has an impact on the entire cycle of the chain, from the producer to the consumer. Indeed, 1 kg of food thrown away at the end of the chain amounts to producing a much larger mass of waste linked to the cumulative loss, at each stage of production (Manalili et al. 2014, 30).

Around the world, waste generation rates are still rising. In 2016, the world's cities generated 2.01 billion tons of solid waste, amounting to a footprint of 0.74 kg per person per day. With rapid population growth and urbanisation, annual waste generation is expected to increase by 70% from 2016 levels to 3.40 billion tons in 2050 (The World Bank 2017, 1). The generation of waste in terms of quantity per capita is highest in developed countries – for example, 700 kg or more in the US, Australia and a majority of European countries; between 440 and 700 kg in China and Russia; between 220 and 440 kg in South America; and 220 kg or less in the majority of African countries (Zaman and Swapan 2016, 32-41).

However, the management of waste is at least as important as the quantity produced. The EU, in its approach towards sustainable development, has fixed several objectives such as reducing volumes of household waste by composting, recycling materials with the recovery of 58% of packaging materials already achieved in 2000, and increasing the use of recycled materials in aggregates from 35 million tons to 50 million tons in 2005. These objectives are being respected by most of EU member states, so that waste management has greatly improved.

Compared with those in developed nations, residents in developing countries, especially the urban poor, are more severely impacted by unsustainably managed waste. In low-income countries, over 90% of waste is often disposed of at unregulated dumps (see Figure 5.1) or is openly burned. These practices create serious health, safety and environmental consequences. Poorly managed waste serves as a breeding ground for disease vectors, contributes to global climate change through methane generation and can even promote urban violence (The World Bank 2017, 1).

Figure 5.1: Urban waste disposed of at unregulated dumps (left); selective waste collection on a construction site (right).

Figure 5.2 shows the damage to biodiversity due to the life cycle (construction, use and end of life) of eco-districts located in 150 countries and modelled by an LCA, while adapting the energy mix, climate and use of materials (construction and waste treatment) in each country (Nematchoua et al. 2020, 81-97). A detailed analysis of the simulations showed that waste is the main cause of biodiversity loss due to an eco-district with high energy performance. The map shows that the degradation of biodiversity is highest in Africa, the Middle East and South Asia, because of their very high rates of non-recycled waste and industrial waste released into the natural environment without purification. This map demonstrates the importance of sustainable management of consumer and construction/demolition waste, as well as the need to strengthen our efforts to achieve a zero-waste society.

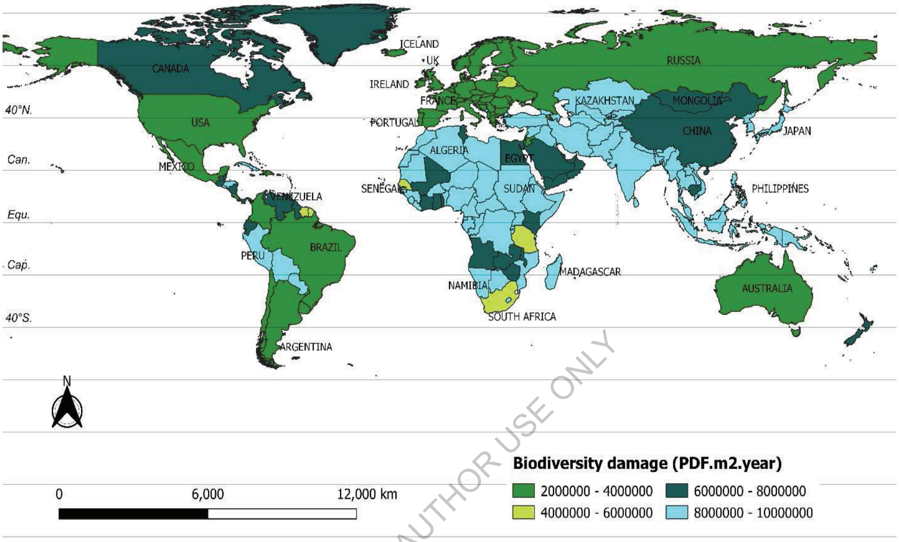

Figure 5.2: Damage to biodiversity (highly dependent on waste treatment) generated by 150 eco-districts, spread over all continents, and assessed over their entire life cycle (Nematchoua et al. 2020, 81-97).

Managing waste properly is essential for building sustainable cities, but it remains a challenge for many developing countries. Effective waste management is expensive, often comprising 20–50% of municipal budgets. Operating this essential municipal service requires integrated systems that are efficient, sustainable and socially supported.

5.2 Waste types

Waste can be classified into four main categories, for which specific methods of collection and treatment are implemented.

5.2.1 Household waste

Household waste arises through the daily life of households, and certain communities and traders, without dangerous characteristics for humans or the environment. It is waste that individuals produce throughout their life, at their places of residence or work.

There are six types of household waste: (1) organic household waste, such as food or garden waste, (2) paper and cardboard recyclable household waste (newspapers, magazines, cardboard boxes, etc.), (3) recyclable metallic and plastic packaging, such as plastic bottles and cans, (4) recyclable glass waste (bottles, pots, etc.), (5) inorganic household waste, such as non-recyclable plastics, soiled packaging, etc., and (6) special household waste, such as light bulbs, batteries, paint cans, etc. Sustainable management of waste consists of sorting it at the source and harvesting the different streams separately, to promote composting and the recycling of waste that allows it. Any residential, tertiary or industrial building should therefore have sufficient space and suitable devices to facilitate sorting and a separate collection of the different types of waste.

5.2.2 Industrial waste

Ordinary industrial waste is generated by a company and is not dangerous for humans or for the environment. Although it is not toxic, it must be treated, recovered or recycled. In fact, it can still burn, ferment, and rust, or take hundreds of years to decompose and pollute the environment. Ordinary industrial waste includes:

- Used packaging: pallets, cases, covers, cans, etc.
- Production waste: scrap, residues, sawdust, etc.
- User products: paper, unsold items, out-of-service equipment, bio-waste, etc.
- Materials: glass, metal, plastic, textiles, leather, paper, cardboard, wood, rubble, etc.

As with household waste, sustainable management of industrial waste consists of sorting it at the source and harvesting the different streams separately, to promote composting and the recycling of waste that allows it.

5.2.3 Hazardous waste

Hazardous waste is a polluting and toxic waste, which can represent a risk to health or the environment. It can be highly flammable, explosive, harmful, irritant, corrosive or even eco-toxic. Because of its toxicity, hazardous waste requires appropriate treatment, in accordance with national regulations. Hazardous waste is generated by various industries and households. Some examples of hazardous waste are solvents, paints, chemicals, etc.

5.2.4 Liquid waste

Liquid waste comes from sewerage and rainwater networks, septic tanks, other pipes and reservoirs. It requires specific sanitation interventions, such as wastewater treatments. Ecological engineering for wastewater treatment or ecological sanitation implies that principles of ecology are applied to the design and implementation of these systems.

Recycling may be facilitated if the wastewater is source separated into black water (toilet waste), grey water (water from showers, sinks, kitchens) and rainwater. The latter can be used inside buildings (for example, to supply toilets) or returned to the environment (by infiltration valleys, etc.).

Wastewater treatment through natural systems (ponds, wetlands, soil infiltration, etc.) can operate by gravity alone and do not need mechanical devices. One of their advantages is that they have low energy requirements. But efficient conventional sanitary systems (a centralised collection system and technically complex treatment processes) can produce an even better ecological result, by optimising resource gains and minimising resource use, at a large scale. For example, energy can be obtained from wastewater through the use of heat pumps and biogas can be generated from sludge. Optimised conventional systems can be cutting-edge ecological solutions.

5.3 Strategies to reach zero-emission waste

Zero-emission waste is a goal that is ethical, economical, efficient and visionary, to guide people in changing their lifestyles and practices to emulate sustainable natural cycles, where all discarded materials are designed to become secondary resources. Zero-emission waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them. Implementing zero-emission waste will eliminate all discharges to land, water and air, which are a threat to planetary, human, animal and plant health.

So, the sustainable management of waste requires choosing low-carbon-emission waste treatments. Waste treatment processes are a direct result of the management policy developed by the public authorities, and also of the international demand for raw materials or energy. The main strategies allowing a reduction of carbon emissions produced by waste treatments are recycling, composting, incineration and biomethanisation. These four solutions reduce waste sent to landfills, but require selective waste collection and sorting.

It is very difficult to reach the goal of zero-emission waste in a city. For example, the sustainable management of waste in building construction and renovation processes requires, first, a reduction of waste production, through various strategies such as: reuse of materials; use of recycled materials; making rational use of natural resources; designing for deconstruction and not demolition; and designing adaptable buildings, infrastructure and systems. Then, architects, engineers and construction workers should also apply sustainable treatments to the waste produced during the construction, renovation and demolition processes (construction debris, elements to be eliminated, etc.), through selective waste collection, sorting, composting, recycling, etc. Two specific actions to be implemented are:

- Installation of different containers to carry out selective sorting of construction debris and waste on all construction sites.
- During any renovation or deconstruction, make sure to separate the materials that can be reused and those that are recyclable, for optimal reuse of the waste.

5.3.1 Recycling waste

Recycling of waste arises in any recovery operation in which waste, including organic waste, is reprocessed into substances, materials or products for the purposes of their initial function or for other purposes. Recycling makes it possible to substitute used substances, materials or products in the place of new substances, materials or products. In developed countries (the US, EU, etc.), the most commonly recycled consumer items are aluminium cans, iron, aerosol cans, plastic bottles, glass bottles, glass jars, cardboard, newspapers and magazines. Other types of plastics (PVC, LDPE, PP and PS) are also recyclable but less commonly collected.

Waste consisting of a single type of material makes it easier to recycle. For example, recycling obsolete computers and electronic equipment is important but expensive because of the problems related to the separation and extraction of components. Much electronic waste is sent to Asia, where the recovery of gold and copper often causes environmental problems because the device screens contain lead and heavy metals, such as selenium and cadmium.

Recycled or reused materials compete with new materials. The cost of collecting and sorting materials explains why, when comparing their cost with new materials, they are often as expensive or even more. This is most often seen in developed countries, where the industries producing raw materials, in place for a long time, are well optimised. Some practices, such as informal waste recovery, can make recycling even less profitable, by removing the most valuable materials (such as aluminium cans). From an environmental point of view, it is essential to promote the use of recycled materials, in priority over the use of new materials. Recycling processes, which reduce the environmental impact of our waste, are only viable if the recycled materials and products are actually used in practice. In some countries, recycling programmes are subsidised.

5.3.2 Composting waste

Composting is an aerobic biological process for the conversion and recovery of organic matter (livestock by-products, biomass, organic waste from domestic sources, etc.) into a stabilised and hygienic product, similar to soil, and rich in humus and mineral compounds: compost. Composting can be done in composters at the scale of a household, a neighbourhood or a few households, or larger (city, region). It can be practised on plots of agricultural land to convert manure, or on platforms to convert household waste and biomass scraps. Composting can be a means of treating all or part of the urban bio-waste (Charnay 2005, chapters 2 and 3). Several phases follow one another in the composting process. When the quantities of material used are significant, the change in temperature of the heap makes it possible to follow the evolution of the composting and the monitoring of the temperature makes it possible to better manage these phases. A relatively high temperature is sought in breeding to break the reproductive cycle of living organisms at the expense of livestock health.

The first phase brings the material to the state of fresh compost; it is an intense aerobic degradation. The second phase is less sustained degradation; it will transform the fresh compost into ripe compost, rich in humus. During the degradation phase, the temperature increases because there is intense biological activity. The most degradable compounds, such as sugars, free amino acids and starch, are consumed first (Charnay 2005, chapters 2 and 3). The decomposition of fresh organic matter takes place under the action of bacteria and fungi, whose activity increases the temperature up to 50–70°C. The temperature rises rapidly to 40–45°C following the respiration of aerobic mesophilic microorganisms. Breathing then gradually raises the temperature to 60–70°C, which leads to the replacement of mesophilic microorganisms by thermophiles and thermo-tolerants. The degradation phase sees the mass of the compost decrease by the mineralisation of organic matter into CO_2 and by significant water losses through evaporation. During the maturation phase, the temperature decreases (Charnay 2005, chapters 2 and 3). After the degradation phase, the quantity of material easily usable by the microflora has already become scarce. We then witness the disappearance of thermophilic microorganisms in favour of more common species and new mesophilic species, while the temperature decreases, and over a long period of ripening, this stabilises at room temperature. Compost enters a constructive maturation phase, during which precursor elements of humus slowly appear.

From a carbon point of view, the impacts that composting have on GHGs fall into categories of avoidance and sequestration. Avoidance refers to situations where a new practice is undertaken that results in reduced emissions of GHGs into the atmosphere. Sequestration covers practices that result in carbon being put back into storage in the earth, such as increasing soil carbon concentrations. The United Nations (through the Kyoto Protocol) has developed approved methods for quantifying and crediting composting projects that reduce methane emissions. Composting can be a GHG conserving practice. Savings in GHG emissions as a result of composting operations are most beneficial when potential methane-emitting feedstocks are diverted from landfills or open storage lagoons into composting operations.

Figure 5.3: Illustration of composting waste (left); collective composting in a Belgian neighbourhood, receiving organic waste produced in the district during garden maintenance (right).

5.3.3 Incineration

Incineration is a technique for waste transformation by the action of fire. Incineration means "reducing to ashes" or, in other words, that the materials to be incinerated are completely burned. It is one of the waste management techniques that can be used to produce electricity and/or heat (used in district heating networks, for example), but which can also be a source of air pollution (Rogaume 2001, Chapter 2). Incineration has two sub-products: bottom ash and smoke purification residues.

Incineration has a limited recovery rate. It destroys the natural resources contained in the waste and it is not possible to recover 100% of the waste's calorific value. The energy recovered comes from cooling the combustion fumes in a boiler. The recovered heat can be used directly via a heating network or indirectly via a turbine, to produce electricity or superheated water. Incineration is identified in several developed countries as the second renewable source of energy for the production of electricity (after hydroelectric power) and for the production of heat (after biomass).

The incineration of solid waste produces a certain amount of air pollutants (dioxins, furans, heavy metals, acid gases, dust), for which specific emission limit values are set by regulations. During the 1990s, advances in the field of release control and new government regulations led to a massive reduction in the quantity of various air pollutants being produced, including dioxins and furans. The EU and the US Environmental Protection Agency (US EPA) have created very strict standards for the incineration of waste.

5.3.4 Biomethanisation

Biomethanisation is the natural biological process of degradation of organic matter in the absence of oxygen. It occurs naturally in certain sediments, marshes, rice fields and landfills, as well as in the digestive tract of certain animals such as insects (termites) or ruminants. Part of the organic matter is broken down into methane, and another part is used by methanogenic microorganisms for their growth and reproduction. Methanisation makes it possible to transform organic waste into biogas and thus produce a renewable energy (biogas), which can then be used to replace electricity or fossil fuel. It is one of the means of recovering organic waste, in particular that produced by agricultural holdings.

Methanisation is also a technique implemented in methanisers, where the process is accelerated and maintained to produce usable methane (biogas), which is called biomethane after purification (Moletta 2015, 686). Organic waste (or solid/liquid products from energy crops) can thus be recovered in the form of energy. Methanisation results from the action of certain groups of interacting microbial microorganisms constituting a food web. We classically distinguish four successive phases:

- Hydrolysis: This is a chemical and enzymatic reaction, in which a covalent bond is broken by the action of a molecule of water. For example, sucrose hydrolysis is defined by the following formula: sucrose + water → glucose + fructose.
- Acidogenesis: These substrates are used during the acidogenesis step by acidogenic microbial species, which will produce alcohols and organic acids, as well as hydrogen and carbon dioxide. This step is 30 to 40 times faster than hydrolysis.
- Acetogenesis: This stage allows the transformation of various compounds from the previous phase into direct methane precursors: acetate, carbon dioxide and hydrogen.
- Methanogenesis: This phase is ensured by strict anaerobic microorganisms that belong to the Archaea domain. This last step leads to the production of methane. It is carried out via

two possible routes: one from hydrogen and carbon dioxide by the so-called hydrogenotrophic species, and the other from acetate by the acetotrophic species.

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Chapter 6: Strategies to reach zero-energy and low-carbon targets in cities: 20 summary questions

In built environments, energy consumption and carbon emissions are mainly dependent on the construction and operation of buildings, transport modes, energy production methods, and urban waste management.

(Q1) What is a zero-energy building and does it necessarily consume little fossil energy?

A zero-energy building (ZEB) is one with net-zero energy consumption, which means that the total amount of energy used, calculated on an annual basis, is approximately equal to the amount of renewable energy generated on the site.

In theory, a ZEB could therefore be a large consumer of fossil energy, if it produces as much renewable energy as it consumes. But in practice, ZEBs are always at least low-energy buildings: they have important energy-saving characteristics, such as very good insulation and airtightness of the envelope, and energy-efficient systems (heat pump, condensing gas boiler, double-flow mechanical ventilation with heat recovery unit, high efficiency electrical appliances, etc.).

However, it is important to remember that, from an environmental point of view, it is always preferable to limit the energy consumption of a building rather than offset it by producing renewable energy.

(Q2) What is the investment cost needed to build a ZEB?

In Europe, the investment cost for a ZEB is 15–40% higher than for the same building designed according to building energy standards in 2020.

(Q3) Should all existing buildings become zero energy?

No, it is a target for new buildings. ZEBs are not normally disconnected from the grid. They compensate for their consumption by producing an equivalent, or greater, amount of clean energy, which is then fed into the grid when the production and building demand do not match. If all buildings were zero energy, the electricity grid would be totally overwhelmed.

With a view to moving towards totally zero-energy built environments, it will be necessary to go a step further and produce energy-autonomous buildings. Off-grid buildings are standalone ZEBs that are not connected to an off-site energy service. They require decentralised renewable energy production and energy storage capacity (when the sun is not shining, the wind is not blowing, etc.). An energy-self-sufficient house is a building concept where the balance between clean energy consumption and production can be maintained on an hourly, or even shorter, basis. Energy-self-sufficient buildings can be taken off the grid. This type of building should be the goal for all future construction, but storage technologies for buildings are still currently very expensive.

As long as the majority of ZEBs are not completely independent from the electricity grid, the generalisation of this concept to all buildings is not realistic, since this would always imply a significant demand for consumption in winter but also a surplus of energy in the summer, which would be problematic for the grid.

(Q4) What is the link between a ZEB and a smart building?

A smart building uses automation technology to maximise user comfort and various functionalities of the building, as well as maximising energy and resource efficiency. To achieve a ZEB, many smart technologies are useful for improving the energy efficiency of building systems (smart heating, cooling, lighting, etc.) and also for preventing unnecessary energy consumption – for example, by the automatic management of solar protection, lights that are automatically turned off in unoccupied rooms, etc.

A ZEB is not necessarily a smart building. From a ZEB perspective, the optimised design of buildings and use of passive solutions should remain priorities, before optimising the systems with smart technologies that are useful to further improve the energy efficiency of the building.

ZEBs can also be part of a smart grid or smart heating network, in particular by exchanging smart-managed energy resources with the network. Energy storage solutions, such as the use of vehicle-to-grid technology or specific batteries for energy storage in buildings, make it possible to optimise electricity exchanges with a smart grid.

(Q5) What is a zero-carbon building?

A zero-carbon building (ZCB) is one with net-zero carbon emissions, calculated over its entire life cycle, which requires the building to be highly energy efficient and powered from on-site and/or off-site renewable energy sources, with some carbon balance offset strategies. The ZEB focuses only on the operational energy, while the ZCB takes into account carbon emissions over the whole life cycle of the building, such as the emissions related to the embodied energy of materials. The definition of zero carbon requires the offsetting of all carbon emissions related to space heating and cooling, ventilation, hot water, lighting, and electric appliances, as well as during the construction, use and end-of-life phases of the building materials.

(Q6) Is it possible to achieve buildings with zero-carbon emissions?

Carbon-neutral status can be achieved with four main strategies: by choosing energy efficient design, renewable energy sources and low-carbon materials to reduce the carbon emissions of buildings, and then the remaining emissions can be absorbed by carbon offset strategies, such as creating landscaped car parks with trees and plants, rather than being paved, or by participating in a policy of reforestation of green areas. However, ZCBs are still rare and should be seen as exemplary buildings for the future.

A ZCB design requires: the use of the best passive strategies related to the climate and microclimate; the use of systems with high energy performance (for heating, cooling, ventilation and lighting); the use of sustainable materials; the use of green roofs and tree planting; the maximised use of renewable energy sources; a reduction of construction and consumption waste; and promoting sustainable waste treatments.

(Q7) What is a zero-energy city?

A zero-energy city is one within which the totality of energy consumed on its territory (calculated on an annual basis) is equal to the energy generated by renewable sources (solar, wind, hydroelectric, geothermal, etc.). To achieve this objective, it is necessary to take into account not only the energy consumption of buildings, but also the energy consumption from the transport of people and goods, as well as the energy consumption of any industry located within the city's perimeter.

A zero-energy city does not necessarily require that all buildings are ZEBs, but a very large majority of them should be at least low-energy buildings. Consumption can be offset by the production of various renewable energies, which are not all localised in the urban territory (production of green electricity at national level, urban heating networks, etc.).

(Q8) How should the reduction of energy consumption in buildings to reach zero-energy cities by 2050 be planned?

Achieving more energy-efficient buildings is a necessity for a sustainable future. Solutions exist and we must act now. Improvement of existing buildings from an energy point of view is a priority: all buildings should be evaluated and their energy efficiency should be increased. We can start by reducing heat exchanges through the building envelope, in order to reduce energy consumption linked to heating and cooling. The first operational strategy concerns thermal insulation and improving the airtightness of the building envelope. This solution should be associated with various complementary strategies, such as solar protection and the possibility of cooling the building by intensive night ventilation coupled with materials offering high thermal inertia for floors or ceilings of the main rooms. Then, the building systems also need to be upgraded through energy-efficient ventilation, lighting, and heating and cooling systems. Finally, it will be necessary to increase the proportion of renewable energy in our electricity, heating and cooling production – for example, through the use of geothermal energy, a combination of photovoltaic panels and heat pumps, or the development of efficient heating/cooling networks at the neighbourhood scale, powered by various renewable energy sources (biomass, etc.).

Designers and engineers have to rethink the whole operating processes of buildings and cities. Buildings and neighbourhoods should pool their resources to generate energy savings (Marique and Reiter 2014, 114-122). Renovation of existing built environments is a key factor for the development of zero-energy cities (Reiter and Marique 2012, 829-838).

(Q9) What does it mean for a city to meet the zero-carbon criteria?

It is a city capable of absorbing all of its GHG emissions (mainly related to buildings, transport and industry). For the time being, zero-carbon neighbourhood and city projects only take into account the operational phase. A transition towards zero-carbon cities includes decarbonising electricity and heat production, using zero-emission transport modes, and capturing the remaining carbon emissions through the use of new carbon capture technologies or by greening our built environments (green roofs, green facades, urban forests, etc.).

The conditions for a carbon balance on Earth are simple: 3 billion tons of carbon are absorbed by the oceans and forests each year, and there are more than 6 billion inhabitants on Earth. Therefore, the planet has the capacity to absorb emissions of 0.5 ton of carbon per person each year. And this value will decrease even further in the future, based on the current population growth. Implementing a stabilisation of the world's population would certainly be the smartest political choice. The renovation of old buildings and changing our mobility behaviours are then two other main steps to reach the zero-carbon target, as well as the development of renewable energies and the greening of our built environment. Renovation of the existing built environment is a key factor for a sustainable development of our societies everywhere on Earth. In addition, issues that go beyond the scale of architecture and urban design are also at work, such as the question of limiting global population growth.

(Q10) How can we reduce carbon emissions in the transportation sector?

Strategies that help reduce carbon emissions from transport include:

- Preventing urban sprawl and promoting a reasonable built density;
- Increasing the multi-functionality of neighbourhoods (dwellings, offices, shops, etc.) while continuing to set aside the noisiest and most polluting activities, in order to preserve the well-being and health of the population;
- Increasing the capacity of public transport, carpooling and/or car sharing;
- Improving the energy-efficiency and carbon emissions of all types of vehicles;
- Developing the use of electric vehicles, such as buses, cars, bicycles, etc., while increasing the share of renewable energy in our electricity production;
- Developing vehicles that use zero-emissions alternative energy sources;
- Creating continuous, safe and pleasant paths for pedestrians and cyclists. The authorities of each city should also encourage walking and the use of bicycles, because they are good for health and have enormous potential for reducing GHG emissions compared with other transport modes.

The most environmentally sound transport modes are: (1) green transport: walking, bicycles and electric bikes, included self-service bikes, (2) highly energy-performant public transport and shared autonomous vehicles, (3) private vehicles using fuels that are less CO_2 intensive than fossil fuels: electricity, biofuels, hydrogen, etc.

(Q11) What are the advantages of walking?

It may sound silly, but for some people it is time to rediscover good old walking. Indeed, if you live near your workplace, walking is the most sustainable and economical means of transport. The advantages of walking are zero expense (except the price of good shoes), a harmless environmental footprint and reduced air pollution in urban areas, direct accessibility, it is a soft physical activity with health benefits (improving cardiovascular health and breathing), and it generates socialisation possibilities and participation in a friendly neighbourhood atmosphere, which improves the conviviality of the built environment. Walking is also the only transport mode that does not require any parking space either inside buildings or in outdoor public spaces.

(Q12) What are advantages of cycling?

The bicycle is a green transport mode with many advantages similar to walking: it is a zero-carbon and affordable transport mode, it promotes physical activity, health benefits and conviviality, and it reduces the space required for parking areas. But, compared with walking, it allows travelling longer distances over the same time.

Over the past 10 years, the bicycle has gone from an object of leisure and sporting activities to a transport mode useful for daily commuting. For urban and inter-urban travel, the bicycle is often presented as a perfect substitute for the car, reducing traffic congestion and parking spaces. Regulations for road users are also starting to favour the development of mobility for cyclists: one example is in Paris where cyclists can now pass through a red light under certain conditions. Corporate travel plans also aim to encourage bicycling behaviours. For example, a bicycle kilometre allowance has been tested and will be generalised through energy transition laws recently adopted in several countries.

Widespread adoption of the (traditional or electric) bicycle requires the establishment of secure infrastructure for two-wheelers. Too often, authorities simply delimit cycle paths by using paint on the ground without any real separation from cars and buses, which generates a situation of insecurity for cyclists. In addition, the cycle paths on their own are rarely well connected throughout a municipal territory. In cities and countries that invest more money in these infrastructures, the modal shift from the car to the bicycle is effective.

However, we must not forget the important proportion of the population (elderly people, young children, people with reduced mobility – even temporarily – etc.) who are not able to use this transport mode. Climate conditions are also sometimes an obstacle to its use. It cannot therefore be considered as the only urban transport solution, but it is one worthwhile solution among others.

(Q13) What are the advantages of public transport and shared transport modes?

Public transport modes, such as bus, coach, metro, tramway, trolleybus, train, etc., not only reduce carbon emissions per kilometre travelled per passenger, but are also generally low cost for users and free up many parking areas in and around buildings, compared with individual cars. Public transport modes are very well suited to use in dense cities.

Carpooling and autonomous shared transport modes also take advantage of sharing a service to reduce their emissions and parking needs. They are greatly appreciated by younger generations and could therefore support a transition towards less polluting transport behaviours. Knowing that it is often difficult to ensure sufficient accessibility to public transport in some peri-urban and rural areas, these alternative shared vehicles (carpooling, self-service car sharing, etc.) should therefore be particularly promoted in these areas, which are less well served by public transport.

(Q14) What are the advantages of electric cars?

The main arguments for electric cars relate to the environmental benefits and the creation of cities that promote well-being. Indeed, an electric car itself does not emit any CO_2, polluting particles, smoke, or hydrocarbons into the atmosphere while moving. It could eliminate the problem of smog in dense cities. Electric vehicles are also much quieter than traditional vehicles. Therefore, they represent an alternative to vehicles powered by fossil fuels, in order to create breathable, calm and pleasant cities.

However, from an environmental point of view, an electric car should ideally be powered by a renewable or low GHG emission energy source. Otherwise, while carbon emissions do not occur when the car is driven, they will still be generated by the electricity production. Nevertheless an electric car, even powered by the current electricity grid, is more energy efficient and emits less CO_2 than a car with a combustion engine powered by petrol or diesel.

Finally, rechargeable electric vehicles (vehicle-to-grid, or V2G) can participate in intelligent management of the electricity network and help to achieve total energy autonomy of ZEBs, thanks to their batteries that may be used to store renewable electricity generated locally on buildings.

(Q15) What are alternative energy sources for eco-friendly transport modes?

Beyond the electricity generated by renewables, which are currently the most promising zero-carbon energy sources for vehicles, the main alternative energy sources are biofuels and hydrogen. Vehicles already exist that run on biofuels, mostly on biomass. The biofuel, often ethanol, therefore does not come from fossil fuel but from agricultural products. These vehicles have a significantly smaller ecological footprint than the same types of vehicles (buses, cars, etc.) with conventional combustion engines running on fossil fuels. Hydrogen vehicles use electrical energy that is supplied by a hydrogen fuel cell, which only emits water when the vehicle is driven.

(Q16) What are eco-adaptive and sustainable architectures?

Ecological architecture and green buildings refer to environmentally responsible buildings that are eco-friendly, resource efficient and produce minimal environmental impacts throughout their life cycle. But today, it is also essential to take into account the changing nature of the environment. Architecture now has to be more eco-friendly, while it also has to adapt to changeable climatic conditions and be resilient to environmental disasters. In 2017, Nguyen and Reiter (16-29) proposed a new approach in architecture – the “Eco-adaptive approach” – as an evolutionary step of the conventional “Bioclimatic approach”. Their concept emphasises the importance of co-operation between architecture and nature when designing buildings, as well as the need to take into account the current changing context to design more adaptable and resilient buildings and cities.

Figure 6.1 shows a representation of the eco-adaptive architecture, which takes into account the co-evolution between an eco-adaptive building and its changing context, including its climate, natural environment, occupants, technological systems and architectural design. For example, the technological operation of building systems should be able to adapt to climate changes: smart technologies may be used for data gathering in the building with an automatic adjustment of its operation, but the building must also continue to function properly if its technological systems malfunction due to a disaster.

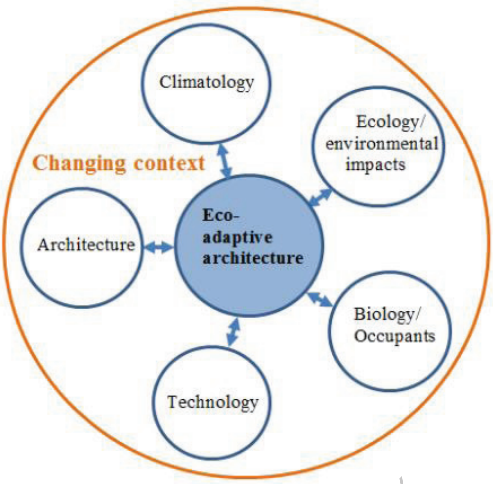

Figure 6.1: Eco-adaptive architecture (Nguyen and Reiter 2017, 16-29).

Because of its co-operation and co-evolution with its environment, the eco-adaptive architecture will meet the environmental needs of present generations without compromising the same needs of future generations. Eco-adaptive buildings will thus help to move towards sustainable architecture, which is likely to be the next step of the architectural evolution.

Sustainable architecture requires balancing the environmental, social, economic and governance issues of building design for current and future generations. Sustainable architectural and urban design will create buildings and cities that participate in the sustainable development of our society. These designs need to balance environmental criteria (such as ZEBs, LCBs, etc.) with social criteria (such as inhabitants' comfort, human health, social equity, etc.), economic criteria (such as limitation of construction and renovation costs, building life cycle costing, local job creation through the use of local resources, etc.) and governance criteria (such as respect for and improvement of local construction standards, and citizens' participation, as well as flexible, removable and/or standardised construction methods).

(Q17) Are energy consumption and carbon emissions the only negative impacts of buildings and cities on the environment?

We are living in a period during which climate change is evolving more strongly than ever and generating adverse effects on humans. Energy consumption and the associated increase in GHG emissions into the atmosphere are the main underlying causes of anthropogenic climate change, and the building sector is one of the principal factors of these emissions. Thus, the magnitude of future climate change will partially depend on the reduction of energy consumption and GHG emissions of buildings and cities. This is why these two criteria are two important environmental criteria, but they are not the only ones.

Energy should be the first resource to targeted, because it is one of the main sources of GHG emissions. Also, if a building is well managed, its energy use should become progressively more efficient, and the ability to distribute and allocate energy will improve resilience to disasters. Obviously, the "net-zero" concept is also applicable to other resources used in buildings: for example, zero water, zero waste, etc.

Seven main environmental impacts of buildings have been selected in the European standards concerning the environmental LCA applied to buildings: CEN. These seven CEN environmental LCA indicators (CEN 2011, 1-2) are as follows:

- Global warming potential. This reflects the warming potential of the various GHGs, converted into tons of CO_2 equivalent over a period of 100 years.
- Depletion potential of the stratospheric ozone layer. The ozone depletion potential of a compound is the relative amount of degradation to the ozone layer it can cause.
- Acidification potential of land and water. This is linked to the phenomenon of acid rain and forest dieback; it is expressed in kilogram sulphate equivalent.
- Eutrophication potential. This is linked to the intake of substances acting as fertilisers (nitrates and phosphates) in surface water, promoting the development of algae, which are toxic to living organisms during their decomposition process.

- Formation potential of tropospheric ozone photochemical oxidants. The decomposition of certain VOCs under the action of the sun contributes to the formation of photochemical ozone, also known as smog, which has harmful effects to the respiratory systems of many living beings.

- Abiotic resource depletion potential of fossil resources. This reflects the depletion of the environment in mineral and fossil resources; the calculation is based on the remaining stocks and consumption rate of the current economy.

- Abiotic resource depletion potential for non-fossil resources.

Other analysis tools and methods also use additional environmental indicators for buildings (Reuter and Reiter 2019, 1-6), such as:

- Ecotoxicity: terrestrial and water. This reflects the ultimate damage to nature in terms of biodiversity damage and is expressed as a percentage of extinct species per square metre per year.

- Human toxicity (including cancer and non-cancer effects, particulate matter, and health effects of ionising radiation). This indicator reflects the impacts on human health, in terms of the number of years of healthy life lost; it is expressed in disability adjusted life years (DALY).

- Water resource depletion. This quantifies total water consumption over the entire life cycle of a structure, measured in cubic metres of water drawn.

- Ultimate waste. This quantifies total waste produced over the entire life cycle of a building.

Nematchoua et al. (2020, 11) evaluated with an LCA the 11 environmental impacts mentioned above of an energy-performant neighbourhood (with a heating requirement of 15.4 kWh/m²·year) recently built in Belgium, as well as eight improvement scenarios (sustainable mobility, better water management, etc.). Global analysis of the reduction of these 11 environmental impacts shows the following results for the cumulative decrease of all environmental indicators: sustainable mobility (282%), vertical densification (163%), photovoltaic panels (138%), rainwater harvesting (76%), soil permeability (11%), orientation (4%) and horizontal densification (−10%). Horizontal densification is therefore the only strategy that does not improve the neighbourhood's environmental score, while sustainable mobility, vertical densification (roof stacking) and the use of photovoltaic solar panels greatly improve the overall environmental score. If we study the results in more detail, most strategies reduce the 11 environmental impacts. This is particularly the case with sustainable mobility, which improves each of the impacts studied by 13–50%, in particular the climate impacts being the most reduced.

Of all the configurations simulated in this study, the one comprising the addition of photovoltaic panels produces the most heterogeneous results on the neighbourhood's LCA. In the photovoltaic scenario, two thirds of the roof area of each building are covered with monocrystalline photovoltaic solar panels, inclined at 35° which is the optimal inclination in Belgium. The average electricity consumption of a building is 12 kWh/m² per year, which is consistent with the Belgian averages for dwellings that did not heat up with electricity. Photovoltaic panels produced an average of 26 kWh/m² over the year. Thus, except for the months of January and December, no electrical energy was drawn from the Belgian grid. The environmental effects of photovoltaics on the neighbourhood are presented in Figure 6.2. It shows that some indicators are greatly reduced, while others are increased considerably. Indeed, the neighbourhood's total waste generation over its entire life cycle increased by 21% and the damage to biodiversity increased by 18%, due to the manufacture and replacement of the solar panels over the 80-year life cycle.

Thus, from an environmental point of view, it is important to take into account the reductions in energy consumption and GHG emissions as a priority when designing buildings and cities, but we must not forget the other environmental impacts, especially the damage to biodiversity.

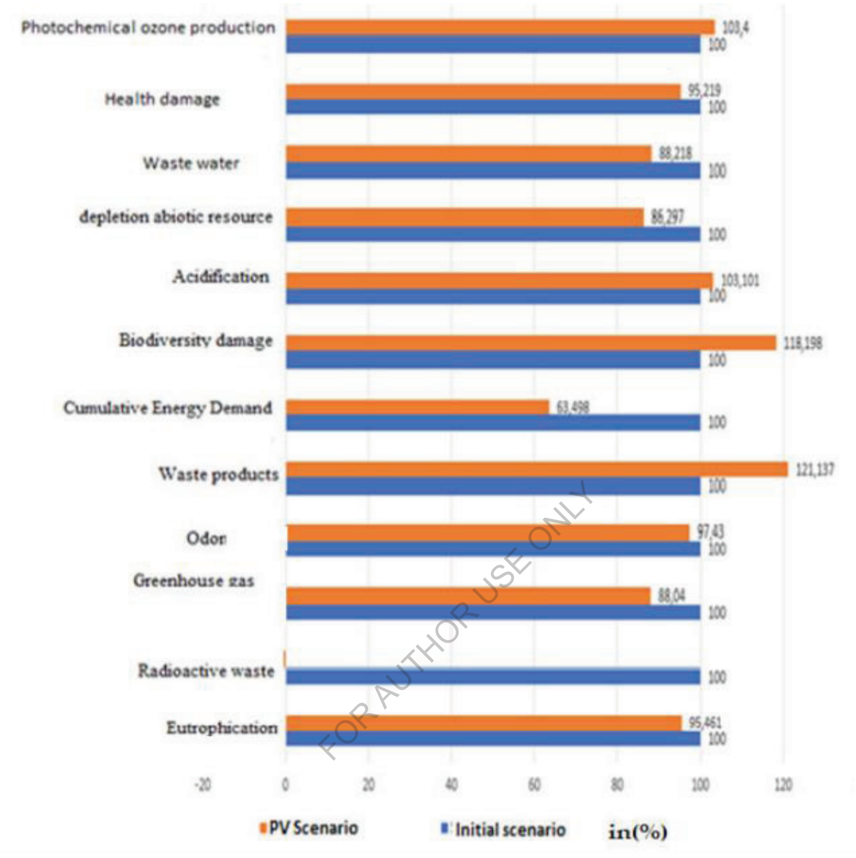

Figure 6.2: Comparative diagram of 11 environmental impacts of the "initial" and "photovoltaic (PV)" scenarios applied at the neighbourhood scale over their entire life cycle (functional unit: entire neighbourhood) (Kameni et al. 2020, 11).

(Q18) How should we reduce the carbon emission rate of industries?

To reduce carbon emissions in the industrial sector, the production of electricity and heat should be shifted as far as possible to low-carbon sources, such as renewable energy or nuclear. Carbon capture and storage technology could be an interesting complementary solution; it consists of capturing CO_2 from its production source and storing it underground. It is of interest to manufacturers, because it would allow them to massively reduce their CO_2 emissions. But this promising solution has yet to demonstrate that it can be industrialised at an acceptable cost.

(Q19) Does nuclear energy production emit CO_2?

Yes. While, CO_2 does not come directly from the emission stacks of a nuclear power plant, nevertheless CO_2 is emitted indirectly. If we take into account the extraction of uranium, its transport, the construction of the power plant, the management of the waste produced and the plant's dismantling, we can conclude that, yes, nuclear energy does emit CO_2. However, these CO_2 emissions are much lower than with fossil fuels, but higher than most renewable energies.

(Q20) How should we manage waste in future cities?

The sustainable management of waste in future cities requires, first, a reduction of construction and consumption waste, through various strategies such as: reusing materials; using recycled materials; making rational use of natural resources; designing for deconstruction and not demolition; designing adaptable buildings, infrastructure and systems; etc. Second, authorities have to impose high standards for sustainable waste treatments, such as selective waste collection, sorting, composting, recycling, etc., in order to reduce waste sent to landfill. Designers and planners should also incorporate these sustainable waste treatments into the management of waste produced during the construction and renovation processes (selective waste collection, sorting, composting, recycling, etc.). For example, crushing the concrete and asphalt from a demolished facility and using it as structural infill material for a new building on the same site avoids waste being sent to landfill, and it also avoids the gravel extraction that would otherwise be needed. In the future, every project should collect and reuse, or recycle, the majority of its construction debris.

References of Chapter 6

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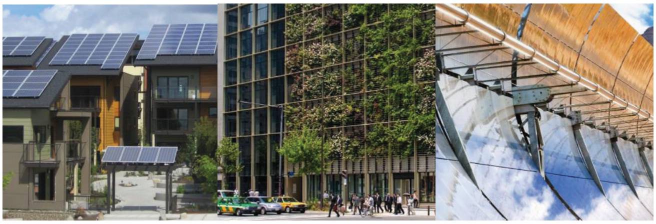
Part 3: Case studies of zero-energy and low-carbon buildings and neighbourhoods

Chapter 7: Case studies of zero-energy and low-carbon buildings

Chapter 8: Towards zero-energy neighbourhoods in existing built environments

Chapter 9: Life cycle energy and carbon analysis of new districts



Chapter 7: Case studies of zero-energy and low-carbon buildings

A zero-energy house, designed by Karawitz Architecture, in Bessancourt (France).

7.1 Studied buildings

Before carrying out a case study of zero-energy and low-carbon buildings, note that the design principles of low environmental impact buildings have been described in chapters 1 and 2. It may be useful for the reader to re-study definitions and concepts, in order to make more understandable the practical cases that are presented in this chapter. A description of the case studies and the different methods used in this research are detailed in the following subsections.

7.1.1 Location and climate data

This study compares buildings located in three developing countries in sub-Saharan Africa (Cameroon, Senegal and Madagascar) under tropical climates, and buildings located in three developed countries (Belgium, France and the US) under temperate climates.

Sub-Saharan Africa is the extent of the African continent south of the Sahara, ecologically separated from the countries of the north by the harsh climate of the largest warm desert in the world. It is home to 48 states, whose borders stem from decolonisation. Its climates are distinguished by annual rainfall variations rather than by temperature variations. It is a very rich area in terms of biodiversity, although it is vulnerable to climate change. Sub-Saharan Africa is the most dynamic part of the planet in terms of population. The subcontinent is the least economically developed area in the world. The three case studies located in tropical regions are: Douala city in Cameroon, Dakar city in Senegal and Antananarivo in Madagascar, an island in the Indian Ocean. These three areas are described in more detail below.

(1) The city of Douala, located around 13 metres above sea level, between 4°03'N and 9°04'E, is considered a port city. It is the economic capital of Cameroon, and is also the main business centre and one of the largest cities in Cameroon. Its area is estimated at around 923 km^2. Douala is dominated by a tropical climate with two main seasons: a rainy season (April to November) and a dry season (November to April).

(2) Dakar is located at the far west of the Cape Verde Peninsula, on the edge of the Atlantic Ocean. It is the political, economic and cultural capital of Senegal. It is the location for 80% of industrial and commercial companies and around a quarter of the country's population. Dakar, like the rest of the country, has a tropical climate. It is thus strongly influenced by the south-west

monsoon, a wind coming from the Atlantic Ocean which is very humid and brings rain, and the Harmattan, a dry wind. At the same time, temperatures vary with the seasons: Dakar experiences a very mild climate from November to April with an average temperature of around 20°C. Finally, Dakar is one of the largest cities in Africa, and its demographic growth is significant and increasing rapidly.

(3) Antananarivo is the capital of the island of Madagascar. It occupies the slopes of a rocky ridge culminating at an altitude of approximately 1435 metres. The city is about 350 km from the east coast of the island and 550 km from its west coast. Antananarivo has a tropical altitude climate, where the average temperature over the year is moderated by the effects of altitude. The climate is characterised by cool, very dry winters and mild, very rainy summers.

Figure 7.1 shows the geographic locations of the three African cities studied.

Figure 7.1: Locations of the three cities studied in Africa.

The three case studies in developed countries are located in Brussels (Belgium), Paris (France) and Washington DC (US), in temperate climates. These three areas are described in more detail below.

(4) Brussels is the capital of Belgium and the seat of several EU institutions. It is located in the north of Europe, with a cold temperate climate influenced by the Gulf Stream. The proximity of

the city to the sea has a strong influence on the climate, which is generally characterised by mild and rainy winters, and relatively cool and humid summers. The annual average temperature in Brussels is 10.4°C.

(5) Paris is the capital and largest city of France, with an area of 105 km^2. It is also the centre of the French economy, politics, traffic and culture. The climate of Paris is said to be temperate and rainfall is significant, with precipitation even during the driest month. The average annual temperature in Paris is 11.3°C.

(6) Washington DC is located in the mid-Atlantic region of the east coast of the US, between Maryland and Virginia. It is the nation's capital, located approximately 40 miles south of Baltimore, 30 miles west of Annapolis and the Chesapeake Bay, and 108 miles north of Richmond. The city of Washington was founded in 1791 to serve as the US capital under the jurisdiction of the Congress and it was established as a federal city. Washington DC is located in a hot temperate climate, with an annual average temperature of 14.6°C, but winters are often cold.

Figure 7.2 shows the geographic locations of the three studied cities in developed countries.

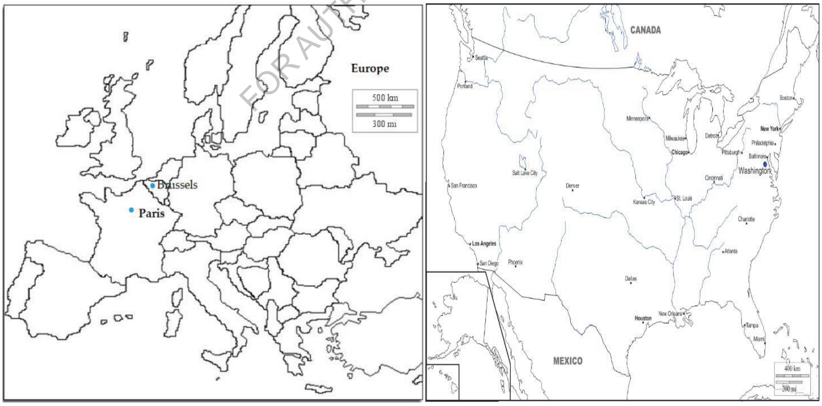


Figure 7.2: Locations of Brussels and Paris (left) and Washington DC (right).

In this research, all the climate data for the simulations have been downloaded from American Meteonorm software (version 7.3.3), based on the geographical co-ordinates of each city. The software allowed data to be downloaded in units of hours, days or months, according to our requirements. Hourly data of temperature, relative humidity, air speed, solar radiation and precipitation for the last 30 years were collected for all the climate regions.

7.1.2 Types of buildings

This research was carried out on residential buildings. The types of construction materials and energy systems vary according to the two main climates (tropical and temperate). In order to better compare the case studies through the six chosen locations, we used two different residential buildings: one designed for tropical climates and another designed for temperate climates.

The first residential building, designed for tropical regions, is a simple family house on one floor, consisting of a living room, four bedrooms, a shower room and a kitchen. The second residential building, designed for temperate regions, is a small residential building with three apartments. These two buildings have the same built-up area but different characteristics in terms of materials and systems. Information regarding the two buildings studied and their construction materials are given in tables 7.1 and 7.2. Each building is modelled through two scenarios: the original building and a revised scenario, which includes low-carbon materials, a passive strategy for sun shading, improved energy systems and electricity from renewable energy.

Table 7.2 gives the thermal characteristics and embodied carbon of construction materials used in the case studies, showing that the majority of materials in the revised scenario have very low embodied carbon. Moreover, in Africa where building standards are less stringent from a thermal point of view, the revised building is designed using materials with a low thermal conductivity. The lower the thermal conductivity of the materials, the more this material limits heat transfer. The goal was to select sustainable materials, adapted to the local context, for reducing carbon emissions of buildings.

However, these envelope compositions should in no case be considered optimal for all buildings; various other design parameters must also be taken into account depending on the context, such as the acoustic performance of the materials, their aesthetics and financial cost. In addition, other sustainable solutions (described in chapters 1 and 2) could also be used to reduce the energy consumption and carbon emissions of buildings.

In this study, we have introduced photovoltaic panels with various surface areas (between 16–75 m^2) on the roofs of the two buildings located in tropical and temperate climates. The cells were made of polycrystalline, with base load, direct current with inverter. The optimal inclination was fixed at 37° towards the south in the case of Paris, Brussels and Washington DC; and 45° towards the north in Douala, Dakar and Antananarivo.

Table 7.1: Input data for building simulations.

Parameters	Residential building located in tropical regions		Residential building located in temperate regions	
(revised residence = low-carbon materials, passive strategy and green energy)	Original building	Revised building	Original building	Revised building
Height (m)	3.5	3.5	3.5	3.5
Area (m^2)	342	342	342	342
Activity template	Domestic house	Domestic house	Building with 3 apartments	Building with3 apartments
Occupancy density (people/m^2)	0.023	0.023	0.0303	0.0303
Activity (met)	0.9	0.9	0.9	0.9
Clothing (Clo)	0.5–1.0	0.5–1.0	0.5–1.0	0.5–1.0
DHW: consumption rate (L/m^2-day)	0.53	0.53	0.52	0.52
Fresh air (L/s-person)	10	10	10	10
Lighting: target luminance (lux)	100	100	125	100
Computer: power density (W/m^2)	0.2	0.2	0.2	0.1
Other equipment: power density (W/m^2)	3.58	3.58	3.58	3.58
Occupancy schedule	24/7	24/7	24/7	24/7
Construction template	Project construction template	Project construction template	Project construction template	Project construction template
Airtightness (vol/h)	0.5	0.5	0.5	0.5
Glazing template	Project glazing template. Preferred height 1.5m. 30% glazed	Project glazing template. Preferred height 1.5m. 30%	Project glazing template	Project glazing template

		glazed.		
Local shading	No	1.0m overhang	No	1.0m overhang
Lighting template	Incandescent	LED	Incandescent	LED
Lighting control	No	Yes	No	Yes
Lighting schedule	24/7	Mon.–Sun.: 6pm–7am	24/7	Mon.–Sun. 6pm–7am
HVAC template	Fan coil unit (4-pipe) + air cooler chiller	Fan coil unit (4-pipe)	Gas condensing boiler (COP = 0.9) + air cooler chiller	District heating with gas boiler and gas cogeneration + natural cooling
HVAC schedule	12/7	6/7	24/7	24/7
Electricity	Electricity from grid	Electricity from green energy	Electricity from grid	Electricity from green energy
Other ventilation	Natural ventilation (NV)	Natural ventilation (NV)	Double flow ventilation with heat recovery	Double flow ventilation with heat recovery

Table 7.2: Thermal characteristics and embodied carbon of construction materials used in the case studies.

Region	Building category	Building element	Layer	Component	Thickness (m)	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat capacity (J/kg K)	Embodied carbon (kgCO$_2$/kg)	U-value (W/m^{2}K)
Tropical region	Original building	Exterior wall	Layer1	Plaster	0.025	0.50	1300	1000.0	0.12	2.75
			Layer2	Concrete block	0.12	1.63	2300	1000.0	0.08	
			Layer3	Plaster	0.05	0.50	1300	1000.0	0.12	
		Partition wall	Layer	Concrete block	0.12	1.63	2300	1000.0	0.08	5.85
		Roof	Layer1	Clay tile	0.025	1.00	2000.0	800.0	0.46	0.160
			Layer2	Stone wool	0.242	0.040	30.0	840.0	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837.0	-	
	Revised	Exterior	Layer	Wood	0.153	0.040	110	1800.0	0.00	0.25

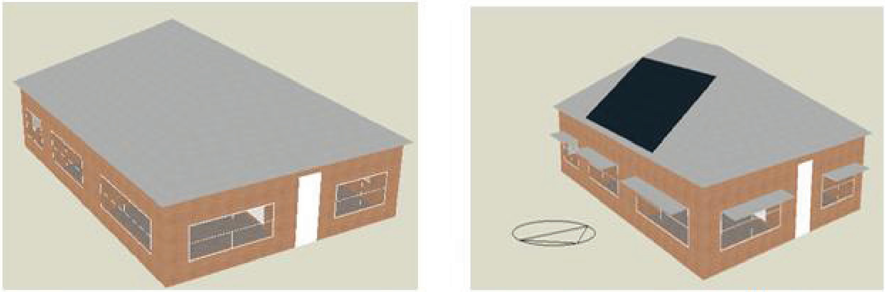
	building	wall								
		Partition wall	Layer	Wood	0.07	0.040	110	1800.0	0.00	0.25
		Roof	Layer1	Clay tile	0.025	1.00	2000.0	800.0	0.46	0.16
			Layer2	Stone wool	0.242	0.040	30.0	840.0	1.05	
			Layer3	Roofing felt	0.005	0.190	960.0	837.0	-	
Temperate region	Original building	Exterior wall	Layer1	Plaster	0.03	0.5	1300	1000	0.12	0.2
			Layer2	Concrete	0.14	0.51	1400	1000	0.08	
			Layer3	Extruded polystyrene	0.12	0.034	35	1400	2.88	
			Layer4	Facing brick	0.09	0.62	1700	800	0.22	
		Partition wall	Layer1	Plaster	0.03	0.5	1300	1000	0.12	1.57
			Layer2	Brick	0.14	0.72	1920	840	0.22	
			Layer3	Plaster	0.03	0.5	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.03	0.55	1900	837	0.05	0.1
			Layer2	Wooden lathing	0.038	0.13	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.12	510	1380	0.45	
			Layer5	Rock wool	0.400	0.10	500	1000	0.98	
			Layer6	Composite wood	0.018	0.04	160	1888	0.19	
	Revised building	Exterior wall	Layer 1	Plaster	0.03	0.5	1300	1000	0.12	0.2
			Layer 2	Concrete	0.14	0.51	1400	1000	0.08	
			Layer 3	Wood frame	0.03	0.12	510	1380	0.45	
			Layer 4	ISOCELL cellulose	0.40	0.037	400	1360	-	
			Layer 5	Composite wood panel	0.020	0.25	900	1000	0.12	
			Layer 6	Wooden cladding	0.022	0.13	160	1800	0.05	

		Partition wall	Layer1	Plaster	0.03	0.5	1300	1000	0.12	1.57
			Layer2	Brick	0.14	0.72	1920	840	0.22	
			Layer3	Plaster	0.03	0.5	1300	1000	0.12	
		Roof	Layer1	Roof tiles	0.03	0.55	1900	837	0.05	0.1
			Layer2	Wooden lathing	0.038	0.13	2800	896	0.45	
			Layer3	Air gap	0.025	-	-	-	-	
			Layer4	Wood	0.042	0.12	510	1380	0.45	
			Layer5	Hemp wool	0.40	0.037	800	1000	0.0	
			Layer6	Composite wood	0.018	0.13	1000	1000	0.01	

7.1.3 Simulation tools and models

In this study, we used the most recent version of the Design Builder software. This software is highly renowned in its field and has served as the basis for thousands of scientific research studies. Design Builder software, as well as TRNSYS, DOE, Pleiades and Helios, is very well-known in the fields of simulation, optimisation, building information modelling (BIM), life cycle cost (LCC) analysis and LCA. This software was coupled with the Energy Plus tool to assess the energy demand and consumption of a building. This software includes most building materials, with their physical thermal properties. The modelling of the two selected buildings is shown in Figure 7.3.

The simulation model has been validated based on the results of previous studies detailed by Nematchoua et al. (2020, 117754), and Nematchoua and Reiter (2020, 5-13).



(a) Original residence in tropical region

(b) Revised residence in tropical region

(C) Original residence in temperate region

(d) Revised residence in temperate region

Figure 7.3: Original and revised residential buildings in tropical climates (a and b) and in temperate climates (c and d).

7.2 Results

The main objective of this study is to confirm whether or not, by applying the recommendations described in chapters 1 and 2, the zero-energy and zero-carbon objectives can be reached at the building scale under tropical and temperate climates.

7.2.1 Buildings located in tropical regions

Energy and carbon emissions results

The simulation results for tropical regions are shown in Table 7.3 and Table 7.4.

Table 7.3: Comparison of monthly air temperature (°C) in the original and revised buildings.

Month		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Original residence building	Antananarivo	25.21	24.83	25.47	24.64	23.45	21.74	20.75	21.10	23.27	24.51	25.56	25.12
	Douala	26.66	26.59	26.36	26.13	26.17	25.80	25.35	25.04	25.10	25.62	26.05	26.54
	Dakar	24.66	24.84	25.18	25.19	26.00	26.64	27.04	26.98	27.20	27.20	26.91	25.90
Revised residence building	Antananarivo	25.25	25.02	25.33	24.48	23.27	21.75	20.75	21.03	23.08	24.56	25.44	25.21
	Douala	26.19	26.24	26.10	25.88	25.89	25.49	25.14	24.96	25.08	25.41	25.52	26.04
	Dakar	24.78	24.96	25.21	25.30	25.82	26.46	26.92	26.91	27.05	27.02	26.71	25.75

Table 7.4: Annual operational carbon and electricity demand in the residential buildings.

Cities		Antananarivo	Douala	Dakar
Original building (Initial residence)	Cooling electricity (kWh)	2843.17	1573.21	19,713.96
	Electricity demand (kWh)	3149.31	10,276.65	21,593.81
	Annual operational carbon emission rate ($kgCO_2$)	1722.95	7366.85	13,085.86
Revised building (applying renovation + passive strategies + PV)	Surface of installed photovoltaic panels (m^2)	16	34	58
	Cooling electricity (kWh)	0.00	0.00	0.00
	Electricity demand (kWh)	2564.80	6944.28	13,874.95
	Green electricity generated (kWh)	−2565.00	−6944.30	−13,875.01
	Annual operational carbon emission rate ($kgCO_2$)	−3149.3	−140.51	3278.49

In Table 7.3, we see that the average indoor air temperature decreases in the revised residence due to better thermal conductivity of its materials. So, even without a cooling device, it is still possible to reach thermal indoor comfort by using passive strategies. Table 7.4 shows that, after the revision of the studied building, the zero-energy objective is achieved: the sum of the electricity demand and green electricity generated by photovoltaic panels is equal to zero. It is important to note that the size of the photovoltaic surface varies according to the region. The cooling energy is zero after the heavy renovation of the residential building and the use of passive strategies. The annual operational carbon emission rate is negative in Antananarivo and Douala. A negative carbon footprint means that the building removes more CO_2 than it emits into the atmosphere. In Dakar, there is a low remaining carbon emission of $9.58 kgCO_2/m^2$.

<u>Cost analysis</u>

- Area: 342 m^2;
- Annual heating requirements: 0;
- Building life span: 50 years;
- Cost of the closed building structural work for the initial building: €30,000 including VAT;
- Electricity price per kilowatt-hour: €0.15;
- Total electricity cost over 50 years: €19,236.

Compared with traditional construction standards, the construction cost of a low-energy building is higher by 35–55% and the cost of a zero-energy building is higher by 40–70%. The transition from a low-energy house to a zero-energy house thus generates a cost increase of 5–15%. A summary of costs is given in Table 7.5.

Table 7.5: Evaluation of residential building costs.

Initial state of the building	**Parameters**	**Values**
	Residence area	342 m^2
	Annual heating requirements	0
	Building life span	50 years
	Cost of the closed building structural work	€30,000 including VAT
	Electricity cost	€0.15 per kWh

	Electricity consumption	2564.8 kWh per year
	Electricity cost	€19,236 over 50 years
Revised residence building + PV installed	Cost of the closed building structural work	€32,000 including VAT
	PV cost	€2400
	Cost saving	€16,836 over 50 years
	Payback	6.23 years

7.2.2 Buildings located in temperate regions

Energy and carbon emissions results

In the temperate climate, we have chosen three cities located in developed countries (France, Belgium and the US). Building typology, occupation space and thermal standards are very different in these countries compared with construction methods in Africa (Senegal, Cameroon and Madagascar). Results for energy and carbon emissions are given in Table 7.6. These values show that the European building standards applied in this climate are very high and require the construction of almost passive buildings.

Table 7.6: Annual operational carbon and electricity demand in residential buildings located in temperate climates.

Cities		Brussels	Paris	Washington DC
Initial building	Cooling electricity (kWh/m^2)	1.02	2.46	2.48
	Heating and domestic hot water (gas) (kWh/m^2)	37.71	34.96	33.20
	Electricity demand (kWh/m^2)	25.46	24.9	22.06
	Annual operational carbon emission rate (kgCO$_2$/m^2)	18.64	18.39	16.89
	Surface of installed photovoltaic panels (m^2) for a building area of 342	58	45	42

Revised building	m²			
	Green electricity produced by gas cogeneration	40.96	38.99	37.03
	Heating and domestic hot water (gas cogeneration) (kWh/m^2)	37.71	34.96	33.20
	Cooling electricity (kWh/m^2)	0	0	0
	Electricity demand (kWh/m^2)	20.36	18.77	14.54
	Green electricity generated (kWh/m^2)	-17.11	-14.74	-10.71
	Annual operational carbon emission rate (kgCO$_2$/m^2)	-2.60	-0.11	2.17

In order to produce green electricity equal to the building energy demand, it is necessary to combine two different renewable technologies: gas cogeneration and photovoltaic panels. With this combined cogeneration solution, the required photovoltaic area is 58 m² in Brussels, 45 m² in Paris and 42 m² in Washington DC. However, it extends to 194 m² in Brussels, 151 m² in Paris and 141 m² in Washington DC without the cogeneration. This combined solution produces nearly zero annual operational carbon buildings in the three cities.

<u>Cost analysis</u>

- Initial investment: €680,000 including VAT;
- Area: 342 m^2;
- Annual heating requirements: 19.71 kWh/m^2 (in the case of Brussels);
- The total investment for the revised building is estimated to be €750,000 including VAT.

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Chapter 8: Towards zero-energy neighbourhoods in existing built environments

An urban pedestrian public space in Namur (Belgium) – renovation of the existing building stock and development of green mobility behaviours are among the most important issues for a transition towards zero-energy cities.

8.1 Objective

The main objective of this chapter is to study the feasibility of applying the concept of zero energy and low carbon to existing built areas at the neighbourhood scale. The building stock of the Walloon Region, located in Belgium in a cold temperate climate, has been chosen to apply this research. It is very difficult to reach the objectives of zero energy and zero carbon in old neighbourhoods or cities because building typologies and materials are already defined. However, it is possible to significantly reduce energy and carbon emissions by applying strategies related to building renovation, modification of mobility habits and the use of renewable energy sources. These strategies are applied in this chapter to the residential building stock of Wallonia, composed of 1,537,385 dwellings.

The subdivision of Wallonia is carried out as follows: there are five provinces (Hainaut, Liège, Luxembourg, Namur and Walloon Brabant), 262 municipalities with 40 main cities, and 9876 statistical sectors (SS). The Walloon Region includes the four main types of built areas: agglomeration, suburban, peri-urban and rural areas. In Belgium, the SS corresponds to a neighbourhood in urban areas or a village in rural areas with more than 150 inhabitants (Nishimwe and Reiter 2021, 135). In the EU, the average annual energy consumption of buildings varies from 150 kWh/m^2 to 320 kWh/m^2, with a mean of nearly 200 kWh/m^2 for existing residential buildings. The residential sector in Wallonia consumes an average of 22,152 kWh of energy (heat and electricity) annually per dwelling. In 2015, the total final energy consumption of the whole Walloon building stock was 30.5 TWh lower heating value (LHV) for the residential sector, 13.1 TWh LHV for the tertiary sector and 44.5 TWh LHV for the industrial sector (ICEDD 2014, 127).

8.2 Methodology

This chapter is divided into three main parts:

(a) Selecting representative neighbourhoods of the Walloon regional building stock through a statistical classification;

(b) An assessment of the current average energy consumption for nine types of neighbourhoods, using regional energy reports;

(c) Evaluating scenarios from a 2040 prospective on the nine selected regional neighbourhoods.

This study is based on the Belgian cadastral database, regional energy reports and an earlier study carried out by the authors of this book (Nematchoua et al. 2021, 5).

8.2.1 Location and strategy

Wallonia occupies the southern part of Belgium. The net density classes of housing have been assessed at an SS level, whereby the built net density was established (Nematchoua et al. 2021, 5). The calculated density is in terms of housing net density per urbanised hectare. More specifically, it is the number of dwellings per urbanised hectare in an SS, by removing public spaces (streets, squares, etc.). The data used are taken from a Belgian cadastral matrix. Belgium is composed of 6,629,332 buildings (residential, tertiary and industrial). There are 1,470,378 residential buildings in Walloon that are used in our study, comprising six types: 462,025 terraced houses, 434,148 semi-detached houses, 542,652 detached houses, 29,926 apartment buildings (for a total of 96,933 individual apartments), 1,495 detached castles and 132 semi-detached castles.

Table 8.1: Number of dwellings in Wallonia found in each category of neighbourhood (Nematchoua et al. 2021, 3).

Class	**Net density (ND)**	**Terraced houses**	**Semi-detached houses**	**Detached houses**	**Apartments**
1	0–4.9	26	139	803	14
2	5–8.9	73	362	1637	40
3	9–13.9	208	681	3365	110
4	14–20.9	418	1598	6576	230
5	21–31.9	1174	3692	13,984	396
6	32–48.9	2282	7110	24,254	731
7	49–78.9	12,845	35,025	111,919	3541
8	79–137.9	294,576	311,005	367,239	64,260
9	138–255.9	150,423	74,668	14,370	27,611

Totals	462,025	434,280	544,147	96,933
Total	**1,537,385**			

Following Nematchoua et al. (2021, 5), the residential Walloon building stock has been split into nine types of neighbourhoods, based on their net density classes. Nine density classes were used to classify the 9876 Walloon SS, according to their net density of dwellings. The housing net density (number of dwellings per hectare) and the typology of these neighbourhoods are presented in Table 8.1.

8.2.2 Energy consumption and scenarios

The distribution of energy consumption according to building categories is presented in Table 8.2, based on regional energy reports.

Table 8.2: Energy consumption of each housing category (ICEDD 2014, 127).

Housing type	**Average living area (m²)**	**Heating consumption per square metre (kWh/m²)**	**Total annual energy consumption per dwelling (heating + electricity) (kWh/year)**
Apartment	60.3	182.28	15,444.61
Terraced house	77.4	230.61	22,982.28
Semi-detached house	85.3	239.72	25,581.37
Detached house	97.7	202.151	24,883.22

In this research, four scenarios have been retained for mitigating energy consumption and carbon emissions in Wallonia,:
(i) Scenario 1 assesses the variations related to climate change, using the number of degree days;
(ii) Scenario 2 involves heavy and light renovations of existing buildings;
(iii) Scenario 3 includes photovoltaic panels on the building roofs;

(iv) Scenario 4 improves inhabitants' mobility, through an increase in the number of electric vehicles or a decrease in distances travelled.

8.3 Results

8.3.1 Application of degree-days scenario

The first scenario shows the variation in energy consumption related to climate change, as a function of the number of annual degree days. These represent the sum over the year for the differences between the daily average indoor temperatures during the heating period and the average outdoor temperatures. The indoor comfort temperature is 18°C and solar gains are recorded at 3°C and deducted from the indoor temperature. Therefore, degree days are determined by the difference between 15°C and the daily outdoor temperature throughout the year. The main results are shown in Table 8.3.

These results show that the application of the degree-days scenario will allow an average reduction in energy consumption of 9.1% in 2040 (compared with the current situation) in the residential building stock in Wallonia.

Table 8.3: Current and forecast energy demand for each category of residential neighbourhood in Wallonia.

	Degree days	**Types of neighbourhoods** in the Walloon building stock								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Current energy demand (GWh)	1914.7	24.351	52.289	107.632	217.669	475.511	849.137	4030.789	24,857.00	6151.187
Energy demand in 2040 (GWh)	1627.8	19.836	42.596	87.680	194.838	425.635	760.072	3450.47	21,278.31	5598.140

Please note that Belgium is located in the northern part of Europe, where climate change will have a positive effect by reducing the energy consumption of residential buildings, but this conclusion should not be extended to all climates. Indeed, in areas where the cooling load is the main source of energy consumption in a building, climate change will have the harmful effect of increasing energy consumption.

8.3.2 Application of renovation scenario

The second scenario consists of the application of heavy and light renovations within buildings. We used the following frequencies of renovation, based on the current trends in the Walloon housing stock (Ruellan 2016, 33):

(i) The annual light renovation rate is fixed at 0.8%;

(ii) The annual heavy renovation rate is fixed at 0.5%.

We calculated energy consumption following three sub-scenarios until 2040:

- Current renovation rate: light renovation of 0.8% and heavy renovation of 0.5% of the building stock per year;
- Light renovation applied to the entire building stock of the region;
- Heavy renovation applied to the entire building stock of the region.

Light renovation works include roof renovation, and fitting of new window frames, a thermostat and a more efficient heating system. Heavy renovations refer to the total energy-related renovation of the entire building (i.e. walls, roof, windows and systems), allowing the renovated building to meet the “low-energy” criterion, with heating energy consumption of 30 kWh/m².year. To reach the level of heavy renovation, it is also possible to demolish and rebuild (according to current standards) more buildings, choosing the oldest and most obsolete buildings with no particular heritage interest. Table 8.4 shows the effects on energy consumption of these three scenarios applied on the Walloon residential building stock until 2040.

Application of the current renovation rate in Wallonia will allow an average reduction in energy consumption of 18.19% in 2040 (heavy- and light-renovation scenario) compared with 2012. Renovating the entire building stock will generate an energy consumption reduction of 44.41% through 100% light renovation, and a reduction of 88.82% through 100% heavy renovation. There should be similar results in various European countries that have the same type of old building stock as Belgium. Among the different types of renovation scenarios, 100% heavy renovation seems to be the best compared with the other two scenarios and it is the most promising for reaching zero-energy residential neighbourhoods. If it seems unlikely that this level of renovation can be achieved for the entire regional stock by 2040, it is a strategy to be favoured in small-scale projects (such as renovation of neighbourhoods).

Table 8.4: Variation in energy consumption in the Walloon building stock, by neighbourhood class, after applying renovation scenarios.

Energy consumption (GWh/year)	**Year**	**Types of neighbourhoods** in the Walloon building stock								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	2012	24.351	52.289	107.632	217.669	475.511	849.137	4030.789	24,857.00	6151.187
Current renovation rate: light (0.8%/year) + heavy (0.5%/year)	2040	19.91	42.74	87.98	177.92	388.63	700.96	3293.75	20,285.78	5014.02
100% light renovation	2040	13.57	29.13	59.96	121.21	264.69	472.52	2242.34	13,764.75	3391.81
100% heavy renovation	2040	2.79	5.97	12.29	24.75	53.88	95.90	453.90	2672.49	632.42

8.3.3 Application of photovoltaic panels scenario

For this scenario, we considered photovoltaic panels installed on an area of 20m² of each building. According to the literature, it can be concluded that these panel arrays for domestic use of 3 kW produce 3000 kWh/year. By applying this scenario to our neighbourhoods, we obtain a consumption reduction in fossil fuel use of more than 4612 GWh/year. This scenario needs to be nuanced by considering a roof correction factor (Marique et al. 2015, 223; Marique et al. 2017, 418-428), taking into account the impact of shading between buildings, according to the type of built density in the neighbourhood. Detailed results are shown for each type of neighbourhood in Table 8.5.

The application of the photovoltaic scenario (20m² of photovoltaic panels on each residential building) will allow an average reduction in non-renewable energy consumption of 9.26% for the existing Walloon residential building stock. This scenario should, of course, be assessed precisely at the neighbourhood scale, to fully take into account climate, maximal available panel area, orientation of the panels, local shading effects, etc.

Comparing the results of this scenario with those of the heavy renovation of all residential buildings in Wallonia, this study shows that it is possible to reach the zero-energy level for the six types of neighbourhoods that have a net density between 0 and 48.9 dwellings per hectare. But even for neighbourhoods with the highest built density, a combination of these two scenarios (heavy renovation and 20m² of photovoltaic panels for all buildings) allows the production by a renewable energy source of 85% of a building's energy consumption. Thus, applying these two scenarios on a neighbourhood in Wallonia would turn it into a zero-energy or nearly zero-energy neighbourhood, according to its density class.

Table 8.5: Variation in energy consumption in the Walloon building stock, by neighbourhood class, after applying the photovoltaic panel scenario.

	Types of neighbourhoods in the Walloon building stock									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
Current energy consumption (GWh/year)	24.35	52.29	107.63	217.67	475.51	849.14	4030.79	24,857.00	6151.19	36,765.57
Solar energy production (GWh/year)	2.95	6.34	13.09	26.47	57.74	103.13	489.99	3111.24	801.22	4612.16
Roof correction factor (RF)	1	0.98	0.98	0.96	0.96	0.95	0.82	0.72	0.7	-
Solar energy production with correction factor (RF)	2.95	6.21	12.83	25.41	55.43	97.97	401.79	2240.09	560.85	3403.55

8.3.4 Application of mobility scenario

Transportation is a major consumer of energy and CO_2 emitter, because commuting is necessary to travel from home to places of work or study, and then to return. Given this fact, in this research, we evaluated energy consumption related to current household travel and also up to 2040. The annual energy consumption for daily mobility was evaluated with indicators such as those shown by Marique et al. (2013, 29-44). The distances travelled by inhabitants in Wallonia are, on average, longer than those made by the inhabitants of Brussels, the capital city of Belgium. The proximity (or not) of amenities around dwellings is one factor that may explain these differences. The average energy consumption figures for different transportation types in Wallonia are: 0.56 kWh/km for diesel vehicles, 0.61 kWh/km for gas-oil vehicles, 0.585 kWh/km for an average motor vehicle, 0.45 kWh/km for a bus, 0.15 kWh/km for a train and 0 kWh/km for non-motorised modes of transport (Marique et al. 2013, 29-44). Next, to calculate the annual transport energy consumption for a resident, we established the average consumption per kilometre (travelled in Wallonia), which is 0.32 kWh/km. After determining current energy consumption related to transportation, we implemented reduction scenarios based on certain assumptions:

(i) Scenarios 1 and 2: the car park is not composed solely of cars running on fuel because some of them are electric. The first scenario assumes that half the cars will be electric by 2040 and the second scenario assumes that the entire car park will comprise electric vehicles by 2040. We adopted the same method described above, by assuming that an electric car consumes 0.17 kWh/km (Cornelis et al. 2012, 352; Nematchoua et al. 2020, 5). The average energy consumption was 0.21 kWh/km for a "half electric" car park and it was 0.11 kWh/km for a "100% electric" car park, because there are also other transport modes, including non-motorised transport.

(ii) Scenarios 3 and 4 assess the impact of a change in the number of kilometres travelled. We considered that the distance travelled by a resident will be reduced by 20% by 2040. This scenario may be reached if residents live closer to their places of work and their children's schools, or if the use of teleworking spreads (for example, if 50% of the population works from home two days a week, or stays in the neighbourhood two days per week). This translates into 24 km per day travelled for urban and suburban residents, and 30 km for those living in rural areas. The results obtained are as follows: the average energy consumption is 0.32 kWh/km (both scenarios); and the distance travelled in one year is 8760 km per resident in urban areas and 10,950 km per resident in rural areas. Similarly, we have determined future energy consumption and the results are shown Table 8.6.

Table 8.6: Variation in energy consumption in the Walloon building stock, by neighbourhood class, after applying the mobility scenarios.

	Types of neighbourhoods in the Walloon building stock									
	1	2	3	4	5	6	7	8	9	Total
Energy consumption due to mobility of residents (GWh)	9.78	21.02	43.43	87.82	191.58	342.21	1354.18	8598.53	2214.32	12,862.87
Energy consumption assuming half of cars are electric (GWh)	6.52	14.03	28.99	58.61	127.85	228.38	903.75	5738.48	1477.79	8584.41
Energy consumption assuming all cars are electric (GWh)	3.40	7.31	15.11	30.55	66.65	119.06	471.13	2991.48	770.38	4475.07
Energy consumption with reduced distances (−20%)	8.14	17.51	36.17	73.14	159.56	285.02	1083.92	6882.51	1772.41	10,318.4

The application of the transportation scenarios will allow an average reduction in inhabitants' mobility energy consumption by 2040 of 65.21% with all cars being electric, 33.26% with half of cars being electric and 16.78% with reduced distances, based on the total building stock in Wallonia.

8.4 Mixed scenarios and conclusion

After elaborating the four previous types of scenarios, we now combine some of them and calculate their impacts on the total energy consumption of the different neighbourhood classes by 2040, including energy consumption by buildings and transport, and the production of renewable electricity, in order to try to achieve the zero-energy community goal. We applied five mixed scenarios to the residential built stock of Wallonia:

1. First mixed scenario: Global warming + light renovations of all buildings + current transport;
2. Second mixed scenario: Global warming + heavy renovations of all buildings + current transport;

3. Third mixed scenario: Global warming + doubling the current renovation rate of buildings' light and heavy renovation + 50% electric cars − solar panels;

4. Fourth mixed scenario: Global warming + heavy renovation of all buildings (100%) + current transport − solar panels;

5. Fifth mixed scenario: Global warming + heavy renovation of all buildings (100%) + 100% electric cars − solar panels.

We calculated the total energy consumption for the previously established scenarios by using the following formula:

Total energy consumption = energy consumption by buildings + energy consumption by transport − local renewable energy

Finally, we evaluated the reductions (as a percentage; see Table 8.7) in total energy consumption following the four mixed scenarios for the nine neighbourhood classes. Based on these applications, we obtained the total energy consumption of each neighbourhood class according to the mixed scenarios. This allowed us to determine which scenarios were the most successful, or conversely the least efficient, for achieving the zero-energy community goal, which comprises targeting the zero-energy objective not only for energy consumption in buildings but also taking into account daily mobility.

Scenario 5 (global warming + 100% heavy renovation + 100% electric cars − solar panels) is the best of all the five scenarios; on average, it allows the reduction of energy consumption of between 90% and 91.5% for all communities in Wallonia by 2040, compared with the reference year. Scenario 5 is the only one that nearly achieves the zero-energy goal at the community level, considering energy consumption by buildings and daily mobility.

Table 8.7: Reductions (as a percentage) in total energy consumption (buildings + transport − local renewable energy) based on mixed scenarios applied to the Walloon building stock, per neighbourhood class.

	Types of neighbourhoods in the Walloon building stock								
	1	2	3	4	5	6	7	8	9
Current total energy consumption of each neighbourhood class of residential building stock in Wallonia									
Control scenario (GWh)	34.13	73.31	151.06	305.49	667.09	1201.35	5384.97	33,455.53	8365.51
Rate of reduction of total energy consumption (buildings + transport − new local renewable energy) of each neighbourhood class in the residential building stock in Wallonia by 2040 (compared with the current control scenario)									
Mixed Scenario 1	35.16%	35.16%	35.53%	35.15%	35.17%	36.11%	39.21%	39.08%	36.63%
Mixed Scenario 2	63.9%	63.92%	63.93%	63.86%	63.92%	64.33%	67.64%	67.46%	66.65%
Mixed Scenario 3	44.85%	44.697%	45.19%	44.54%	44.24%	45.05%	46.64%	45.94%	43.28%
Mixed Scenario 4	72.55%	72.39%	72.42%	72.03%	72.24%	72.49%	75.10%	74.16%	73.35%
Mixed Scenario 5	91.20%	91.09%	91.17%	90.95%	90.97%	91.06%	91.50%	90.92%	90.62%

This research was conducted by issuing several hypotheses used in research studies in Belgium. It would be worthwhile comparing the results if other assumptions, or other climatic and regional characteristics, were used.

The average reduction in energy consumption for residential buildings only in Wallonia by 2040 (compared with the current situation) will be 9.10% due to evolution in degree days, 27.29% due to climate change and the current annual renovation rate, and 44.41% and 88.82% with light or heavy renovation of the entire building stock, respectively. Considering the energy consumption of buildings only, this study shows that it is possible to reach the zero-energy level for the six types of neighbourhoods that have a net density between 0 and 48.9 dwellings per hectare, and to nearly reach the zero-energy level for the other neighbourhood types with the highest built density, through a combination of the climate change effect, heavy renovation of all buildings and 20m² of photovoltaic panels on all roofs. Transport energy consumption by 2040 could be reduced by 65.21% with all cars being electric, 33.26% with half of cars being electric and 16.78% following a 20% reduction in all distances travelled.

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Chapter 9: Life cycle energy and carbon analysis of new districts

Nieuwland 1 MW photovoltaic project in Amersfoort (The Netherlands). The project consists of over 500 houses, schools and a sports facility with photovoltaic solar modules integrated into the facade and roofs, generating a total of 1.35 megawatt peak (MWp), on about 12,300 m². (Photo: Eneco Group)

9.1 Case studies

In this chapter, we will study how to reduce the life cycle energy consumption and carbon emissions of new (sustainable) neighbourhoods in temperate and tropical regions.

Tropical climates include quite large regions that extend from the Tropic of Cancer to the Tropic of Capricorn, 14° north and south latitudes around the equator, including the entire Caribbean and Central America, a large northern half of Australia, and South America, as well as most of sub-Saharan Africa, the Indian subcontinent and South-East Asia. Two main criteria characterise a tropical climate, according to the classification of the meteorologist Köppen: precipitation with a non-arid climate, and temperatures with monthly averages that must exceed 22°C (Pouffary and Delaboulaye 2015, 191). In these climates, seasonal temperature variations are often small.

Temperate climates of Earth occur in the middle latitudes, which span between the tropics and the polar regions of Earth. In most climate classifications, temperate climates refer to the zone between 35° and 50° north and south latitudes (between the subarctic and subtropical climates). These zones generally have wider temperature ranges throughout the year and more distinct seasonal changes compared with tropical climates.

9.2 An eco-neighbourhood located in a temperate climate

This section presents the results of an LCA applied on a sustainable neighbourhood located in Belgium (Nematchoua et al. 2020, 5). The district is modelled over its whole life cycle, including the construction, operation and end-of-life of its buildings, roads, parks and parking areas, as well as the operational phase for inhabitants' daily mobility. Different scenarios, such as building orientation, water management, renewable energy and population mobility, will be evaluated to analyse their impacts on life cycle energy demand and GHG emissions at the neighbourhood level. The built environment includes buildings and public spaces (roads, parking areas, square, etc). During the operational phase, energy consumption caused by inhabitants' daily mobility is also taken into account.

The eco-neighbourhood selected offers different types of buildings, such as apartment buildings, and terraced and semi-detached houses. A majority of the built surface is dedicated to housing but we also find spaces dedicated to commercial functions or the liberal professions and small businesses. Private parking spaces are planned near the buildings. The accommodation on ground floors has private gardens and the apartments upstairs have terraces. Figure 9.1 shows the studied neighbourhood.

Figure 9.1: The studied eco-neighbourhood in Belgium, designed by FLW Architects.

The site has a density of 40 dwellings per hectare. Outdoor spaces are landscaped with more than 30% "green" or "blue" surfaces, and separate water management for rainwater and wastewater. Valves and water recovery tanks are also implemented. The area of this neighbourhood is estimated to be 3.5 ha, comprising 1 ha of roads, driveways and parking lots, 17,800 m² of green space, 6580 m² of built ground floors, and 13,160 m² of built spaces (including all floors), housing around 220 inhabitants.

9.2.1 Simulation of the eco-neighbourhood

The software used in this study is Pleiades ACV. In the implementation process of this modelling, we defined thermal zones and occupancy scenarios, in order to carry out dynamic thermal simulations. In the day zone, the heating set point temperature was 16°C between 22:00 hours and 07:00 hours, and 19°C during the day. In the night zone, the temperature was about 18°C between 22:00 hours and 07:00 hours, and 16°C during the day. The data analysis allowed us to set the occupancy of our apartments at 0.033 inhabitants/m², which corresponds to one occupant per 30 m². For each thermal zone, we defined the ventilation parameters. We considered very good airtightness, resulting in an infiltration of 0.25 volumes per hour through the walls. Table 9.1 shows characteristics of the different building materials used in this new neighbourhood.

Table 9.1: Building materials used in the studied eco-neighbourhood.

Element	**Component**	**Thickness e (cm)**	**Mass per unit area ρ*e (kg/m²)**	**Thermal conductivity λ (W/mK)**	**Thermal resistance R (m².K/W)**
Coated exterior wall	Exterior coating	1.5	26.0	1.150	0.01
	Expanded polystyrene	32.0	8.0	0.032	10.0
	Limestone silico block	15.0	270.0	0.136	1.10
	Ceiling	1.3	11.0	0.325	0.04
Barded outer wall	Cement fibre cladding	2.0	36.0	0.950	0.02
	Air blade	1.2	0.0	0.080	0.15
	Polyurethane	24.0	7.0	0.025	9.60
	Limestone silico block	15.0	27.0	0.136	1.10
	Ceiling	1.3	11.0	0.325	0.04
High floor	PDM sealant	-	-	-	-
	Polyurethane	40.0	12	0.025	16.00
	Concrete slab	25.0	325	1.389	0.18
	Ceiling	1.3	11	0.325	0.04
Intermediate floor	Chappe + coating	8.0	144	0.700	0.11
	Polyurethane	1.0	0	0.030	0.33
	Aerated concrete	8.0	48	0.210	0.38
	Concrete slab	25.0	325	1.389	0.18
	Ceiling	1.3	11	0.325	0.04
Low floor	Chappe + coating	8.0	144	0.700	0.11
	Polyurethane	25.0	8	0.025	10.00
	Concrete slab	25.0	575	1.750	0.14
Internal wall	Ceiling	1.3	11	0.325	0.04
	Limestone silico block	15.0	270	0.136	1.1
	Expanded polystyrene	4.0	1	0.032	1.25
	Limestone silico block	15.0	270	0.136	1.10
	Ceiling	1.3	11	0.325	0.04

The energy data were evaluated under the Belgian electricity mix in the software, which is 52% nuclear, 27% natural gas, 17% renewable energy sources and 4% coal. The heating production system was a natural gas condensing boiler with a 92% lower heating value (PCI) efficiency. The water consumption was fixed at 100 l/person per day.

Regarding the use of waste, the policy of selective sorting of waste is also taken into account (*Less of waste.wallonie.be*). This sorting is considered equal to 90% for glass, and 75% for paper and cardboard. Thus, this proportion of waste will be considered recycled and not landfilled. According to Belgian statistics, 40% of the 1500 g of daily household waste per person is sent for incineration, with a yield of 85%. The distance from the neighbourhood to the household waste site is 10 km, and it is 100 km to the incinerator and 50 km to the recycling site.

We considered that 80% of occupants make a daily commute by car, meaning that 20% use a bicycle or walk. For car drivers, an average distance of 20 km is indicated for commuting to work. This is performed five days a week, 47 weeks a year. The trips between dwellings and shopping centres (5 km) are undertaken once a week, 47 weeks a year.

9.2.2 Scenarios and results

Orientation impact assessment

We studied the impact of orientation on LCA results at the neighbourhood level. In this scenario, initially, a majority of the buildings were positioned so that the longitudinal facades were oriented to the north and to the south. We named this initial scenario “0° orientation”. We tested other orientations by rotating the mass plane by an angle of 45°, 90° and 180°. We performed the standard deviation of all buildings for each of the orientations. Next, we selected the worst orientation and performed the neighbourhood’s complete LCA for this orientation. Finally, we compared the results of this LCA with those of the core neighbourhood, in order to quantify the impact of the orientation on the global energy demand and on the GHG emissions of the studied neighbourhood during its operational phase.

A 90° rotation of the neighbourhood is the worst orientation, generating an increase in heating energy consumption of buildings by 13%. However, by taking into account the energy consumption due to electricity appliances, domestic hot water and transport at the neighbourhood level, the impact of building orientation on the total energy demand of the neighbourhood during its operational phase is limited to a 1% increase and also a 1% increase in GHG emissions for the worst orientation.

Water management impact assessment

Initially, we did not consider any rainwater harvesting system, although the real eco-district is equipped with it. There was no segregation network and the floor coverings were not designed to provide high permeability. Thus, all rainwater falling on roads and buildings had to be taken back into the wastewater and treatment network. However, we did not consider the use of drinking water for watering gardens.

Scenario 1: rainwater recovery systems. In this scenario, rainwater recovery tanks are modelled. The rainwater will be used for watering gardens, cleaning outdoor and indoor spaces, flushing toilets and in washing machines. We have a total of 6580 m² of surface area consisting of the gravel roofs on buildings. In addition, rainwater will be supported by a separate network consisting of not only these tanks but also waterbodies, valleys and ditches. Garden water is taken up by the ditches and valleys and directed towards a body of water, which is the same for the water in the alleys, squares and parking areas. The water recovered from the roofs is stored in tanks, whose overflow discharges into the valleys. Thus, we considered that all of the site's rainwater is managed by a segregated network and that no part of this water will be taken over by the wastewater network. However, the soil retains its initial permeability.

Scenario 2: permeable floors. In this scenario, we implement more permeable floor coverings than in the basic option. In this manner, aisles, squares and car parks are constructed with permeable materials, concrete pavements without pointing and concrete–grass slabs. Thus, the total impermeability of the site is reduced from 66% in the initial state to 58% once the permeable options are implemented. This small difference between the average permeability of the two scenarios is explained by the large proportion of green spaces in the initial scenario of the studied neighbourhood, which results in high permeability. In this second scenario, we considered that no other rainwater harvesting system would be implemented. All of the water that does not infiltrate directly into the soil is sent to the wastewater network.

The eco-neighbourhood with rainwater recovery systems allows a saving of 1.5% of primary energy demand and reduces GHG emissions by 2.3% compared with the initial neighbourhood over its whole life cycle. However, the permeable neighbourhood only allows a saving of 0.2% of life cycle primary energy demand and reduces life cycle GHG emissions by 0.46%.

Urban mobility impact analysis

In the reference scenario, we considered a significant use of the car for daily commuting. We will compare this scenario with a second one, where the site is considered urban, perfectly integrated with public transport networks and at a short distance from the shops of primary needs. Let us review the mobility hypotheses:

- Initial scenario: 80% of the occupants commute daily; the distance from home to work of 20 km is travelled daily by car; the distance from home to shops of 5 km is undertaken weekly by car.
- Urban scenario: 100% of the occupants commute daily; the distance from home to work of 2.5 km is travelled daily by bus; the distance from home to shops of 300 m is undertaken weekly by bike or on foot.

A neighbourhood with green mobility allows the saving of 29% of primary energy demand and a reduction by 44% of GHGs emitted during its entire life cycle, compared to the initial neighbourhood.

Urban density impact analysis

Vertical density: In the vertical density scenario, we raise each building by an additional floor. These new floors are identical to those below and are divided into thermal zones “day” and “night” of the same total area. Thus, we increase the built density of our neighbourhood and consequently the number of inhabitants. The district in its initial state counted 220 inhabitants, while the vertical density scenario shelters 321 inhabitants. We performed dynamic thermal simulation of all our buildings with one more floor and then obtained the life cycle environmental impacts of the neighbourhood.

Horizontal density: In the horizontal density scenario, we increase the number of buildings on the site. We added four new buildings to obtain the same built-up area as in the vertical density scenario, with the same number of inhabitants. We removed a portion of the public space, so that the surface of our site remains unchanged. In addition, we make sure that the buildings added are, in all respects, identical copies of those already existing within the district. Thus, we are able to compare the environmental impact of the two types of neighbourhood densification.

The vertical density scenario allows a saving of 14% of cumulative energy demand per built square metre and a reduction by 21% of GHG emissions per built square metre during its life cycle, compared with the initial neighbourhood. However, the horizontal density scenario increases both the life cycle cumulative primary energy demand by up to 4% and the life cycle GHG emissions per built square metre by 0.7%. The vertical density scenario allows a saving of 18% of cumulative energy demand and 22% of GHGs, over its entire life cycle, compared with the horizontal density scenario.

Urban renewable energy impact

In the initial scenario, all the electricity that was used came from the Belgian electricity grid and the associated production impacts were taken into account. In the first scenario, photovoltaic panels are installed on all the roofs on the site and we considered having a panel area equivalent to two thirds of the roof area of each building. It must be noted that our dwellings only use electricity for lighting and to power household appliances. The photovoltaic installation consists of monocrystalline photovoltaic solar panels. The sensors are placed using a support on the roof terrace. They are oriented towards the south and inclined at 35°, which is the optimal inclination in Belgium. The second scenario assumes that, by 2050, there will be 100% use of electric cars and 100% renewable energy in the electricity mix.

A neighbourhood with photovoltaic panels allows a saving of 40.5% of primary energy demand and a reduction by 20% of GHGs, over its whole life cycle, compared with the initial neighbourhood. In the second scenario (electric cars and green electricity), 45% of life cycle cumulative primary energy demand and 23% of life cycle GHG emission are saved over the neighbourhood's life cycle.

9.3 Case of a new district under a tropical climate

In this section, we propose the design of a new district in sub-Saharan Africa, in which we will try to reach the zero-energy and zero-carbon criteria. In developing countries, due to their current demographic and economic growth, the final energy consumption of cities and their corresponding GHG emissions could double or even triple by 2050. Africa is experiencing rapid urbanisation, which is likely to continue over the next decades, fuelled by strong demographic growth. If the current growth rate is maintained, it is likely that Africa's population will reach 2.4 billion inhabitants by 2050, including 1.34 billion urban dwellers (55%), compared with 455 million today. The continent already brings together over a quarter of the 100 cities experiencing the strongest urban growth and should have several megalopolises by 2035. It is therefore urgent in these countries to use sustainable strategies for the design and construction of new districts and cities.

9.3.1 Case study

The choice of Madagascar as the location for this study was not made at random. It is the largest island in the Indian Ocean and the fourth largest in the world. It also has the largest population of any country in the Indian Ocean, which has increased from 3 million to 25 million inhabitants over the past 60 years. Over 92% of the island's population live on less than $2 a day; half of its population is under 18 years of age; 70% of the island's population does not have access to drinking water in their dwelling; and only 20% of households have access to electricity and even only 4% in rural areas. Today, Madagascar is considered the third most vulnerable country to climate change. Designing a sustainable city in Madagascar will be an asset for this country. It will also be an asset for all the Indian Ocean countries and other sub-Saharan Africa countries, which are regularly attracted by this country.

Madagascar has significant potential for renewable energies, which are currently only less than 10% exploited. No national survey of the energy demand of buildings has yet been carried out in Madagascar, as it has in several other countries in sub-Saharan Africa. Even today, power cuts still remain a major problem for the island. This problem could be resolved by designing a sustainable city that can serve as a benchmark in terms of design strategies and management rules for energy-efficient and low-carbon cities.

Madagascar is classified among the countries that are rich in solar energy, with a potential estimated at more than 2000 kWh/m².year. Its hydroelectric potential is greater than 8 GW and its wind power potential is greater than 2000 MW. The rural population of Madagascar depends mainly on subsistence agricultural activities, which contribute to the degradation of the habitat, in particular deforestation. In Madagascar, energy is obtained either by the development of natural resources, such as biomass, forest residues, crop residues, water, sun and wind, or by the import of petroleum products. The country does not produce oil, despite the many prospecting works carried out there.

The island of Madagascar has an estimated area of approximately 592,000 km². It is located between 47°0 east longitude and 20°0 south latitude. The island is essentially subject to a tropical climate dominated by two seasons: a rainy season from November to April, and a dry season from May to October. The location of the country and the territory selected for this study are shown in Figure 9.2.

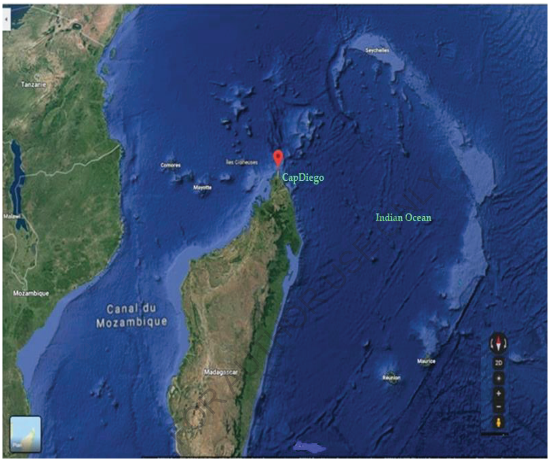

Figure 9.2: Location of the territory selected for this study.

The choice of this location is based on the availability of two natural and renewable potentials that facilitate the implementation of the zero-energy and zero-carbon concept: a very high wind potential ranging from 5 m/s to 10 m/s, and solar availability estimated at more than 3000 hours per year.

9.3.2 Location of a new district

Cape Diego city (latitude 12°15 south; longitude 49°16 east) is a peninsula in northern Madagascar that advances from the west to the centre of the bay of Diego-Suarez, which joins with the Indian Ocean. Cape Diego is the most isolated urban district of the Antsiranana city, which is the capital of the Northern Province. The location chosen for a new district is shown in Figure 9.3.

Figure 9.3: Location of the new (sustainable) district.

This new district will be built in Cape Diego covering a total area of 15 ha (150,000 m^2), including 2 ha reserved for the installation of a solar field and wind turbines; 1.5 ha for roads; 1.75 ha for driveways and parking areas; 5.5 ha for green spaces and public gardens; and 4.25 ha for residential and commercial buildings.

In this new district, buildings will include:

(i) 22 large residential buildings consisting of 464 apartments, designed to accommodate up to 1392 inhabitants;

(ii) several commercial buildings: shops, school, office building, hospital, hotel, restaurant, police office, church, concert hall/opera house, waste treatment station, sports complex, etc.

Figure 9.4 shows components of this new city and its main buildings.

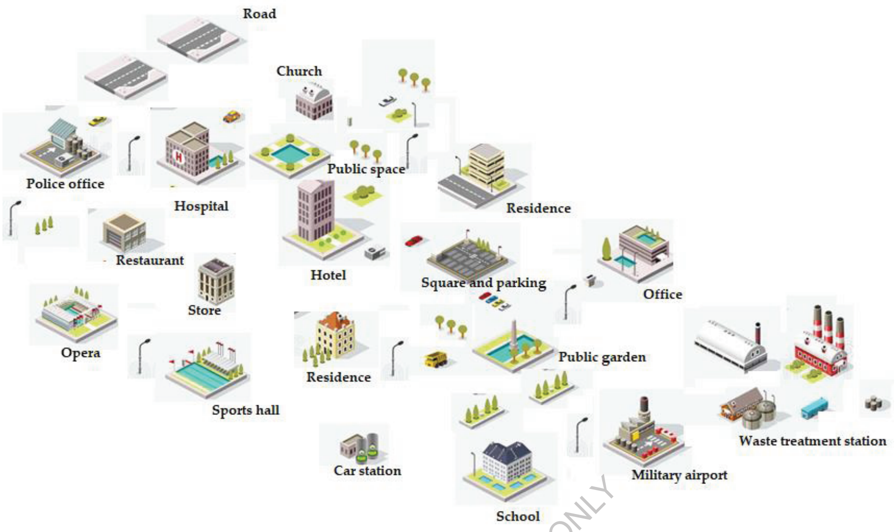

Figure 9.4: Components and building types of the designed district.

9.3.3 Simulation tools

In this study, we coupled seven tools, as given in the Table 9.2, to evaluate the best energy and carbon strategies for the new city.

Table 9.2: Research tools.

Tools	**Role**
AutoCAD	Building modelling
Meteonorm	Weather simulation
Design Builder	Optimisation
Energy plus	Inventory of energy consumption
Pleaides ACV	Life cycle assessment
IBM SPSS Statistical	Data calibration
R	Statistical analysis of data

9.3.4 Generated energy

The main energy sources used in the new district will be:

- A solar field with a total area of 96,000 m^2 consisting of polycrystalline cells with an inverter and oriented at 45° towards north.
- Seven wind turbines of medium size. Available schedule: 24/7; rotor type: horizontal; rotor speed: 41 rev/min; rotor diameter: 19 m; overall height: 31 m; number of blades: 3; maximum tip speed ratio: 8; and maximum power coefficient: 0.4. All the seven wind turbines are installed near the sea.

Figure 9.5: Types of renewable energy sources for the new district

9.3.5 Characteristics of the designed district

The district model is shown in Figure 9.6. Strategies and scenarios applied to design this new district are:

(i) Responding to demographic change by providing a range of housing adapted to different situations and households, in a spirit of social and intergenerational balance. A policy of diversity and social integration promoting the mixing of all categories of populations is elaborated. The principal building facades are oriented towards the south.

(ii) Promoting short distances travelled, by the good territorial distribution of functions and the creation of good quality equipment and infrastructure, accessible to the entire population:

- daily distance from home to shops or supermarket: 500 m (maximum);
- distance to the common transport network: 250 m (maximum);
- daily distance from home to the workplace: 2500 m (maximum).

(iii) Developing alternative modes of transport to the private car:
- Over 80% of private cars will be electric vehicles;
- Public transport will be based on electric buses.

(iv) Promoting soft modes and intermodal mobility, through continuous and secure pathways to encourage walking and cycling (including e-bikes) for distances under 12 km.

(v) Contributing to a lively and diversified territorial dynamic, by creating jobs, and stimulating new economic and commercial dynamics.

(vi) Using 100% renewable energy sources: wind turbines and photovoltaic panels.

(vii) Using techniques, materials and devices specific to eco-planning and eco-construction. The majority of building materials used in this study have low thermal conductivity and zero-carbon emissions. Examples of such materials include: mycelium (thermal conductivity is 0.04 W/mK and embodied carbon is 0); hemp (thermal conductivity is 0.04 W/mK and embodied carbon is 0); wood (thermal conductivity is 0.04 W/mK and embodied carbon is 0); rammed earth (thermal conductivity is 0.05 W/mK and embodied carbon is 0); Ashcrete (thermal conductivity is 0.04 W/mK and embodied carbon is 0).

(viii) Application of passive strategies, such as: (a) choosing insulation with low thermal conductivity (hemp, polyurethane, extruded polystyrene); (b) application of phase change material; (c) application of green roofs on 80% of buildings; (d) application of energy-saving light bulbs – for example, LED and fluorescent-triphosphate; and (e) choosing the most efficient cooling system.

(ix) Creation of alternative sanitation and rainwater management systems, based on rainwater recovery systems and permeable floors. Rainwater recovery systems include tanks that have been sized to satisfy the demand for watering gardens, cleaning outdoor and indoor spaces, flushing toilets, and for use in washing machines. Rainwater is managed by a segregated network consisting of cisterns, waterbodies, valleys and ditches. The water recovered on roofs is also stored in tanks. All of the site's rainwater is managed by a sewerage system and no part of this water will be taken over by the wastewater network. Soils keep their initial permeability. Areas with permeable floors include alleys, squares and car parks covered with drainage pavements and concrete–grass slabs. The totality of water not infiltrating directly into the soil is sent to the wastewater network. The total impermeability of the site decreases to 58%, once the permeable pavements are used.

(x) The drinking water network efficiency is 90% and allows a maximum water consumption of 140 litres per day per person.

(xi) Waste treatment is performed through selective waste collection, sorting, recycling, composting, etc., allowing the collection of 100% of glass and 100% of sorted paper; 100% of metal is recycled; and 100% of remaining household waste is incinerated. The distance from the district to the household waste site is 10 km; the distance from the district to the incinerator is 20 km; and the distance from the district to the recycling plant is 50 km.

(xii) The district life cycle is fixed at 100 years.

Figure 9.6: District model.

The main building types of the new district are grouped into 14 categories: low-rise residential, high-rise residential, office, shop, police station, restaurant, hotel, hospital, school, station, airport, opera/concert hall, sports hall and church.

Data Availability: Characteristics of each residential building in this new city and input data that support the research, and also other findings of this book, are available from the author upon the reasonable request of each reader.

The majority of materials used in this study have very low embodied carbon. Bio-PCM material and green roofs are also used in different building types. The choice of bio-PCM has not been made randomly in this study but according to its technical specificities (PCS 2020, 1). Bio-PCM is used in products offering easy-to-install solutions that yield significant energy and carbon savings. Bio-PCM is non-toxic, non-corrosive and manufactured using sustainably grown food-grade by-products. The bio-PCM material was developed to reduce the stress placed on cooling systems, ultimately yielding significant energy and carbon savings while providing a more comfortable environment. Impacts of bio-PCM vary depending on building type, age, location and active systems. When bio-PCM reaches its melting point, it absorbs large amounts of heat at an almost constant temperature, cooling the accompanying space. Bio-PCM continues to absorb huge amounts of heat without a significant rise in temperature until the material is transformed into a liquid state. When ambient temperatures fall, bio-PCM solidifies and releases stored latent heat into the environment.

Green roofs are interesting from a physical and construction point of view, because they increase thermal and acoustic insulation, protect against overheating in summer, and increase the life of the roof's waterproof membrane. In addition, green roofs bring more nature and biodiversity to the city and they naturally absorb CO_2.

9.3.6 Results and analysis

The results of the new district simulation are given in Table 9.3.

Table 9.3: Simulation results at the district level.

Parameters	**Per year**
Heating energy (GWh)	0.00
Cooling energy (GWh)	0.00
Energy demand (GWh)	3.74
Energy generated from photovoltaic panels + wind turbine (GWh)	3.74
Operational carbon emissions (t CO_2e)	−1047.12

Table 9.3 shows that in the new district the energy demand (3.74 GWh per year) is equal to the energy generated by seven medium-sized wind turbines and a solar field of 9600 m^2. This result shows that the designed district is a zero-energy district: the amount of energy produced annually is equal to the amount of energy consumed. In addition, during the operational phase of the city, the emission rate is estimated at −1047.12 tCO_2 per year. A negative carbon footprint means that this city removes more CO_2 than it emits into the atmosphere. It is interesting to note that energy used for cooling is zero in all buildings – this is the result of the choice of building materials best suited to the tropical climate and with very low thermal conductivity. The design of this new district can also be applied to all countries with the same climate as Madagascar.

These results show that Madagascar, as well as several other countries in sub-Saharan Africa, is full of significant potential resources, and it may be favourable to design new cities with zero energy and low carbon. Wind, solar, hydropower and biomass are renewable energy sources that are found in abundance in these countries.

In summary, it has been found that the solutions proposed to design zero-carbon and zero-energy cities in tropical regions cover a wide field of expertise, from the energy performance of buildings and use of low embodied carbon materials, to the implementation of smart mobility and the optimisation of public lighting and security, as well as the decentralised production of green energy.

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Conclusion

Following the alarming evolution of the climate, ecological and economic challenges related to energy supply, and other disasters linked to the destruction of the environment by human beings, it is urgent that all new cities of the world should become autonomous in terms of energy and emit almost zero carbon by 2050. Moreover, to limit the average world temperature increase to 1.5–2°C, as recommended by the IPCC, the energy consumption and carbon emissions of existing building stocks should also be greatly reduced. Developing sustainable cities is needed in all countries of the world. However, design strategies and the best technologies for zero energy and zero carbon still remain unknown by several specialists, building designers and urban planners.

So far, most of the world's population is oblivious to the climate challenges facing humanity. Over 65% of carbon emissions and energy consumption comes from a few countries, including China, the US, the EU-28, India, Russia, Japan and Iran. Another important environmental risk is population growth, which currently is greatest in Africa, the Middle East, and South-East Asia. There are therefore two types of drastic changes to be applied to reduce polluting emissions in the world: it is necessary to reduce the GHG emissions per person in the most polluting countries and it is also essential to reduce the currently strong growth of the world's population in developing countries, which generates fast growth in energy consumption and carbon emissions.

This book has presented design strategies, construction methods, building technologies and materials that might be useful for helping building designers, architects and urban planners to design new green districts and cities, which thus fills the gap of a lack of education in these fields. Five main sectors and their CO_2 emissions have been studied in this book: buildings, transportation, industry, energy production and waste management. Case studies from several continents have been illustrated in this book, which have demonstrated practical applications of the presented concepts and techniques.

The first chapter studied design strategies to achieve the zero-energy goal in the building sector. The second chapter described how to reduce carbon emissions of buildings. The third chapter presented strategies to apply zero-energy and low-carbon objectives in the transportation sector. The fourth chapter addressed strategies for zero-energy industries and sustainable power generation. The fifth chapter developed strategies to reduce carbon emissions due to waste treatment, while the sixth chapter gave 20 summary questions and answers about zero-energy and low-carbon cities. The last three chapters of the book described case studies to achieve zero-energy and low-carbon buildings and districts, in existing and new built environments under various climates.

Modernising cities through the construction of new eco-districts and increasing substantial renovations of outdated buildings worldwide could mitigate the amount of GHGs emitted by 53–97% by 2050. For example, in old neighbourhoods located in a temperate climate, it is possible to reduce up to 91.5% of total energy consumption by 2050, by combining the heavy renovation of all buildings, replacement of all petrol and diesel cars by electric cars, and the integration of photovoltaic solar panels on suitable roofs. Moreover, by combining substantial building renovations with the installation of photovoltaic panels and sustainable heating sources, the objective of operational zero carbon at the neighbourhood level could be achievable by 2050 in various regions of the world. Note also that several countries in tropical and hot climates, such as sub-Saharan Africa, have many renewable energy sources, which facilitate the design of zero-energy built environments. Radical changes in the judicious choice of construction materials, including reused, recycled and low-carbon materials, as well as city greening strategies and the use of renewable energy production, represent additional challenges for life cycle zero-carbon built environments.

The following rules should be applied at the district and building levels to achieve zero-energy and zero-carbon cities:

- use of passive strategies in buildings, reducing cooling and heating loads;
- use of renewable energy sources;
- promotion of short travel distances, development of alternative modes of transport to the private car, and promotion of soft transport modes and intermodal mobility, as well as 100% electric cars;
- use of sustainable construction methods (adaptive design, prefabrication, etc.);
- use of materials with low thermal conductivities and carbon emissions (such as reused materials, recycled materials, green roofs, hemp, wood, rammed earth, etc.);
- protection of landscapes and existing natural spaces, while greening built environments;

- treatment of all waste through the selective collection of waste, sorting, recycling and composting;
- improvement of wastewater treatment and separate rainwater management.

The authors hope that this book will contribute to a greater awareness of climate issues, and that it will help when developing zero-energy and zero-carbon built environments around the world. A transition to zero-energy and zero-carbon cities is an important step towards achieving both healthy and comfortable built environments, bringing well-being to local populations, while also being beneficial for the environment and the biodiversity on Earth.


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