

Context and Issues

1.1. The building through the ages

The energy efficiency of a building refers to the concept of the energy performance of a building, which consists of comparing the “useful” energy produced by the building and the energy it consumes. The objective is to reduce a building’s energy consumption and carbon emissions while maintaining a level of comfort for occupants.

Over the centuries, humans initially sought comfort, safety and health quality from their habitat. Energy efficiency is a more recent issue.

The nomadic prehistoric humans protected themselves from the weather and wild animals by sheltering at the entrance of caves or by building huts from branches, bones and skins. As humans subsequently became sedentary, habitats evolved into shelters made of rammed earth and straw. In ancient times, houses evolved, and stone, brick, tile and cob started to be used as building materials. During the Middle Ages, glass gradually appeared, especially in rich houses, churches and palaces. In the 16th century, windows occupied a large part of the facades. From the 19th century onward, cities were transformed (large avenues, building industrialization, multi-story building, etc.). It was at this time that new materials (concrete, steel, aluminum, etc.) were used in the evolution of buildings. The 20th century was marked by a rural exodus with the development of cities, skyscrapers and mass housing. The notion of comfort started to be included in the housing discussion. Today, a building is expected to be healthy, comfortable, safe, energy efficient and environmentally friendly. We see new biobased materials on the market (vegetable wools, animal wools, biobased building materials, etc.). Future housing is currently moving toward energy-generating building design, energy sharing at the community level and indoor pollution reduction.

1.2. Energy and environmental issues in the building sector

The energy problem has been a major concern of global economic policies since the 1970s' energy crisis. Major energy-saving efforts have been made, especially in the most energy-intensive sectors.

In France, the construction sector is currently the largest consumer, with 62.3 Mtoe, compared with the transport sector (45.2 Mtoe) and the industry sector (27.5 Mtoe). In 2019, the construction sector accounted for 45% of the total energy consumed (Ministère de la Transition écologique 2020).

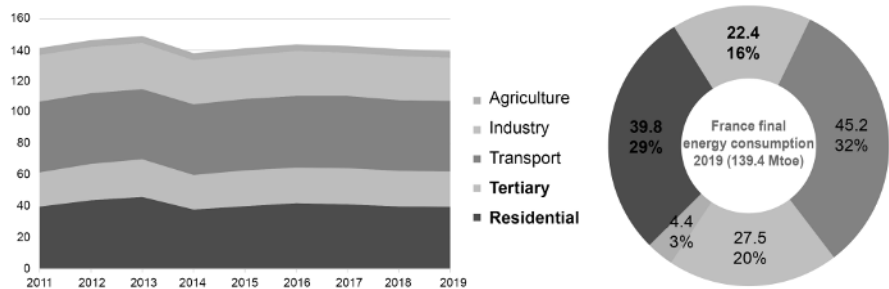


Figure 1.1. Evolution of final energy consumption in France in Mtoe by sector for all energies between 2011 and 2019 (SDES, Bilan énergétique de la France 2019; Ministère de la Transition Écologique (2021)). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

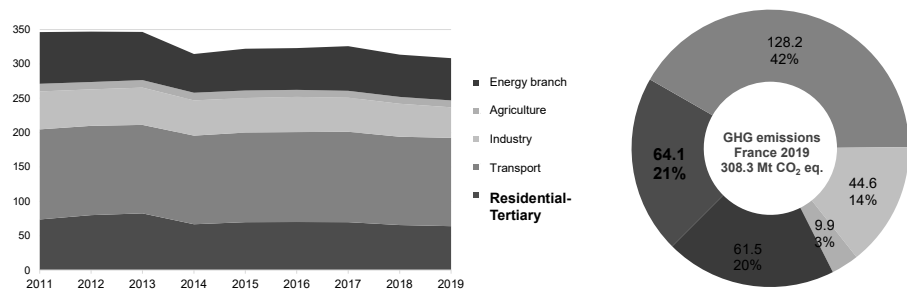


Figure 1.2. Evolution of GHG emissions in France from 2011 to 2019 in Mt CO₂ eq. (SDES, Bilan énergétique de la France 2019; Ministère de la Transition Écologique (2021)). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

In 2019, this energy consumption caused the emission of 64.1 Mt CO₂ eq. (million tons of CO₂ equivalent), namely, 21% of national emissions (approximately two-thirds for residential and one-third for tertiary) (Citepa n.d.). Retrofitting poorly insulated buildings offers opportunities to reduce carbon emissions.

The figures are consistent for European (European Parliament n.d.) and non-European (Plan Bâtiment Durable n.d.) countries, with 40% versus 36% for energy consumption and 36% versus 40% for CO₂ emissions, respectively, in 2017.

The building sector is also a major consumer of raw materials. A study carried out by ADEME (2019) gave the following figures. For new single-family dwellings, the quantity of materials was 1,190 kg.m⁻² SHON_{RT} (net floor area or adjusted gross floor area) compared with 1,570 kg/m² SHON_{RT} for collective housing. This quantity was 28 kg.m⁻² SHON_{RT} for a low-energy-certified house (BBC in French) refurbishment and 20 kg.m⁻² SHON_{RT} for collective housing. In France, for the entire housing stock, by 2050, new construction could require up to 1.3 billion tons of materials, with 85% only for aggregate, sand and cement.

The urgent need to reduce CO₂ emissions and the gradual depletion of resources requires a significant reduction in the consumption of non-renewable energy in housing. This consumption is primarily associated with heating and the production of domestic hot water, which accounts for more than 90% of energy use in these areas. Many European countries share this perspective. European members have come together to establish a strategic framework for addressing climate change. This includes an energy policy that emphasizes the critical role of the building sector. The first European directive, called the Energy Performance of Buildings Directive (EPBD), was established in December 2002. Member states must adopt new rules regarding thermal insulation and ventilation. The second directive, established in December 2008, known as the “Climate Initiative” (or 20–20–20 Directive), imposed three targets for the building sector: (1) raise the share of renewable energies to 20% of consumption by 2020; (2) improve energy efficiency by 20% by 2020; (3) and reduce by 2020 the greenhouse gas (GHG) emissions by 20% from 1990 levels.

The building sector is undergoing a significant transformation, shifting from being one of the most energy-intensive sectors to aiming for Nearly Zero Energy Building (NZEB), as defined in Directive 2010/31/EU. This transition requires a ten-fold increase in research and development efforts across various areas, including materials, components, envelopes, systems or control of indoor environments. Ensuring the comfort, health and safety of occupants at virtually zero energy cost is crucial.

The construction of high-energy-efficiency buildings and the thermal retrofitting of existing buildings have resulted in a decrease in energy consumption for residential and tertiary buildings over the past decade. In 2019, the final energy consumption adjusted for climate change was 41.7 Mtoe (487 TWh) for residential buildings and 24.7 Mtoe (289 TWh) for tertiary buildings.

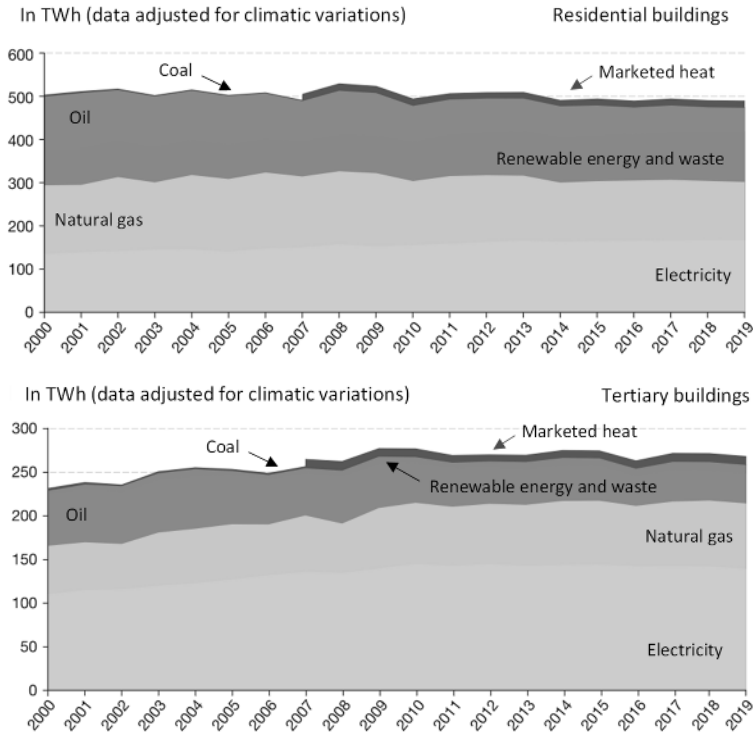


Figure 1.3. Final consumption by energy for residential and tertiary buildings from 2000 to 2019 (Ministère de la Transition Écologique 2021). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

For residential buildings, electricity is the primary energy source, accounting for 34% of usage. This is followed by natural gas at 29%, renewable energies at 23% and petroleum products at 11%. Over the past few years, the shares of natural gas and oil have decreased in favor of renewable energy and electricity.

In tertiary buildings, electricity accounts for 52% of consumption, followed by natural gas (28%), petroleum products (13%), renewable energy (4%) and grid-distributed heat (4%).

Figure 1.4 shows the energy consumption for a dwelling in 2000 and 2016. The energy used for heating decreased (73% vs. 66%), whereas the specific electricity increased (12% vs. 17%) because of the diversity of electrical equipment (Internet, computer, etc.).

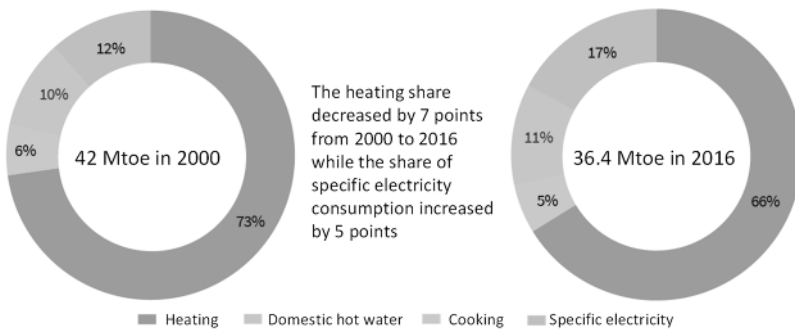


Figure 1.4. *Distribution of energy consumption by households in their dwellings per use (Ceren 2017). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip*

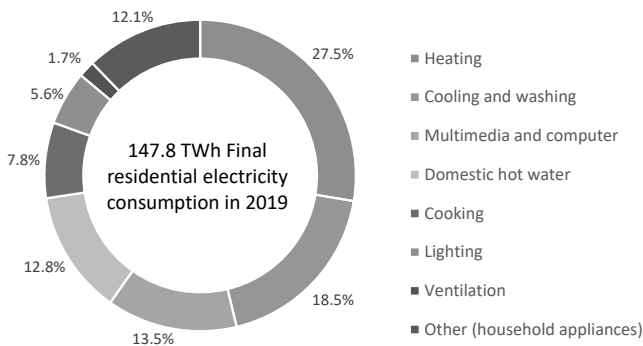


Figure 1.5. *Residential electricity consumption per use in France (according to ADEME (2019)). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip*

If we focus on electrical energy, we see its strong presence in all residential uses (Figure 1.5).

The construction sector faces numerous challenges, including the need to address energy consumption, the use of raw materials and the impact of buildings on their environment. One of the most pressing issues is climate change.

The production of GHGs during construction and the refurbishment of buildings as well as their use could contribute to climate change. However, buildings may also suffer from the effects of climate change. For example, global warming can lead to drought, which can generate cracks in buildings constructed on clay soils. Additionally, rising sea levels necessitate adaptations to buildings along the coast. Heat waves also contribute to increased air conditioning usage, leading to higher energy costs and additional sources of GHG emissions. As illustrated in Figure 1.6 (heat waves observed in mainland France from 1947 to 2017 and projections for 2017–2100), heatwaves are expected to become more frequent, numerous and intense in the future.

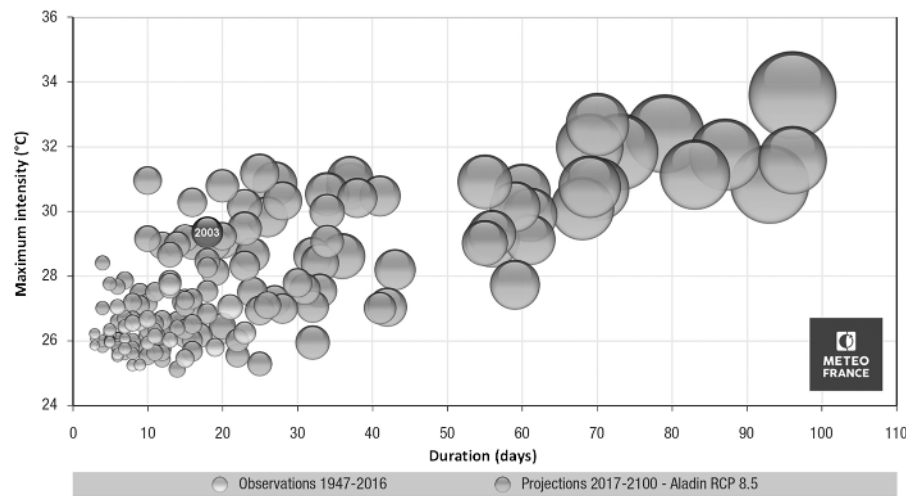


Figure 1.6. Heat waves in France – bubble sizes: seriousness (Météo-France n.d.). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

Construction stakeholders must find innovative solutions to increase resilience against climate change, enabling adaptations during extreme heat periods.

The French construction sector faces several immediate and significant challenges. With respect to older buildings, we can identify issues such as fuel poverty, the poor condition of some houses, the aging of the building stock and its low renewal rate of only 1% per year. The emergence of water-related issues along with fungal development creates significant challenges during refurbishment projects. Poor indoor air quality (VOC, particulate pollution, viruses like SARS-CoV-2, bacteria, etc.) can lead to adverse health effects. Additionally, there are concerns surrounding interseasonal energy storage and the intermittent nature of renewable energy sources such as wind and solar gains.

1.3. Characteristics of the building stock

The building stock in France includes residential, tertiary, commercial, industrial, agricultural, logistics and mixed-use buildings.

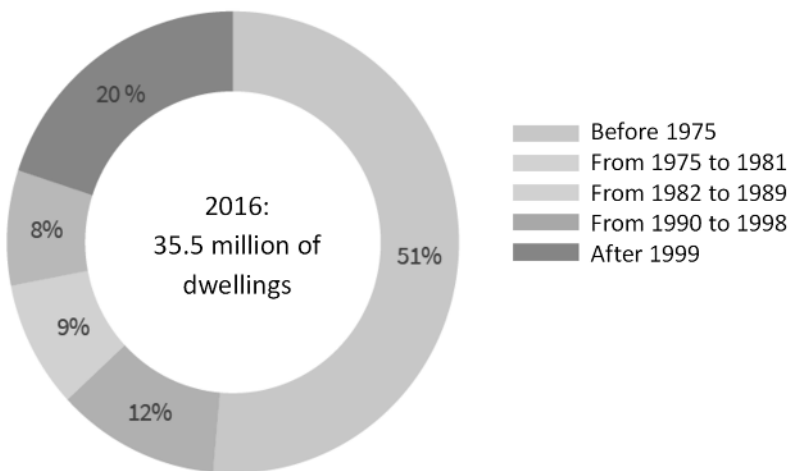


Figure 1.7. *Distribution of dwellings per construction years (Ceren 2017). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip*

The 2016 French stock (including overseas departments) consisted of 35.5 million dwellings, with 56% being single-family dwellings and 44% being collective dwellings (single ownership or co-ownership). Stock growth is approximately 1% per year. In 2018, the distribution of primary residences was as follows: 47% were owner-occupied, 33% were tenant-occupied, 2% were free-of-charge or other primary residences, 10% were second homes, and 8% were vacant. With respect to the age of the dwelling, 51% were built before 1975, 29% between 1975 and 1998,

and 20% after 1999 (Figure 1.7). The typical dwelling was a three-bedroom apartment, averaging 90 m² in habitable floor area. The average surface area per capita was approximately 40 m². In 2018, the residential sector consumed, on average, 198 kWh of final energy per square meter per year or 296 kWh of primary energy per square meter per year. Definitions of the final energy and primary energy are provided in section 1.4.

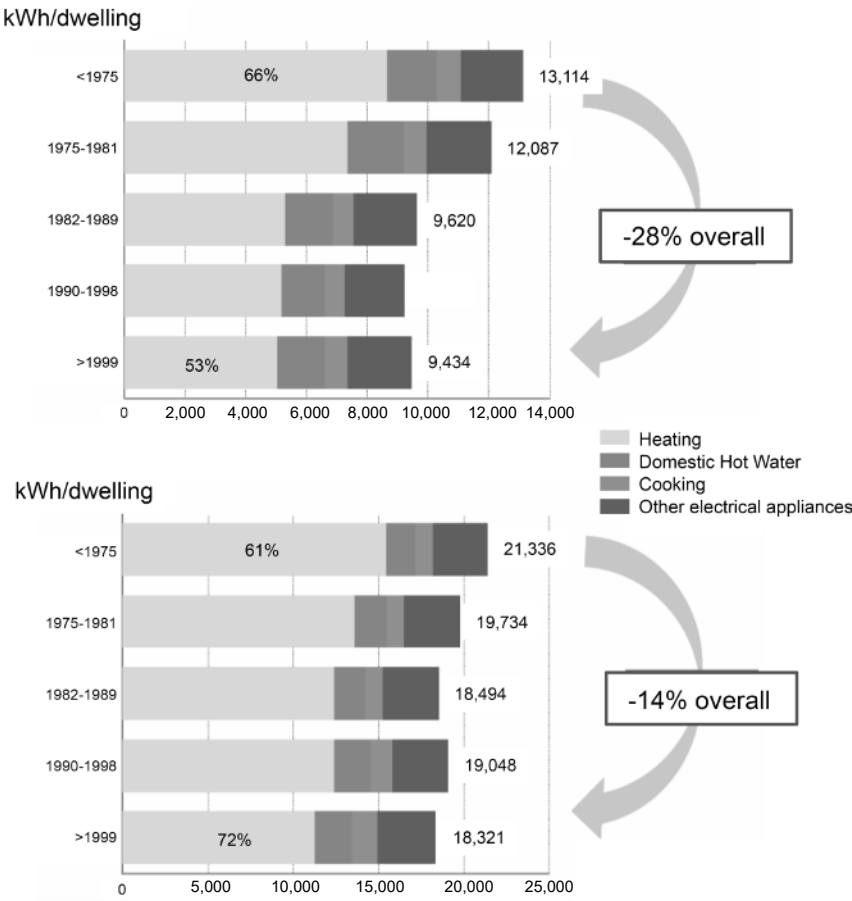


Figure 1.8. Evolution of final energy consumption per use in single-family dwellings (SFD) and collective dwellings (CD) (Ceren 2017). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

With the introduction of various thermal regulations aimed at reducing thermal transmittance in buildings, heating consumption steadily declined from over 70% of total consumption in 1975 to approximately 50% in 1999. In 2022, hot water consumption was frequently the highest among energy use categories (see Figure 1.8).

Tertiary buildings encompass a diverse array of activities, including education, health, sport, leisure, catering, accommodation, administrative, commercial, financial, real estate, office, transport, and service, as well as all buildings intended for public access. In 2015, the tertiary sector accounted for 966 million heated square meters, with an average consumption estimated to be 233 kWh per square meter per year (Figures 1.9 and 1.10).

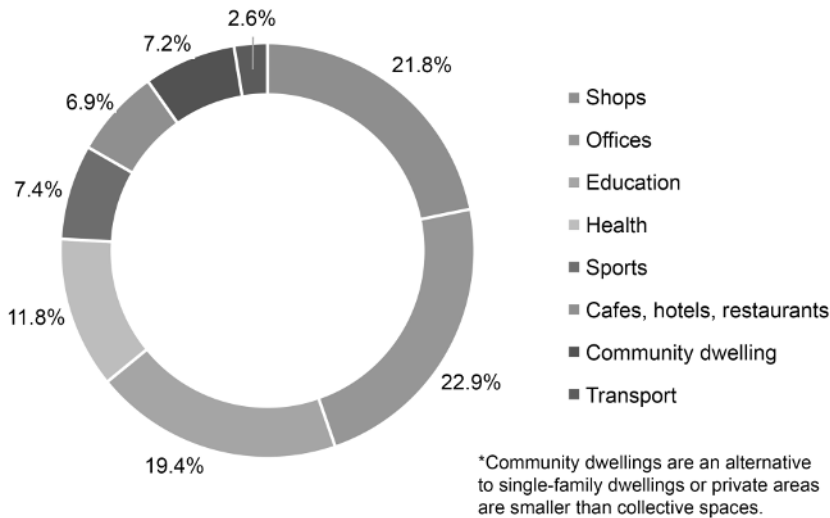


Figure 1.9. *Heated areas of the tertiary stock in France (Ceren 2017). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip*

Industrial buildings cover activities related to processing or manufacturing in various sectors, including the mechanical, food and beverage, pharmaceutical and textile industries. In 2013, these industrial buildings covered a total area of 500 million m² and had an average energy consumption of 545 kWh/m² per year for both processes and building usage.

Agricultural buildings, such as those used for livestock and greenhouses, occupied a total area of 900 million m² in 2013, 50% of which were unheated sheds.

The average energy consumption for agricultural buildings was relatively low at approximately 22.7 kWh/m² per year for both the processes and the building usage.

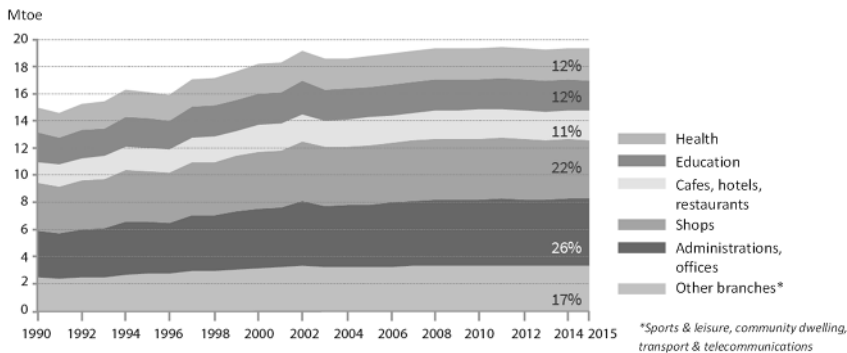


Figure 1.10. Evolution of final energy consumption of the tertiary stock in France (ADEME 2018). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

In 2013, the logistics sector, including warehouses and refrigerated warehouses, covered a small surface area of 100 million m², with an average consumption of 150 kWh/m² per year accounting for both processes and buildings (Figure 1.11).

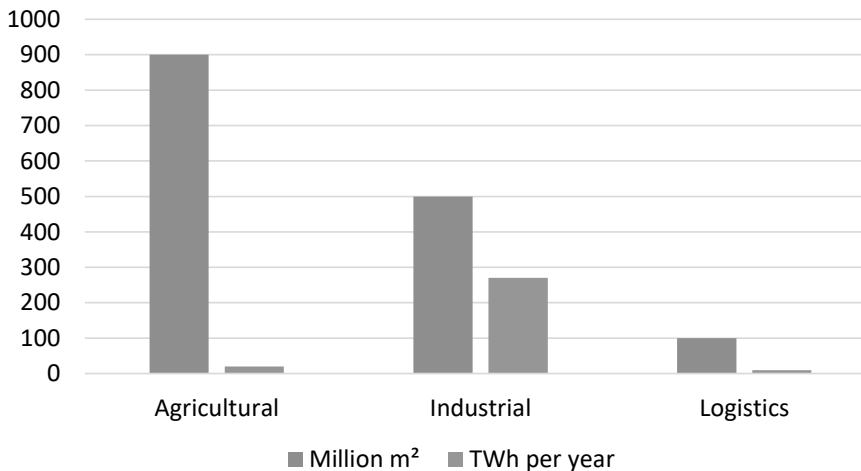


Figure 1.11. Distribution of surface areas and energy consumption per industry in 2013 (ADEME 2013). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

Mixed-use buildings accommodate spaces for various purposes, such as housing and offices.

1.4. Energy in buildings

Before energy is used in buildings, various stages occur (see Figure 1.12). Primary energy (or raw energy) is the “potential” energy present in natural resources before any transformation occurs. This energy exists without storage and after extraction. It is measured in kilowatt-hour of primary energy (kWh_{pe}). Primary energy sources include biomass (such as wood and waste), fossil fuels (including coal, oil, natural gas and hydrocarbons), hydropower (from the ocean or waterfalls), solar energy (from the Sun), wind energy, and geothermal energy (from the earth). However, uranium is not classified as primary energy. In conventional terms, the heat produced by nuclear power plants is considered the primary energy source.

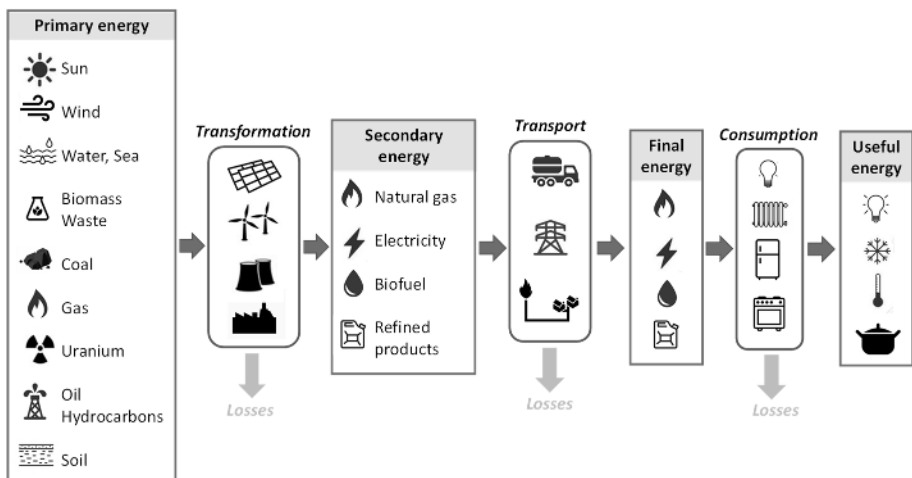


Figure 1.12. *Different types of energy and transformations*

Primary energy is transformed into secondary energy through various methods, such as thermal power plants, nuclear power plants, hydraulic power stations, solar collectors, refineries, wind turbines and co-generators. During this transformation process, some energy is lost as heat. The various types of secondary energy include energies that can be immediately used, such as electrical energy, refined hydrocarbons and biofuel.

Secondary energy is transported to the place of use through various means, such as tankers, natural gas networks or electricity networks. This transportation results in losses due to factors such as mass loss and thermal loss from the Joule effect. The energy that is ultimately consumed and measured in cubic meters of heating oil, cubic meters of gas and kilowatt-hours (kWh) of electricity is named final or available energy for each building. The measurement accounts for losses that occur during the production, transportation and processing of fuel. The unit of measurement is the kilowatt hour of final energy (kWh_{fe}).

Type of energy	Energy conversion system	Use in the building
Renewable energy		
Solar energy	Absorption machine	Air conditioning
	Photovoltaic collectors	Electricity
	Thermal collectors	DHW/heating
	Hybrid collectors	Electricity/heating/DHW
Sky energy	Thermal collectors	Air conditioning/cooling
Wind energy	Wind turbine	Electricity
Biomass energy	Incinerators, fermenters, individual stoves, thermal power plants, boilers	Heating/DHW/electricity
Energy recovery	Exchanger + heat pump	Heating/DHW/air conditioning
Marine energy	Heat/cold network, heat pump	Heating/DHW/air conditioning
Energy linked to outside air	Heat pump	Heating/DHW/air conditioning
Hydraulic energy	Hydroelectric power plant, tidal power plant, tidal turbine	Electricity
Geothermal energy	Deep geothermal energy	Electricity/heating/DHW/Air conditioning
	Surface technologies: heat pump, Canadian wells, groundwater, etc.	Heating/DHW/air conditioning
Non-renewable energy		
Nuclear energy	Nuclear power plant	Electricity/heating/DHW/air conditioning
Fossil energies	Thermal power plant, combustion turbine	Electricity
	Stoves, boilers	Heating/DHW

Table 1.1. Different uses and transformations of energy in buildings

Within the building, we can identify a final type of energy known as useful energy. This is the energy that is available to the consumer after it has been transformed by various equipment, such as boilers, electric convectors, electric bulbs, refrigerators, ovens, etc. Most of these systems operate with an efficiency of less than 100%. A summary of the different energy conversion systems and their uses within the building is presented in Table 1.1.

In the French construction sector, the conversion rate of primary energy into final energy, as specified by the 2012 Thermal Regulation (Kalegos 2012) is 1. However, for electrical energy, the conversion rate is 2.58. This conversion rate was established in 1972, based on the average efficiency of electricity production at French power stations, which stands at 43.7%, along with approximately 5% losses occurring during distribution. Consequently, the effective electricity production efficiency is 38.7%, leading to a conversion coefficient of 2.58. In the 2020 Environmental Regulation (RT 2020), the conversion rate for electric energy was revised to 2.3. However, the actual coefficient for electricity in 2020 was closer to 2.7 (Bâtiment Énergie Carbone 2019) and varied depending on supply from neighboring countries. The value selected for RT 2020 represents the average primary energy conversion rate that could be expected over the next 50 years, assuming that all energy efficiency targets on the electricity grid are met. For other energy sources, such as oil, gas and wood, the rate is set to 1 with a rationale of no losses associated with transformation, as transport and extraction factors are not considered.

1.5. Regulatory aspects

At the national and international levels, many laws, directives and agreements have been signed.

1.5.1. National and international laws

The *Rio Summit* (United Nations Conference on Environment and Development – UNCED) was held from June 3 to 14, 1992. This summit marked a significant milestone in the international response to environmental problems. During the summit, a series of conventions were signed to align with global environmental legislation.

The *Kyoto Protocol* (COP 3) was signed on December 11, 1997. The participating countries committed to reducing their GHG emissions by at least 5% over the 2008–2012 period compared with 1990 levels.

The *Doha Summit* (COP 18) in December 2012 extended the Kyoto protocol from January 1, 2013 to December 31, 2020. Thirty-seven industrialized countries committed to collectively reducing their GHG emissions by 18%.

The *Paris Agreement* (COP 21), signed on December 12, 2015, was adopted by 197 countries with the aim of addressing global warming issues. The agreement seeks to reduce global GHG emissions and limit the increase in global temperature to 2°C over the century, with efforts to reduce this increase to 1.5°C.

At the European level, *Directive 2010/31/EU* of May 19, 2010 (revising the 2002 European Directive on the “energy performance of buildings”) aimed to improve the energy performance of buildings. The requirement was for all member states to establish national action plans ensuring that by December 31, 2020, all new buildings built in Europe were nearly zero energy. Moreover, strengthening the thermal retrofitting of the building stock at an increase rate of 3% per year is needed to achieve a fourfold reduction in the total energy demand of the construction sector by 2050.

In 2018, Directive 2010/31/EU was amended by *Directive 2018/844/EU* to accelerate the refurbishment of existing buildings and promote smart technologies. This directive is currently being revised and is expected to be adopted soon. This new version, which is more oriented toward environmental aspects, should promote “zero emission buildings”, which produce no local emission of GHGs.

In France, the *Grenelle de l’environnement* has highlighted three main priorities: combating global warming, protecting biodiversity and reducing pollution. As a result, two laws were enacted: the *Grenelle I Act* (Act No. 2009–967 of August 3, 2009) and the *Grenelle II Act* (Act of July 12, 2010). These laws address the national commitment to address ecological emergencies and the need for ecological transition.

In 2018, the *ELAN Act* (where ELAN is Housing, Planning, and Digital Development) mandated, through a tertiary decree, a gradual reduction in energy consumption for tertiary buildings larger than 1,000 m². The targets are a 40% reduction by 2030, a 50% reduction by 2040 and a 60% reduction by 2050.

1.5.2. French regulation

Following the first oil crisis in 1973, France implemented its first Thermal Regulation (*réglementation thermique* (RT)) in 1974 to reduce its energy consumption. Over the years, this regulation has evolved (Figure 1.13) to improve

the energy efficiency of buildings and building energy production systems to integrate environmental impacts into the 2020 Environmental Regulation (*réglementation environnementale* (RE)).

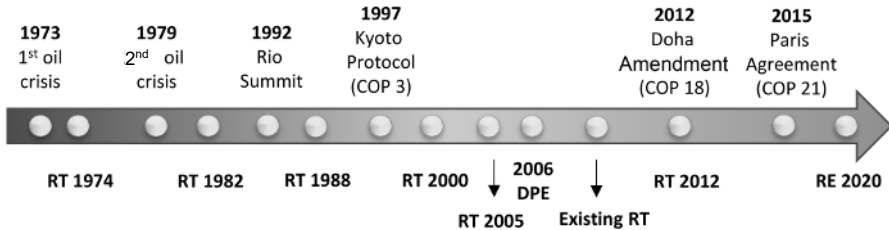


Figure 1.13. Evolution of regulations. For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

RT 1974 was introduced in response to the first oil crisis, making public authorities aware of the need to reduce building energy consumption. This regulation applies only to new residential buildings. Its objective is to reduce building energy consumption by at least 25% compared with the latest standards introduced in the late 1950s. *RT 1974* thus requires owners to install a thin insulation layer and implement automatic controls of heating systems. In 1982, in response to the second oil crisis, *RT 1982* was introduced with a new target of a 20% reduction in energy consumption compared with that in 1974. This RT emphasizes the consideration of internal and solar inputs when determining heating requirements. *RT 1988* extended the application of the previous regulation to include non-residential buildings such as offices and shops. It introduced the notion of “consumption”, particularly through the coefficient of performance for equipment. *RT 2000* stemmed from the 1997 Kyoto Protocol. It aimed to reduce energy consumption by 20% compared with that in 1988 and by 40% in tertiary buildings. The concept of summer comfort involves the conventional indoor temperature (TIC) and the overall performance requirements of the building. Starting in 2005, *RT 2005* incorporated bioclimatism and renewable energies and targeted an additional 15% reduction in energy consumption for new buildings. Energy consumption must not exceed an average value of $90 \text{ kWh}_{\text{pe}} \cdot \text{m}^{-2}$ per year for France. This safeguard value for residential dwellings varies based on the climate zone and the type of fuel used. This energy consumption, expressed in $\text{kWh}_{\text{fe}} \cdot \text{m}^{-2}$ per year, was provided according to this regulation in $\text{kWh}_{\text{pe}} \cdot \text{m}^{-2}$ per year. Additionally, several labels were established: high energy performance (HPE), very high energy performance (THPE), high energy performance renewable energy (HPE EnR), very high energy performance renewable energy (THPE EnR) and low consumption building (BBC).

RT 2012, known as the Grenelle 2 Act, is based on the requirements of the BBC label. It strongly promotes the use of renewable energy sources and introduces new constraints on thermal insulation (to address thermal bridges) and airtightness. Under this regulation, all new buildings cannot exceed an energy consumption of $50 \text{ kWh}_{\text{pe}} \cdot \text{m}^{-2}$ per year. In addition to *Cep* (primary energy consumption) and *TIC*, the concept of *Bbio* (bioclimatic demand), which measures the performance of the building's envelope without considering the systems in place, was introduced. This measurement uses the net floor area (SHON) as a reference. This *Bbio* indicator assesses the requirements for heating, lighting and cooling. *RT 2012* applies to all building permits filed from October 28, 2011 for new buildings in the tertiary sector, as well as public and residential buildings in ANRU zones (French National Agency for Urban Planning). From January 1, 2013, it applied to all other new buildings.

RE 2020 (Environmental Regulation) (Cabassud 2020) is now applicable with different implementation dates: January 1, 2022 for residential buildings; July 1, 2022 for office buildings and educational premises; and January 1, 2023 for other types of buildings. This regulation focuses on the positive energy building (PEB) concept. The shift from thermal to environmental regulation is significant, as the primary aim is no longer just energy efficiency but rather the overall environmental impact of buildings. This marked a complete paradigm change. The updated 2022 EU Energy Performance of Buildings Directive (EPBD) reinforces this new approach, introducing various indicators that must meet specific thresholds. In terms of energy, the regulation references *Bbio* and *Cep*, as defined in *RT 2012*. *Cep_{nr}* refers to non-renewable primary energy consumption (excluding wood and the renewable share of urban heat networks), alongside the degree-hour (*DH*) indicator, which replaces the *TIC* metric and focuses on summer comfort. For reference, *RE 2020* specifies that, compared with *RT 2012*, the reference surface area is now defined as the SHAB (habitable surface) for residential buildings and the SU (usable surface) for tertiary buildings. In terms of carbon emissions, *RE 2020* requires a dynamic life cycle assessment (LCA). New indicators, including *Ic_{energy}*, which quantifies carbon emissions related to energy consumption in production and encourages the use of decarbonized energy sources, were introduced. Additionally, the *Ic_{construction}* indicator assesses the impacts of climate change on construction materials and their installation. Table A.1 in the Appendix shows the changes between *RT 2012*, the E+C label and *RE 2020*.

These regulations apply to new constructions. For existing buildings that require refurbishment, the *existing RT* must be followed, as illustrated in Figure 1.14. This depends on the scale of the energy retrofitting being considered. The “Element by Element” *RT 2007* applies to envelope components and systems that must achieve a

minimum level of performance. The “global” RT 2008 requires a thermal calculation and sets a performance level for the entire building.

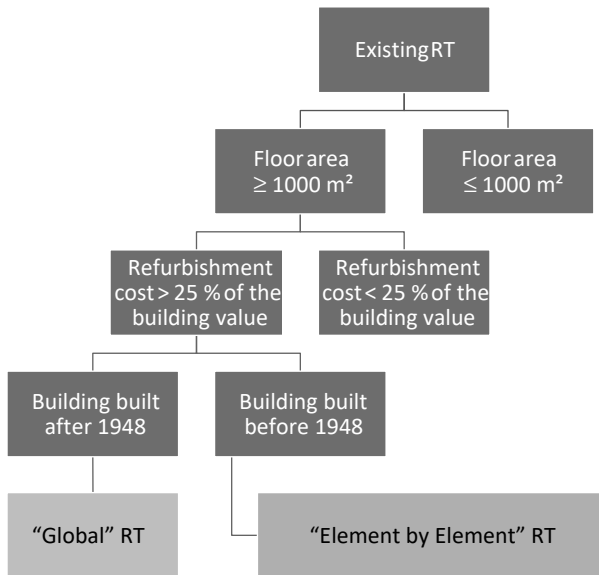


Figure 1.14. Existing thermal regulation

Following the European Directive on the energy performance of buildings No. 2002/91 published in January 2003, the concept of *energy performance diagnostics* (*diagnostic de performance énergétique (DPE)*) for buildings was introduced. The DPE has been mandatory since 2006 for the sale of existing dwellings and since 2007 for the rental of dwellings. This document serves as an awareness tool, informing the future owner/tenant about the energy consumption of the property (in kWh.m⁻² per year) through an “energy” label. It also aims to increase awareness of the environmental impact of energy consumption by indicating the emission of CO₂ (kg.m⁻² per year) associated with a dwelling through a “climate” label. The labels categorize dwellings according to their energy performance from A – energy-efficient dwelling – to G – energy-intensive dwelling. In 2021, the French Ministry of Housing introduced a reform of the DPE, revising the calculation method to be more reliable and reflecting reality. It now includes lighting and ventilation, making it easier to read and providing estimated energy costs. The classes (E, F, G) are gradually being phased out for rental property, with G being prohibited in 2025, F being prohibited in 2028 and E being prohibited in 2034. The calculation based on invoices has been removed. Since September 2022, an energy

audit has been mandatory for all sales of single-family dwellings and collective residential buildings in single ownership. Finally, the DPE has become “enforceable”, meaning that the seller/lessor is liable for any error that could be detrimental to a future buyer or tenant.

These different regulations have changed building consumption (Figure 1.15).

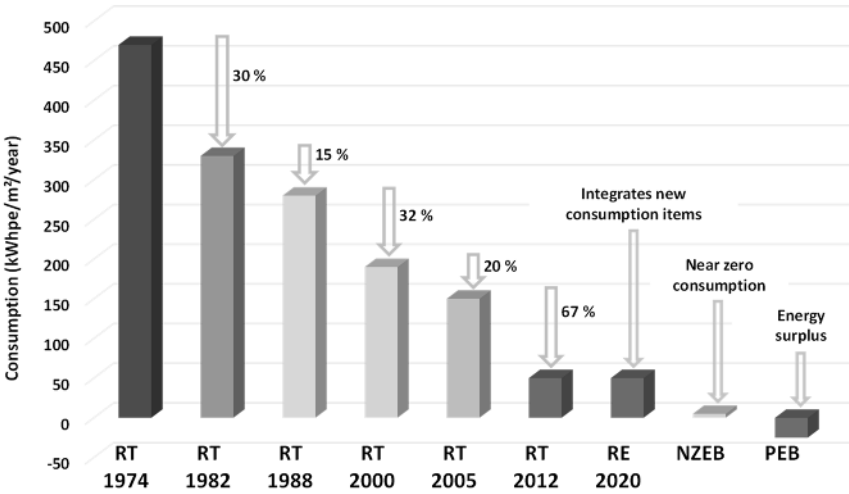


Figure 1.15. Evolution of new building consumption (1% of the stock per year) depending on regulation. For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

The previous graph illustrates two types of buildings: nearly zero energy buildings (NZEBs) and positive energy buildings (PEBs). The concept of *NZEB* originates from the European Directive on Energy Efficiency of Buildings, which was revised in 2010. NZEBs produce *nearly as much energy as they consume*, with energy sourced primarily from *renewable resources*. The directive defines an NZEB as *a building that has a very high-energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*. In contrast, PEBs generate more energy than they require for their operation.

An example of PEBs is given in Figure 1.16. The head office of the regional branch of Charente-Maritime/Deux Sèvres of the Crédit Agricole has received the Bepos-Effinergie 2013 classification. This office building of approximately 15,000 m²

(SHON_{RT}) consumes 66 kWh_{pe}/(m².year) and produces 66.6 kWh_{pe}/(m².year) using rooftop photovoltaic panels. Its heating and air conditioning needs are met by two thermal pumps connected to a field of 32 vertical geothermal probes.



Figure 1.16. *PEB building of the regional branch of the Crédit Agricole in Lagord, France*

1.5.3. Labels and certifications

To go beyond basic regulatory standards, many countries have proposed voluntary “energy” labels or certifications to control and approve a set of elements for achieving high energy performance. While some labels focus solely on energy performance, others address additional targets, such as the environment impact, water usage, resource consumption, waste management and noise reduction. These labels are characterized by their objectives and the specificity of their criteria, which can include reference surfaces, consumer items and energy conversion coefficients. Labels and certifications have been created by private organizations or government bodies. They often influence regulations by proposing more stringent requirements. Typically, certifications consider multiple criteria, whereas labels concentrate on a single performance criterion, usually energy efficiency.

Notable labels include BBC, HPE, THPE, Effinergie+, BEPOS-Effinergie 2013, E+C-, BEPOS, BEPOS+ 2017, BBC 2017 Passiv’Haus, Minergie-S and Minergie-P. Some labels, such as the BBC label, have become obsolete because their features have been integrated into regulations.

The *BBC* (*bâtiment base consumption*, low-consumption building) label was created in 2007 as an extension of RT 2005. This requires “new” buildings to

consume less than $50 \text{ kWh}_{\text{pe}}\cdot\text{m}^{-2}$ per year. For refurbished buildings, a BBC *Rénovation* label was created in 2009, allowing a maximum consumption of $120 \text{ kWh}_{\text{pe}}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$. However, the implementation of RT 2012 rendered these labels obsolete.

The *HPE* (*haute performance énergétique*, high energy performance) and *THPE* (*très haute performance énergétique*, very high energy performance) labels target buildings with energy consumption levels below 10% and 20% of the RT 2005 and RT 2012 standards, respectively, and they replaced the BBC label in 2013. The *Effinergie+* label is awarded to buildings achieving an energy consumption that is 20% lower than the RT 2012 standards.

The *E+C* label, introduced in 2016, certifies the energy and environmental performance of new buildings. This requires the building to be energy positive and low in carbon. The certification includes four levels of energy performance and two levels of environmental performance.

The Effinergie association offers three labels: *BBC 2017* (E2C1), *BEPOS* (E3C1) and *BEPOS+ 2017* (E4C1). These labels are based on the RT 2012 and the E+C–reference.

Table 1.2 provides a comparison of the three main European labels. However, comparing these labels can be challenging because each one uses its national convention method, which varies across France, Germany and Switzerland.

Certifications have seen less change over time. At the international level, several key certifications stand out:

French *HQE* (*haute qualité environnementale*, high environmental quality) certification concerns sustainable buildings over their lifetime. It is based on various criteria, including the environment, waste and water management, acoustic comfort and energy performance. HQE is internationally recognized.

The American *LEED* (Leadership in Energy and Environmental Design) certification operates on a point-based system with several levels: certified, silver, gold or platinum. It evaluates buildings based on several criteria, including waste reduction, energy savings, use of sustainable transport and water conservation.

The British *BREEAM* (Building Research Establishment Environmental Assessment Method) certification is assessed based on several criteria, such as energy, health, materials, pollution and resource management.

Labels	BBC Effnergie	Minergie	Passiv'Haus
Origin	France	Switzerland	Germany
Consumption "New" ($\text{kWh}_{\text{pe}} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$) $\text{*kWh}_{\text{ue}} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$	50	<i>Minergie-S</i> : < 38 <i>Minergie-P</i> : <30 (other) <15 (*heating)	<15 (*heating requirement) <120 (other)
Consumption "Renovation" ($\text{kWh}_{\text{pe}} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$) $\text{*kWh}_{\text{ue}} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$	80	<i>Minergie-S</i> : <60 <i>Minergie-P</i> : <30	<15 (*heating requirement) <120 (other)
Setpoint temperature	19°C	20°C	20°C
Surface area	SHON	SRE	SHAB
Weighting	Place and altitude	Altitude	Altitude
Heating, DHW, cooling	×	× (except cooling)	×
Auxiliary (including ventilation)	×	×	×
Lighting	×	—	×
Household app.	—	—	×
Gas/heating oil	1	1	1.1
Electricity	2.58	2	2.7
Wood	0.6	0.5	0.2
Solar thermal	0	0	0
Solar PV	1	2	0.7
Tightness	<i>Single-family dwel.</i> : $Q_4 < 0.6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ <i>Col. dwelling</i> : $Q_4 < 1 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$	<i>Minergie-P</i> : $n_{50} = 0.6 \text{ vol} \cdot \text{h}^{-1}$	$n_{50} = 0.6 \text{ vol} \cdot \text{h}^{-1}$

Table 1.2. A few label characteristics

The *WELL* (International Well Building Institute) certification was established in 2014 by the International Well Building Institute in the United States. This certification differs from others in that it focuses on the health, comfort and well-being of building occupants. In May 2018, version 2 was released. *WELL* covers ten key themes: air, water, food, light, physical activity, thermal comfort, acoustic comfort, materials, spirit (aesthetics and natural environment) and

community. An additional theme, innovation, is also included. WELL certification is available at three levels: silver, gold and platinum.

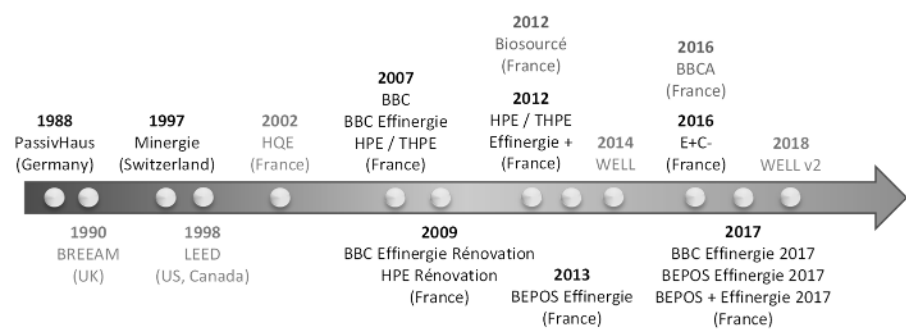


Figure 1.17. Labels and certifications. For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

1.6. Designing a healthy and performant building

Historically, buildings were designed primarily to protect people from the weather. Over time, humans have adapted their dwellings to suit local climatic conditions and available resources. With progress and industrialization, we have developed systems for heating and air conditioning that not only increase comfort but also consume a significant amount of energy and have a considerable environmental impact.

As a result, the role of buildings has evolved to accommodate new needs focused on comfort, health, safety and energy efficiency while being environmentally friendly. This shift has led architects and designers to return to “common sense” solutions and create “buildings whose design and location take into account the present climate and environment to reduce energy requirements for heating, cooling and lighting”. This approach is called bioclimatic design, which aims to achieve optimal comfort in the most natural way possible. To promote bioclimatic design, RT 2012 introduced the concept of *Bbio*, which stands for bioclimatic demand.

A bioclimatic building maximizes the advantages of its location and requires strategies tailored to the climate—whether cold, temperate, or hot.

In French regions, the winter strategy (as illustrated in Figure 1.18) involves capturing free heat such as solar inputs, storing this heat within the building (utilizing the thermal inertia of walls and floors), distributing this energy effectively

within the building (using ventilation to reduce thermal stratification) and minimizing heat loss (through insulating and minimizing openings to the north-facing facade). Conversely, during summer (as illustrated in Figure 1.18), the strategy involves protecting against solar inputs, minimizing internal heat sources (such as lighting), dissipating the heat accumulated during the day and cooling through ventilation.

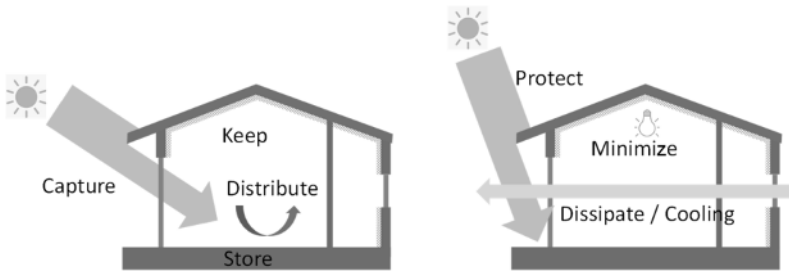


Figure 1.18. Winter (on the left) and summer (on the right) strategies

The environment surrounding a building significantly influences various design strategies. The *orientation of the building* is crucial for maximizing solar gain. Utilizing solar energy can help reduce heat requirements in winter and minimize artificial lighting needs by allowing natural light to enter the building. To optimize these winter solar inputs, it is important to maximize the glass surface facing south (in the northern hemisphere) while avoiding shading due to the surrounding environment, such as trees, buildings and topography. According to RT 2012, for houses, at least 17% (or 1/6) of the habitable area should consist of glass walls, with approximately 50% ideally facing south. In summer, however, it is essential to limit solar gain to prevent overheating inside the building. There are several passive solutions for this, including the addition of horizontal sun protections (such as casquettes, roof overhang, brise-soleil and balconies) to the south-facing facade and vertical protections to the east- and west-facing facades. Incorporating deciduous plants can also provide summer shade while allowing sunlight to filter through in the winter. Additionally, changing glass opacity and using immobile protection (such as blinds, shutters and curtains) can help manage light and heat. It is advisable to minimize north-facing glass surfaces to reduce winter heat losses.

The *layout of rooms* is another key factor. It is preferable to position unheated spaces such as garages, service rooms, bathrooms or corridors on the north side to limit heat losses and create a buffer zone. Living areas such as living rooms and kitchens should be located on the south side to benefit from solar gain and natural light.

Moreover, the *compactness* of a building plays a significant role in its energy performance. Generally, the more compact a building is, the better its energy efficiency. One way to assess compactness is through the “compactness factor”, which is the ratio of the surface of the walls in contact with an unheated area (known as loss walls) to the building’s heated volume. The larger this ratio is, the greater the area of loss, leading to greater energy consumption to maintain thermal comfort. The ideal shape for compactness is a sphere. An example of compactness is given in Figure 1.19. For the same heated volume, a more compact building will have a lower demand for heating or cooling compared to single-family homes.

The *selection of land and its layout* are also two critical factors that can impact building energy performance. Prevailing wind can increase thermal losses in exposed facades, making it essential to protect against these winds. This can be achieved by adapting the building’s shape to the terrain, creating barriers such as hedges, walls or embankments, adding vegetation to the facade and minimizing openings that are directly exposed to cold winds. A proper design can also take advantage of night ventilation to help cool the building during the summer. In addition to considering the building’s integration with its environment, it is important to focus on its envelope, the air circulation within it, thermal insulation, thermal inertia and airtightness.

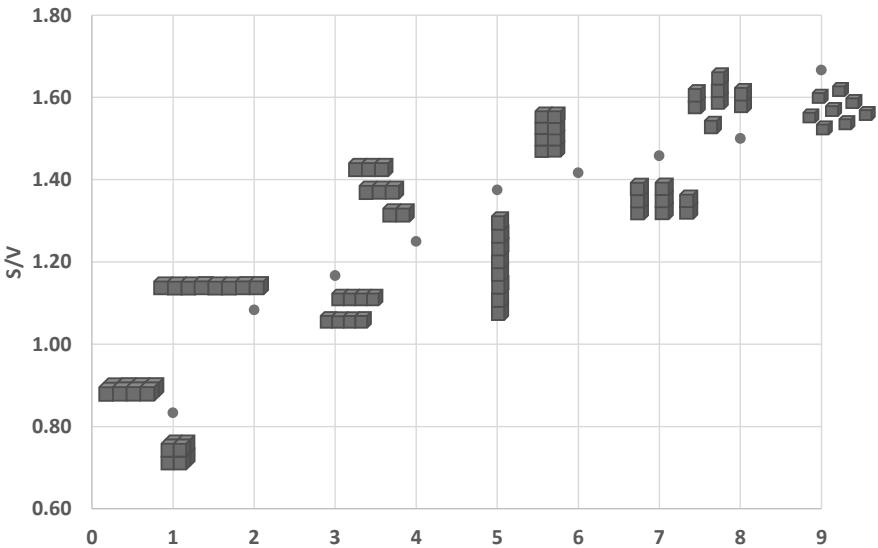


Figure 1.19. Compactness depending on the building type (base $3 \times 3 \times 3 \text{ m}^3$)

The primary objective is to reduce the need for heating and air conditioning through proactive design.

This bioclimatic approach can be enhanced by the negawatt approach (Association négaWatt n.d.), which takes into account:

- energy efficiency (prioritizing essential energy needs);
- system energy efficiency (reducing the amount of energy required to satisfy individual need);
- the integration of renewable energy sources.

1.6.1. Bioclimatic solutions for heating

There are many heating solutions that are compatible with the concept of “bioclimatism”. Without being exhaustive, here are some easy-to-implement actions:

– *Limit losses* to the outside by effectively isolating the building and creating “buffer” zones. This could involve placing unheated spaces, such as corridors, cellars and garages, on the north side and creating an entrance hall, among other measures.

– *Enhance solar inputs*: a veranda was installed on the south-facing façade to maximize the amount of thermal energy captured from sunlight. This energy can then be stored and transmitted throughout the dwelling via ventilation or conduction.

– *Implement energy storage solutions*: several techniques can be employed to store energy. For walls, wall inertia is an essential element. High-density walls made of materials such as concrete or stone or those incorporating phase change materials (PCMs) have a significant capacity for thermal energy storage. PCMs can release stored energy through phase shifts when solar inputs are low. Additional storage options, such as hot water tanks, can store energy at a lower cost (e.g. during off-peak hours) and supply it on demand.

– *Use of renewable and free energy sources*: devices that harness geothermal energy, such as “Canadian” wells that inject warm air into the dwelling in winter or heat pumps, are beneficial. Technologies that utilize solar radiation, such as solar thermal or photovoltaic panels, and biomass, such as wood burning or pellet stoves, offer sustainable energy production using renewable resources, often at little to no cost.

– *Recover waste energy*: waste energy is heat lost by a system, which in some cases can be recovered. For example, heat from gray water from the shower or air extracted through a heat recovery ventilation (HRV) system can be recovered. Temperature levels can vary considerably, from 30°C for wastewater to 500°C for combustion gases. This energy can be recovered through hot water tanks, heat pumps or heat exchangers.

1.6.2. Bioclimatic solutions for air conditioning

To reduce or even eliminate air conditioning in summer, several strategies can be used:

– The heat transfer from the outside to the inside or phase shift is limited. This requires proper insulation of the building and careful selection of materials to achieve the desired thermal inertia, including the use of phase change materials and heavy materials.

– Minimizing solar inputs during peak heat hours. Effective strategies include selecting the right façade orientation, determining the optimal size of windows, employing glass protection, considering the use of external shade, using reflective coatings and incorporating greenery.

– Reducing internal heat generation from equipment: appliance, lighting and audiovisual equipment that have high energy efficiency ratings (A, A+, A++, etc.) are chosen to limit unnecessary internal heat production.

To manage cooling within a building, passive or semipassive systems can be considered. Some examples include:

– *Night-time overventilation* (natural or forced): overventilation typically occurs at night to take advantage of lower outside air temperatures and prevent discomfort in high buildings. In naturally ventilated buildings, the management of overventilation will use the stack effect principles and openings. It is important to orient the building in the direction of prevailing winds for optimal airflow. In forced ventilation, the building can also be cooled by increasing the fan flow rate (free cooling).

– *Provençal wells*: these systems circulate outside air through tubes buried underground. As the tubes are in contact with the ground, the air cools down and enters the dwelling after losing a few degrees.

– *Ceiling fans*: these fans increase the movement of air and thus generate heat loss through convection and evaporation at the skin level of the occupants.

– *Geocooling*: the process involves circulating, via a heat exchanger, coolant fluid (either water or glycol water) from a geothermal system (geothermal sensor or groundwater) directly to a terminal unit within the building.

– *Direct or indirect adiabatic systems*: these systems cool the outside air by passing it through a wet medium before it is supplied into a room. The transformation of air is isenthalpic.

Additionally, we can consider the use of compact systems that integrate different equipment (such as a tank, heat pump or mechanical ventilation system) to ensure three or even four functions: heating, domestic hot water, ventilation and air conditioning/cooling.

1.7. Thermal comfort

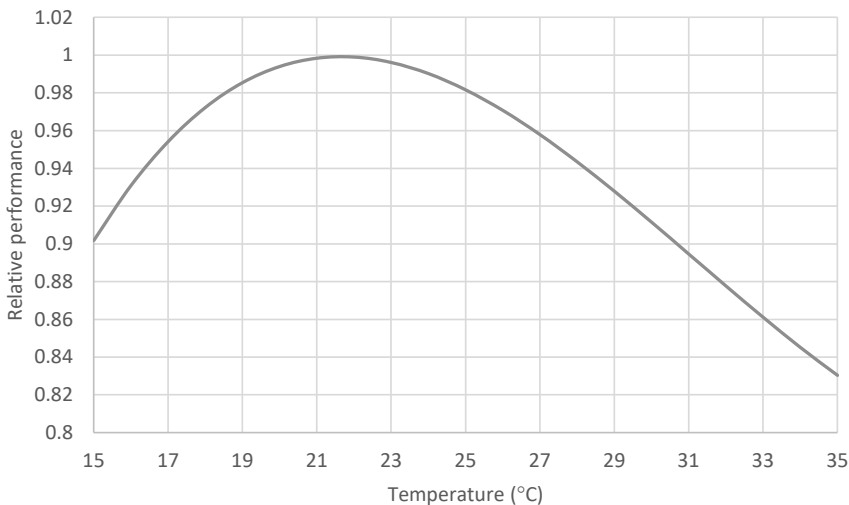


Figure 1.20. *Effect of temperature on work performance in an office-type environment (Seppänen and Fisk 2006)*

The purpose of technical equipment is to create interior conditions that ensure the comfort of the occupants of a room. The concept of comfort is complex and varies from person to person, involving many parameters:

- air and wall temperatures;
- air relative humidity;
- air velocity;
- activity level and clothing level;
- age, gender, culture, health, etc.

Thermal comfort impacts quality of life, safety and efficiency at work. For example, Figure 1.20 shows the impact of temperature in an office on the efficiency of employees present. Notably, the performance increases with increasing temperature up to 21–22°C and then decreases beyond 23°C.

1.7.1. *The human body and its metabolism*

The human body produces heat, requiring a stable internal temperature between 36.5°C and 37°C, regardless of the external environment. To function, the body's energy is derived from food breakdown. The mechanical and thermal power developed by the body is called total metabolism. To regulate its internal temperature, the human body exchanges heat with its environment in various ways:

- by conduction with the ground;
- by convection with ambient air;
- by radiation with the different walls of the room;
- by evaporation (sweating or sensible perspiration) on the skin surface;
- by gas exchanges (insensible perspiration or transepidermal water loss) at the pulmonary alveoli level and through the skin surface (without sweating);
- by respiration (volume of air exhaled at body internal temperature and saturation).

Figure 1.21 shows the percentages of the different heat exchanges obtained from Fanger's model (ISO n.d.) under indoor conditions varying according to the season (winter or summer) and at a human metabolism of 1.2 met and with seasonal clothing.

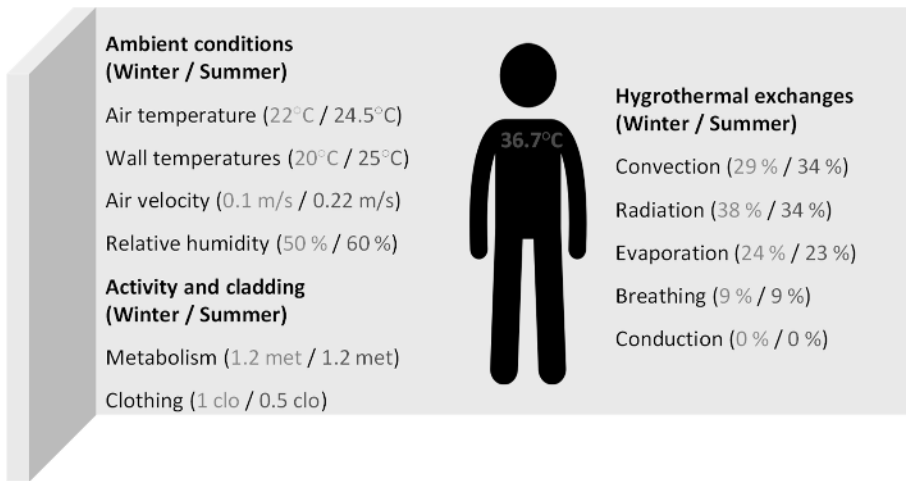


Figure 1.21. *Thermal exchanges between a human and their environment for optimal comfort. For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip*

Human metabolism is expressed in “met” ($1 \text{ met} = 58 \text{ W.m}^{-2}$). This depends on a person’s activity level. The average skin area used for calculation is 1.8 m^2 .

– Sitting or resting	1 met
– Sitting with light activity	1.2 met
– Standing with light activity	1.6 met
– Standing with moderate activity	2 met

Clothing is characterized by an average thermal resistance and expressed in “clo” ($1 \text{ clo} = 0.155 \text{ m}^2.\text{K.W}^{-1}$):

– Naked	0 clo
– Short clothing	0.1 clo
– Light summer clothing	0.5 clo
– Winter indoor clothing	1 clo
– Formal European clothing	1.2 clo

1.7.2. Thermal balance

To maintain a constant body temperature, a thermal balance exists between internal heat production (metabolism, Mth) and the different thermal transfers (Φ) between the body and the surrounding environment:

$$Mth = \Phi_{convection} + \Phi_{radiation} + \Phi_{evaporation} + \Phi_{breathing} + \Phi_{conduction} \quad [1.1]$$

This balance can be maintained either through body actions (change in temperature and/or wettability of the body surface) or by adjusting ambient conditions by following the instructions of the technical equipment. Four parameters are then involved in these exchanges with the environment: air temperature, average radiant temperature of the walls, air humidity and air velocity in the vicinity of the subject.

The air temperature is regulated in winter by heating devices and in summer by cooling or air conditioning systems. The wall temperature depends on the radiative properties and the envelope insulation level. Some heating/cooling systems integrated into floors, walls or ceilings can directly impact this temperature. Moisture mainly comes from indoor sources (dampness of the rooms) and the ventilation system. In summer, moisture can be controlled by the air conditioning system. The air velocity is influenced by the ventilation system and the occupant's activity level.

1.7.3. Comfort criteria

Various models, such as Fanger's model or the adaptive model for thermal comfort, help identify comfort zones. These models rely on a key variable known as the operative temperature (T_{op}). This temperature is defined as follows:

$$T_{op} = \frac{h_{conv} T_{air} + h_{rad} T_{rm}}{h_{conv} + h_{rad}} \quad [1.2]$$

where T_{air} is the air temperature ($^{\circ}\text{C}$), T_{rm} is the average radiant temperature of the walls of the room ($^{\circ}\text{C}$), and h_{conv} and h_{rad} are the coefficients of convective and radiative surface exchanges ($\text{W.m}^{-2}\text{.K}^{-1}$), respectively. When the air velocity at the user level is less than 0.1 m.s^{-1} , the formula of the operative temperature is reduced to:

$$T_{operative} = \frac{T_{air} + T_{rm}}{2} \quad [1.3]$$

The relative humidity range should be between 30% and 70% at a temperature of 20°C. The air velocity varies according to the type of room. For accommodations, hospitals, education, offices, commercial, premises, etc., the typical values are between 0.15 and 0.17 m.s⁻¹, whereas a greater velocity of 0.25 m.s⁻¹ is used for sports, industrial premises, department stores, etc.

The interior conditions of a dwelling significantly impact the well-being of its occupants as well as energy consumption. Individuals who are more sensitive to cold may increase the temperature of their homes, resulting in increased heating costs. A study by ADEME (n.d.) indicated that for older buildings, a 1°C increase in temperature corresponds to an approximately 7% increase in heating consumption and an approximately 15% increase in efficient buildings.

Similarly, for air conditioning, if the set temperature is increased by 1°C (e.g. from 25°C to 26°C), the annual consumption of the equipment is reduced by 5–10% (ADEME n.d.).

1.7.4. Application: impact of set temperature

On the basis of the example presented in section 2.8 for a single-family dwelling (RT 2000 and RT 2012), we examined how a change in set temperature affects heating and air conditioning demands. The results are presented in Figure 1.22.

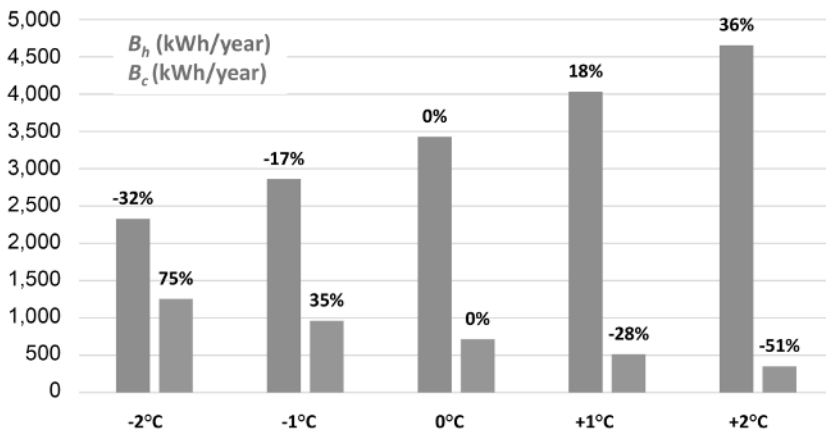


Figure 1.22. Heating (B_h) and cooling (B_c) requirements for an RT 2000 house for different temperatures compared with set temperatures (19°C for heating and 26°C for cooling). For a color version of this figure, see www.iste.co.uk/salagnac/energyefficiency1.zip

When the heating setpoint is raised by 1°C (from 19°C to 20°C), the heating demand increases by 18%, and when the air conditioning setpoint drops by 1°C (from 26°C to 25°C), the demand for air conditioning increases by 35%.

1.8. Conclusion

In summary, thermal comfort is essential for the well-being of individuals and depends on multiple factors, including the temperature, humidity, air velocity, activity and clothing of occupants.

Achieving optimal thermal comfort while ensuring a comfortable, healthy, sustainable and efficient building requires considering these factors and finding a balance adapted to each individual. Designing buildings that meet these criteria requires high levels of insulation, effective air tightness and significant thermal inertia of the building envelope.

Additionally, employing efficient heating, ventilation and air conditioning systems is crucial. The dwelling should be adapted to its specific climate and location, optimizing the use of free and renewable resources such as solar energy, wind and the sky. Furthermore, the use of efficient equipment preferably powered by renewable energy sources and energy recovery systems (such as graywater) is highly recommended.