

Indoor Environment and Sustainable Building
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Morteza Nazari-Heris *Editor*

Natural Energy, Lighting, and Ventilation in Sustainable Buildings

 Springer

Indoor Environment and Sustainable Building

Series Editors

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Morteza Nazari-Heris

Editor

Natural Energy, Lighting, and Ventilation in Sustainable Buildings



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Editor

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Preface

The energy consumption of buildings globally is enormous and accounts for almost one-third of all primary energy resources. Sustainable buildings reduce energy use and are a crucial component of urban planning that aims to mitigate climate change. Natural energy, lighting, and ventilation can contribute to attaining sustainable development goals while maintaining ventilation and lighting rates consistent with acceptable interior air quality and natural illumination needs and meeting buildings' energy demands. Although scientists and researchers have been working on this problem for a long time, it still exists. This topic should be investigated considering modern buildings and their developments in terms of smart operation, the high rate of integration of renewable energy sources and emerging technologies in buildings, and the importance of the efficiency and quality indexes of the buildings. The book's objective is to convey all the essential and comprehensive research that has been done so far on sustainable and green buildings. This book is suitable for electrical engineers, energy engineers, architectural engineers, and professionals, as well as researchers and developers from engineering science. Moreover, this book can be used by undergraduate, graduate, and Ph.D. students to become familiar with the most recent developments in electrical and architectural engineering.

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Morteza Nazari-Heris

About the Book

The book covers the theoretical background and experimental analysis of the application of innovative approaches to deploy natural energy resources in sustainable buildings. The authors focus on improving the performance of the sustainable buildings in this book, which can help to provide effective and promising solutions for novel challenges in sustainable buildings design. The topics covered in this book are presented in the following.

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About the Editor

Morteza Nazari-Heris is an Assistant Professor at Lawrence Technological University. Before joining Lawrence Tech, he worked as a Graduate Research Assistant in Areas of National Need at Pennsylvania State University and earned his Ph.D. specializing in energy systems. During his graduate studies at Penn State, he performed projects on future, flexible, equitable, and robust networks of charging stations for high adoption of electric vehicles, application of machine learning and deep learning methods to energy systems, and sustainable design of buildings with renewable energy sources and energy storage facilities. He has also obtained B.Sc. and M.Sc. degrees in Electrical Engineering from the University of Tabriz, where he worked on design and performance analysis of zero-energy buildings, residential load energy management, and multi-carrier energy systems. Dr. Nazari-Heris has an academic background in the techno-economic-socio analysis of critical infrastructure, including the transportation and energy sectors, life-cycle analysis, and research. During his time as an Assistant Professor and Research Assistant, he has delivered four research projects and has authored 63 technical journal articles, 28 conference proceedings papers, and 28 book chapters. In the past decade, he has had a strong background as a researcher in universities in different countries, working on several small-scale projects, which revolved around the power network in different regions, short-term and long-term planning, and optimal energy management systems considering demand and generation side management, load forecasting, optimal power flow, dynamic pricing, sensitivity analysis, and market mechanism design. Dr. Nazari-Heris is an expert in transportation electrification and energy systems, focusing on developing tools for the intelligent, sustainable, and resilient transportation system and energy sectors, infrastructure systems, communities, and cities. His main areas of interest are energy system operation, energy management, sustainability, zero-energy buildings, transportation electrification, electric vehicles, microgrids, multi-carrier energy systems, renewables, and energy storage technologies.

Chapter 9

Thermal Energy Storage (TES) for Sustainable Buildings: Addressing the Current Energetic Situation in the EU with TES-Enhanced Buildings



Francesco Valentini, Giulia Fredi, and Andrea Dorigato

Abstract In the last century, global primary energy consumption and related CO₂ emissions increased 10 times, and they are still on the rise. The environmental sustainability and the limitation of the energy consumption of buildings are of substantial importance in reducing greenhouse gas emissions and mitigating the consequences of climate change. The main problem of the next years will be the necessity to find a compromise between energy demand and available energy resources. Europe, despite the lower emissions compared to other regions, will face very hard challenges due to (i) the extreme rise of energy prices that occurred in 2022 and (ii) the necessity to cut CO₂ emissions and energy consumption to reach the targets of the European Green Deal for 2050. The technologies and systems able to store thermal energy allow the accumulation of energy when available (e.g., thermal energy from sun) in order to use it when and where necessary, with a consequent reduction of CO₂ emissions. The use of insulating materials with TES capability may result in the compensation of energy absorption peaks caused by air conditioning or by space heating with a consequent reduction of energy consumption and related CO₂ emissions. The present study, starting from some considerations regarding the energetic problem, greenhouse gas emissions in EU, and used energy source, presents the available energy storage technologies with particular attention to thermal energy storage. Different applications and available commercial technologies are analyzed.

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9.1 The Energetic Problem

Energy is a key pillar for human well-living. In recent years, due to the rapid demographic growth and the boosting of industrial production, energy consumption became a burden on conventional energy resources due to the continuous increase of climate-altering emissions and the consequences in terms of climate change [1, 2]. As reported in Fig. 9.1, global primary energy consumption increased 10 times in the last century, and it is still on the rise.

The increase in energy available around the world is important to guarantee higher living standards for many populations but makes the transition to low-carbon energy sources more difficult due to the additional clean energy that is needed to substitute fossil fuels [3]. In 2019, one-third of the global electricity was derived from renewable resources but, if also transport and heat production are considered, it results that only 16% of the total energy was derived from renewable energy resources due to the strong dependence of transportation on oil and of heat generation on natural gas [3]. Moreover, the continuous traffic growth and the retention of the turnover of carmakers make the transition to a decarbonized transport system difficult to achieve [4].

Similarly, as reported in Fig. 9.2, also CO₂ emissions increased 10 times in the last century and around 75% of them are related to energy consumption, mainly due to the combustion of coal and oil [3].

A crucial role is made by the energy consumption of residential and commercial buildings. As shown in Fig. 9.3, energy use in buildings is responsible for 17.5% of global greenhouse gas (GHG) emissions, which reaches values up to 40% in some developed countries [5, 6].

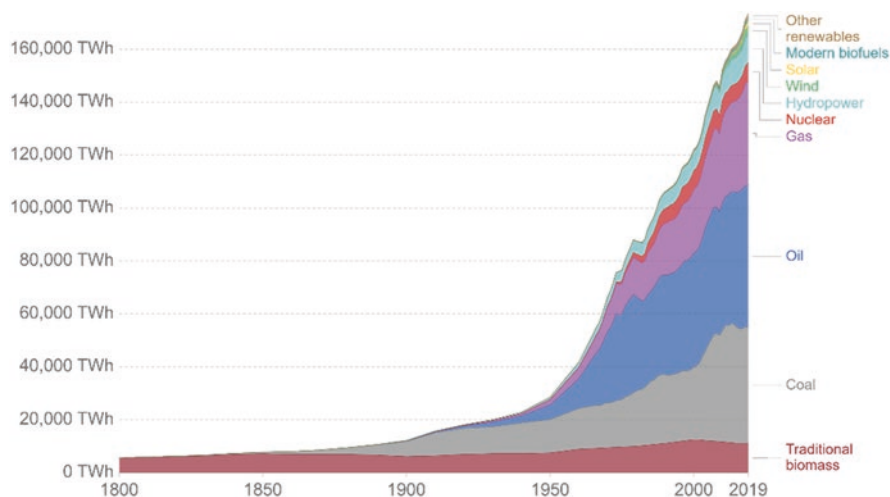


Fig. 9.1 Global primary energy consumption by source [3]

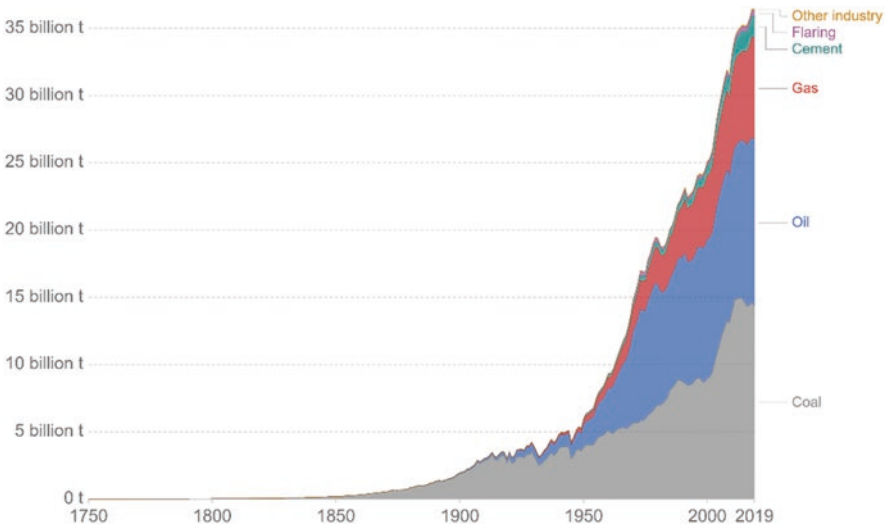


Fig. 9.2 CO₂ emissions by fuel type [3]

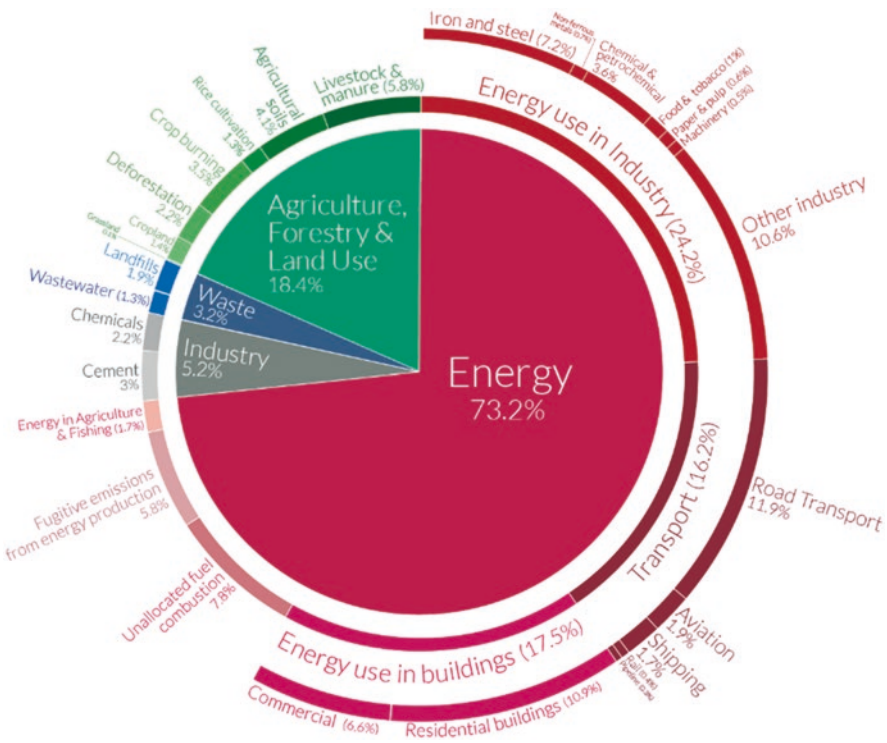


Fig. 9.3 Global greenhouse gas emissions by sector [5]

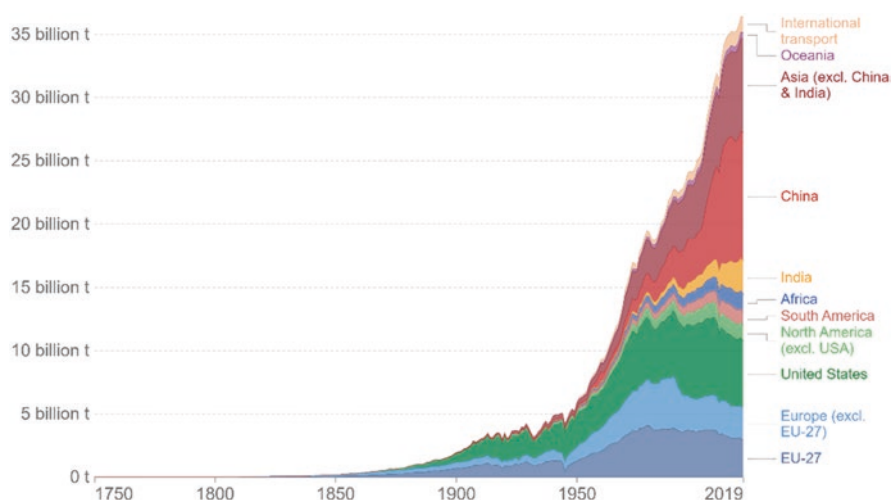


Fig. 9.4 CO₂ emissions by region [5]

From Fig. 9.4, it is evident that the distribution of CO₂ emissions in the twentieth century was dominated by Europe and United States, causing around 90% of global CO₂ emissions in 1990. Starting from 1950, the situation changed significantly: emerging countries, mainly in Asia, caused a strong rise in CO₂ emissions that is still continuing nowadays, although the contribution of other countries has stabilized (United States) or reduced (EU) starting from 1990 [5].

9.2 The Situation in the EU

9.2.1 Greenhouse Gas Emissions

Comparing the CO₂ emission per kilowatt-hour of different countries in 2018, it results that the EU has lower values (270 g CO₂/kWh) than the United States (500 g CO₂/kWh), China (600 g CO₂/kWh), India, and Australia (700 g CO₂/kWh). In 2019, the reduction of CO₂ emissions in the EU was the largest worldwide (235 g CO₂/kWh compared with 270 g CO₂/kWh in 2018) [7–9].

In 2018, the greenhouse gas emissions in the EU were reduced by 23% in 1990, even though the EU population grew by 7%. Hence, the EU was able to reach the targeted reductions of CO₂ emissions in 2020 (–20% with respect to 1990) [10, 11]. Despite this, according to projections of the European Environmental Agency (EEA) (Fig. 9.5), the reduction by 2030 would be around 30% considering the existing legislation or 36% in case of extraordinary measures, below the target of –40% [12]. According to data from the EEA, the EU average annual reduction in greenhouse gas has been equal to 46 Mt. CO₂eq between 1990 and 2017, while it should

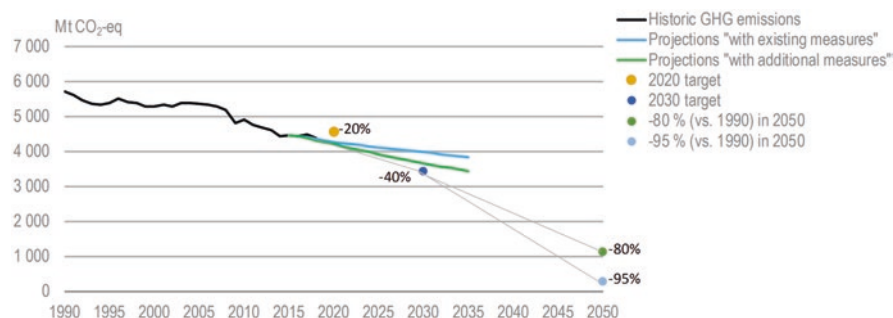


Fig. 9.5 Greenhouse gas emissions in the EU from 1990 to 2018 and projections for 2030 and 2050 [7, 12]

be around 100 Mt. CO₂eq in order to reach the 2030 target and around 114–157 Mt. CO₂eq to achieve the 2050 target (–90% CO₂ emissions) [12, 13]. Moreover, scenarios proposed by the European Commission indicate that, between 2030 and 2050, the primary energy consumption should decrease by around 4–14 Mtoe per year [14].

In 2017, greenhouse gas emissions were caused mainly by oil (42%, 66% of which was due to transports), followed by coal (29%) and by gas (28%). By sector, CO₂ emissions were caused mainly by heat and power generation (35%) and transport (25%), followed by energy use in residential and service buildings (17%), industry (8%), agriculture, forestry and fishing (10%), and waste management (3%) [7, 11, 15]. The Land Use, Land-Use Change and Forestry (LULUCF) sector contributed to a net removal of around 5% of GHG emissions [11].

Figure 9.6 illustrates that the carbon intensity of power generation is very low in countries with high contribution of renewable energy sources (RES), such as Sweden, Finland, Estonia, and Belgium, and nuclear energy, such as France, while it is high in countries with a strong dependence on solid fuels (Greece, Cyprus, Poland, Lithuania). By 2030, the situation will improve thanks to the higher contribution of RES in several countries [16].

9.2.1.1 Power and Heat Generation

Power and heat generation caused, in 2017, around 35% of the total CO₂ emissions, and the residential sector alone contributed 17%. In the EU residential sector, in 2018, about 64% of the total energy consumption was used for space heating, 15% for domestic hot water, 14% for lighting and appliances, 6% for cooking, and 1% for space cooling [17].

Natural gas boilers are the most widely used in the EU with 88 million units installed, followed by oil boilers (18 million) and coal boilers (3.4 million). Natural gas boilers are used mainly in the UK (23 million), Italy (16 million), Germany (13 million), and France (9 million). Oil boilers are used mainly in Germany (6

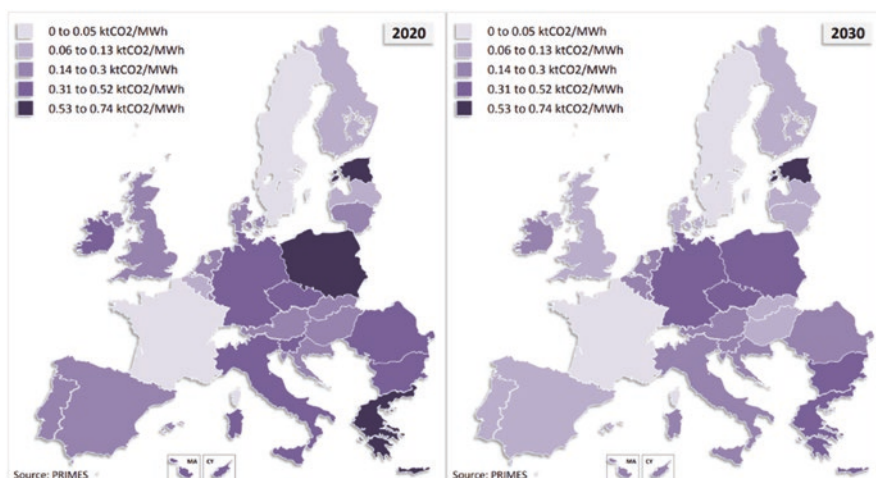


Fig. 9.6 Carbon intensity of power generation in the EU for 2020 and 2030 [16]

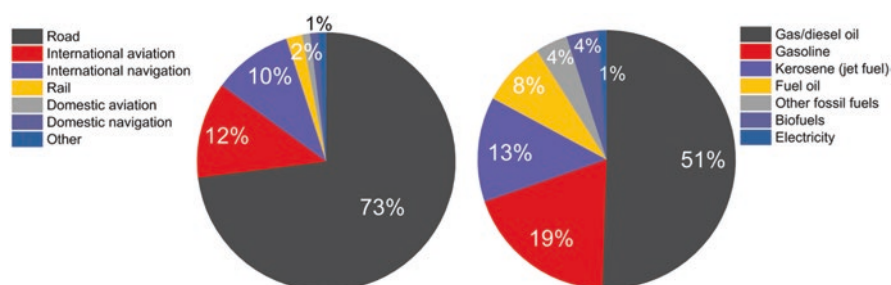


Fig. 9.7 Energy consumption in the transport sector by type (left) and fuel (right) [23, 24]

million), France (4 million), and Belgium (2 million). Coal-fired boilers are used mainly in Poland (2 million). Electric heating systems are diffused mainly in France (9.5 million), Spain (7 million), and Portugal (2 million). Heat pumps are used mainly in Italy (15 million), France (5 million), and Sweden (0.8 million) [18].

9.2.1.2 Transport Sector

In 2018, transport emissions were 21% higher in 1990, and in 2017 around 72% of emissions of this sector came from road transport that covers 94% of the energy demand related to domestic transport [7, 12, 19, 20]. The transport energy demand is almost entirely covered by petroleum products (92% in 2018) and in particular by diesel, which covers 67% of the energy demand (Fig. 9.7) [21]. The tendency in recent years is changing: in 2019, only 60% of new cars in Europe used petrol and the number of diesel cars is decreasing year by year [22].

In the transport sector, the EU legislation on CO₂ emission limits is the most stringent worldwide, and great efforts should be made by companies in order to reach the imposed target of -37.5% in 2030 compared to 2021 levels for cars (95 g CO₂/km in 2021), -31% in 2030 compared to 2021 levels for vans (147 g CO₂/km in 2021), and -30% in 2030 compared to 2021 levels for heavy-duty vehicles. However, part of these efforts could be fruitless due to the increase in sales of low-efficiency vehicles such as sport utility vehicles (SUVs) [9, 12, 14, 25–27]. The amount of SUVs sold in the EU increased from 7% to more than 30% of new register vehicles in the last 10 years: this trend is favored by carmakers that try to maximize sales of SUVs, which provide higher profits than low-emission economy cars [19]. Moreover, by 2030, zero- and low-emission vehicles (ZLEV) must account for 35% (cars) and 30% (vans) of sales in the EU, but the potential benefits of this regulation could partly be vanished because plug-in hybrid cars, under pressure from car-manufacturing member states, have been comprised within the ZLEV category [19]. To reach the target imposed by the European Green Deal (-90% of greenhouse gas by 2050), it is estimated that around 75% of road transportations should be performed by train [25].

The domestic aviation sector in the EU contributes less than 0.5% of total GHG emission, but international aviation from and to the EU contributes to 3% of total emissions, which doubled between 1990 and 2017. The EU Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) requires airlines to reset the growth of CO₂ emissions starting from 2020 [12, 28].

9.2.1.3 Industry

The European industrial sector accounted, in 2017, for 12.6% of CO₂ emissions, with a reduction of only 0.3% compared to 2013, and, despite this, no specific targets for energy efficiency or use of renewable resources are present [7]. The Industrial Emissions Directive (2010/75/EU) sets emission limits based on the best available techniques (BAT). The permissions, according to the directive, are based on an integrated approach that considers emissions to air, water and land, waste production, use of raw materials, energy consumption, noise, and restoration of the site upon closure [16, 29].

In the case of particular industries like large combustion plants, waste incinerators, and solvent-using activities, limitations have also been imposed for specific pollutants, such as fluorinated gases; in particular, by 2030, fluorinated greenhouse gas emissions should be reduced by 2–3% compared to 2014 levels, below a limit of 1.5 Gt CO₂eq [30]. As alternatives to the common hydrofluorocarbon (HFC) gases for refrigeration, iso-butane is the most widely used for domestic fridges and freezers, while propane is the most diffused for air-conditioning and commercial refrigerators [16].

9.2.1.4 Agriculture

The agricultural sector was responsible, in 2017, for 10% of GHG emissions, with a decrease of around 20% compared to 1990. The main reasons for the decrease are the reduction in nitrous oxide emissions due to a lower use of nitrogenous fertilizers and the reduction in methane emissions due to enteric fermentation due to a reduced number of ruminant livestock. It should be noted that the emission reductions have also been compensated by increased production outside the EU due to a strong increase in the import of food since 1990 [15, 31].

9.2.1.5 Land-Use, Land-Use Change, and Forestry (LULUCF)

Concerning emissions from land use and forestry protection, the LULUCF regulation requires that the GHG emissions from a land use category are completely compensated by an equivalent CO₂ removal from another category (such as forestry). Moreover, the conversion of forests to other land uses (deforestation) or the increase of the cropland surfaces should be paralleled with an increase in the forest surface (afforestation) in other sites, thereby equilibrating the CO₂ balance [12, 32, 33]. In 2012, the LULUCF sector contributed with a net carbon sink of approx. 258 Mt. CO₂eq but, by 2030, a decline of around 32% is expected. The two main reasons are the aging of EU forests, with a consequent reduction of carbon sequestration, and an increase in forest harvest, due to the higher demand for wood for material uses and energy production and due to a decrease of forest increment (from 751 million m³ in 2005 to 725 million m³ in 2030) [12].

9.2.2 Energy Consumption

In 2018, renewable energy sources (RESs) contributed to 32% of electricity production (Fig. 9.8), with an annual increase of around 1.3% from 2005. Renewables are constituted by hydropower (35%), wind energy (34%), photovoltaic (12%), and solid biomass (9%) [34]. RES contributes only to 18% of the gross energy consumption due to the minor role of renewables in transport (8%) and heating/cooling (20%) [7].

The energy mix of the European Union is still dominated by fossil fuels that, in 2017, covered around 72% of the energy demand (lower respect to 80% at the global scale). In detail, oil contributed for 33%, natural gas for 25%, coal for 14%, nuclear for 13%, and bioenergy, wastes, and other renewable for 15%.

9.2.2.1 Oil

Oil is the largest energy source in the EU and, from 1990, its contribution declined only of 4–5% due to the strong consumption from the transport sector, which accounts for more than half of oil demand [7, 36].

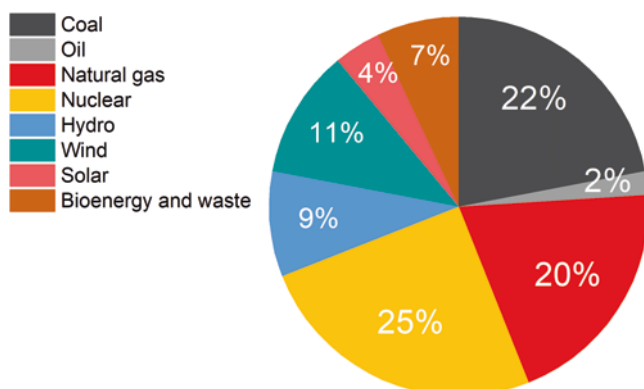


Fig. 9.8 EU electricity production sources in 2017 [7, 35]

9.2.2.2 Natural Gas

Gas is the second largest energy source in the EU, with a consumption of 487 billion m³ in 2017, 29% higher than in 1990. It is mainly used for power and heat generation, residential heating, and industrial processes; the projections for 2030 see a decrease in gas use for residential heating but an increase for power generation [7, 36].

9.2.2.3 Coal

In 1990, coal contributed for 40% to the gross energy production, and since then, it is continuously lowering due to the decommissioning of the coal power plants planned by 2022 in Sweden, by 2025 in Austria, France, Italy, Ireland, Spain, and the United Kingdom, by 2029 in Netherlands and Finland, by 2030 in Portugal and Denmark, and by 2038 in Germany. Only a few countries in Eastern Europe, such as Poland and the Czech Republic, have not planned a phase-out from coal use yet [7, 36].

9.2.2.4 Nuclear Energy

Regarding nuclear energy, the EU has the largest number of nuclear power plants operating worldwide, but it is entering a critical stage due to the approaching to the end of the planned lifetime. The EEA expects, by 2050, a decrease of the installed capacity of around 25 GW, with respect to the 125 GW installed in 2017, with a consequent decrease in the contribution to electricity production from 25% in 2017 to 15% in 2050 [7, 28, 36]. The majority of nuclear reactors in the EU were built between 1970 and 1980: by 2015, 91 plants were decommissioned and the

decommissioning of other 89 reactors is planned before 2030. To limit the fall of nuclear energy production, the European Commission estimates that investments of around 50 billion € are required for the lifetime extension of existing plants and 450 billion € for the construction of new plants [28]. At the moment, only a few countries are building new plants (Finland, France, Hungary, Slovakia, and the United Kingdom), while France planned a 50% reduction by 2035, Germany the complete decommissioning by 2022, and Belgium by 2025 [37].

9.2.3 *The Building Sector in the EU*

The Renewable Energy Directive 2018/2001/EU (RED II) raised to 32% the target for the overall share of energy from renewable sources in the EU's gross final energy consumption by 2030 and ensured that consumers could produce, store, or sell the surplus electricity that they did not need. Moreover, consumers can aggregate in communities (Renewable Energy Communities, REC) that have the same rights of single consumers with the advantage of a possible exchange of renewable energy within the same community [33, 38].

The contribution of renewable energies in residential and service buildings in the EU increased from 9% in 1990 to 24% in 2017, but the main problem is related to building inefficiency with less than 3% of buildings satisfying A-label performances: 14% of buildings have been built before 1910, more than 40% before 1960, and 25% between 1970 and 1990 [39, 40]. Moreover, due to the very low turnover of buildings, the main chances for the reduction of energy demand are in the retrofitting of existing constructions [6, 41, 42]. Moreover, to achieve the target of 32.5% reduction of primary and final energy by 2030 (with respect to 1990) established in the Energy Efficiency Directive 2018/2002/EU (EED), 97% of buildings should be subjected to major renovations by 2050, with an annual renovation rate three times higher than the actual one (1%) [43, 44]. Moreover, the directive aims at implementing also the energy efficiency of air conditioning systems, lighting, heaters and water pumps, and all domestic electric appliances [45].

A scenario proposed by the Buildings Performance Institute Europe (BPIE) estimates that, to achieve the EU's target of emission neutrality by 2050, a decrease of 22% of the final energy demand for heating and cooling will be required by 2030 with a consequent necessity of a building renovation rate of around 4.4%, higher than the 3% required in the period 2020–2050. This value demonstrates that the postponement of the required measures necessary to reach the targets implies stronger efforts in the future. Moreover, by 2030, a reduction in floor space per capita of around 6% is expected, reaching a value of 44.8 m²/person [46]. The Energy Efficiency Financial Institution Group estimated that, starting from 2020, annual investments of around 100 billion € are required for building renovations [47].

The Energy Performance of Buildings Directive of 2010 and revised in 2018 (2018/844/EU) established energy efficiency targets for new buildings, energy performance certificates (EPC), and verification methods. Energy performance

certificates were introduced in order to increase the transparency of building's energy performance, to improve the demand for buildings with low-emission classes, and to improve the indexing of building's performances [48]. Furthermore, the directive required that, starting from the end of 2020, all new buildings must be nearly zero-energy buildings (nZEB), in which the nearly zero amount of energy required should be mainly satisfied by renewable energy resources. The directive did not provide a precise definition of nZEB, leaving the EU member states the possibility to define it [32, 38, 47, 49–51].

The regulations imposed by member states established, in some cases, a minimum percentage of energy that should be covered by RES and, in other cases, extremely low levels of primary energy (between 20 and 90 kWh/m²/year) that, practically, can be reached only using RES [52]. Studies carried out in 17 EU countries, evidenced that nZEB requires 15–25 kWh/m²/year for heating in cold-climate regions and 8–10 kWh/m²/year in temperate-climate regions [53].

In Italy, RES should cover at least 50% of energy consumption for heating, cooling, and hot water, and the transmittance levels of envelope, roof, and windows should be lower than reference values depending on different climatic areas [52]. In France, the primary energy consumption of residential buildings must be lower than 50 kWh/m²/year [53]. Moreover, by 2025, all buildings with a primary energy consumption higher than 330 kWh/m² (F, G efficiency classes) must be renovated to reach a performance comparable to new buildings, and by 2050, all buildings should be in class A or B [47]. In Germany, three types of house efficiency have been defined (KfW40, KfW50, KfW70), considering the fact that the annual primary energy consumption should be 40, 50, 70% lower compared to a corresponding reference building. Moreover, the minimum share of RES is 15% while using solar heating and 50% while using biomass and geothermal energy [54]. The European Passive House standard states a limit for heating energy use lower than 15 kWh/m²/year (120 kWh/m²/year considering heating, cooling, hot water, and electricity), which can be reached by reducing heat losses to 45 kWh/m²/year, with 15 kWh/m² covered by solar heating, 15 by internal heat gains and the remaining part by active heating [55].

It is estimated that a deep retrofitting of buildings located in the EU and the United States could allow a reduction of 33% and 50%, respectively, of energy consumption by 2050 [55, 56]. From an economical point of view, the retrofitting of buildings according to the passive-house standard is quite convenient: the cost for the renovation of a traditional residential building is estimated in the order of 500–600 €/m² and the incremental cost of a new passive house is around 8% of the cost of a standard house. If amortized over 25 years at 4% interest and divided by the saved energy, the cost of the saved energy would be around 0.06 €/kWh, equal to the cost of natural gas in the EU in the first half of 2021 and much lower with respect to the cost of natural gas in 2022 [45, 52, 57].

9.2.4 Energy Prices and Road to 2050

Starting from the second half of the year 2021, a strong and continuous increase in natural gas (and consequently electricity) prices has been observed worldwide. From the data reported in Fig. 9.9, referring to the Italian market, it is possible to observe that the price for natural gas (day-ahead-market, MGP) increased from 16.8 €/MWh to 67.2 €/MWh in the period from the 01/01/2021 to the 01/01/2022, reaching a peak of 183.7 €/MWh on the 22/12/2021 [58]. In the same period, the price for electricity in Italy (single-national-price, PUN) increased from 51.2 €/MWh up to 167.2 €/MWh, with a maximum of 437.9 €/MWh on 21/12/2021, as shown in Fig. 9.10 [59].

The reason for the exceptionally high prices lies in the extreme reduction in global energy consumption during the year 2020 (−10% with respect to 2019 in Europe) due to the Covid-19 pandemic that drove the prices of many fuels to their lowest levels in the last years (4.6 €/MWh for gas, 21.8 €/MWh for electricity), followed by the very fast global economic recovery that resulted in a strong increase of energy demand, not counterbalanced by the gas supply that was lower than expected [7, 58–61]. In Europe, the situation was exacerbated by the limited Russian pipeline supply, the level of underground storage that was below average, and the fact that more than 90% of the gas consumed in the EU is imported from extra-EU countries

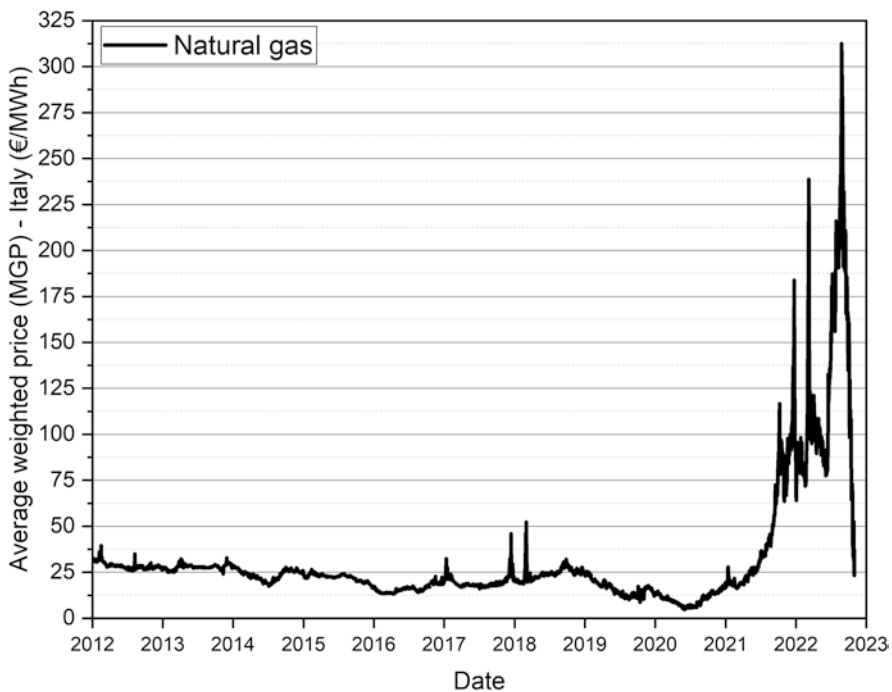


Fig. 9.9 Average weighted price of natural gas (MGP) in Italy from 01/01/2012 to 31/10/2022 [58]

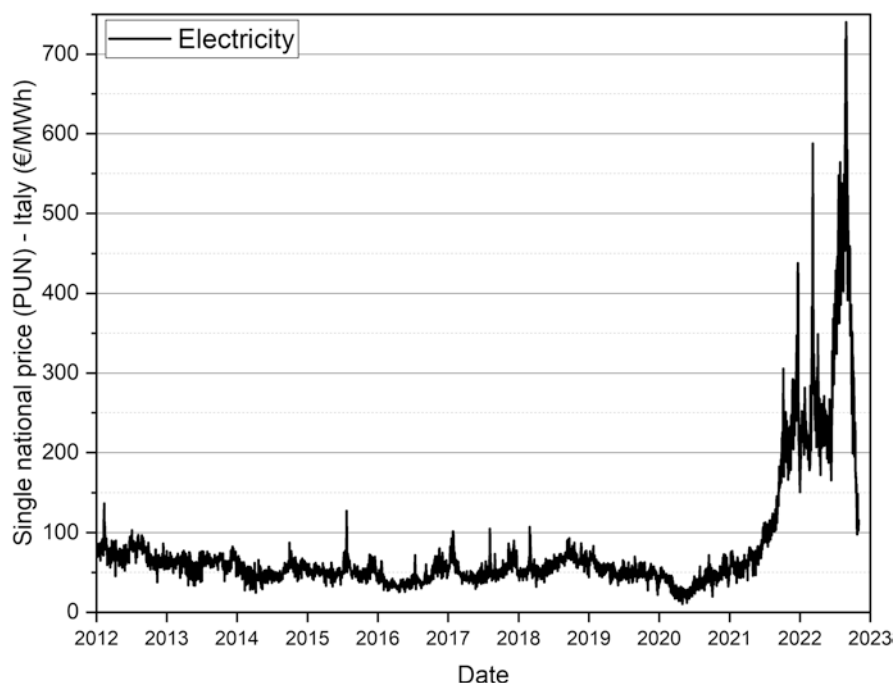


Fig. 9.10 Single national price (PUN) of electricity in Italy from 01/01/2012 to 31/10/2022 [59]

(Russia 41.1%, Norway 16.2%, Algeria 7.6%, Qatar 5.2%, others 29.9%) [60, 62, 63]. Moreover, at the end of February 2022, the situation in the EU was even worsened by the outbreak of war in Ukraine that led to a further rise of energy prices (on August 29, 2022, a peak of 312.4 €/MWh for natural gas and of 740.1 €/MWh for electricity was recorded in Italy, as shown in Figs. 9.5 and 9.6) [58, 59].

Projections of the European Commission estimate that, by 2050, the gross final energy production will be covered for around 75–80% by RES (Fig. 9.11), with a share of around 97% in electricity production that will cover 50% of the final energy demand. Moreover, the reduction of energy demand from buildings and the increased market share of RES will result in a limited dependence on fossil fuels that will drastically reduce the price volatility, and the import dependency will decrease to 35–45%, much lower than the 58% of 2012 [35, 45, 64].

A similar trend is expected for GHG emissions (see Fig. 9.12): the most impactful sectors (transport, power generation, industry, and residential) will progressively decrease their contribution in order to achieve the target of carbon neutrality by 2050. An increased effect of carbon sequestration will be achieved by increasing the LULUCF contribution and by the use of carbon sequestration technologies [35].

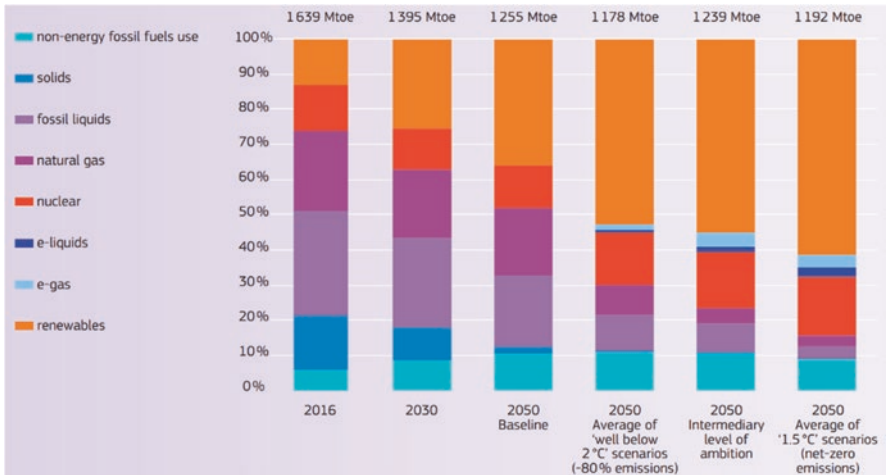


Fig. 9.11 Gross inland consumption of energy in the EU [35]

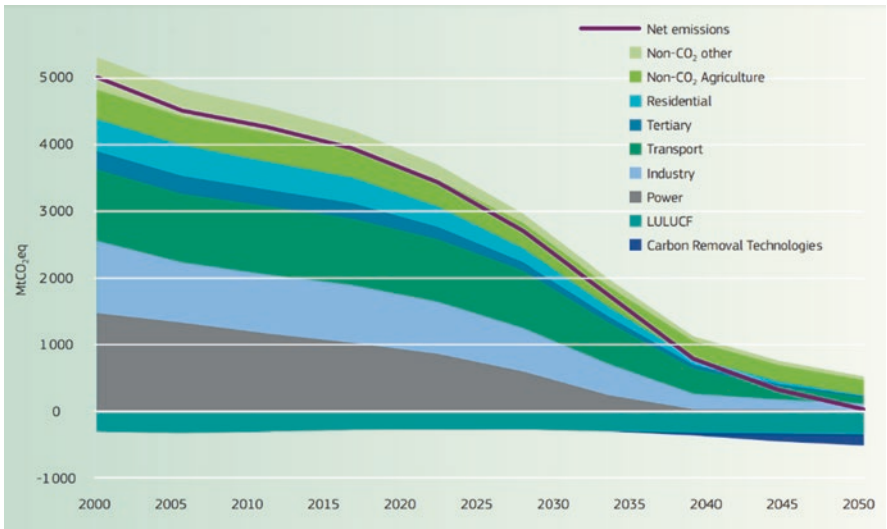


Fig. 9.12 GHG emissions in EU by sector with projection up to 2050 [35]

9.3 Energy Storage Technologies

The need for the reduction of CO₂ emissions and the increasing awareness of the limits of non-renewable energy resources has stimulated the demand for renewable energies [65, 66]. Solar energy is the largest energy source on Earth since the energy that Earth receives from the sun is around 10,000 times higher than the total energy

demand. Several technologies are used to convert solar energy into other energy sources, in particular [67–69]:

- *Photovoltaic technology* enables the direct conversion of solar energy into electricity using semiconductors.
- *Solar thermal technology* collects solar energy to convert it into electricity through the transformation into other forms (e.g., heat).
- *Heat storage*, in which solar energy is collected to obtain and store heat without further transformations.

However, as other renewable energies, solar energy is characterized by an intrinsic variability and intermittency that can result in strong and sudden power fluctuations [65, 66, 69]. Thus, the best approach is to store excess energy of renewable sources to mitigate power fluctuations and increase the system flexibility. The main problem related to energy storage is the impossibility of storing large amounts of electrical energy for an unlimited time without losses and, therefore, the necessity of the conversion of electricity into other energy forms [70–73]. Different technologies for energy storage can be identified:

- **Water systems (reservoirs):** the potential energy of water is stored in two reservoirs, located at different altitudes. During the high-demand period, water flows from the upper basin to the lower, producing electricity through hydroturbines. During the low-demand period, water is pumped from the lower basin to the upper, transforming electrical energy into potential energy [70, 74].
- **Pneumatic systems (compressed air):** the potential energy of compressed air is stored in large underground reservoirs at pressures up to 50–80 bar. During the high-demand period, the stored air is used to run a gas-turbine generator to produce electricity. Otherwise, electricity is used to compress air into the reservoir [70, 74].
- **Mechanical systems (flywheels):** the energy storage is based on the kinetic energy of a moving cylinder. The kinetic energy is proportional to the mass of systems, the square of the angular velocity, and the square of the radius [70, 74].
- **Electrochemical systems (batteries and supercapacitors):** in the case of batteries, energy storage occurs through the chemical reactions between chemical compounds separated by an electrolyte. Supercapacitors are double-layer capacitors consisting of two porous-carbon electrodes immersed in an electrolyte. They allow storing a high amount of energy but at low voltages and for a short time [70, 74]. In recent years, great effort has also been devoted to hydrogen storage to be used as buffer system coupled with nonprogrammable renewable resources, in particular photovoltaic and wind power that are estimated to increase several times by 2050 (14 times with respect to installed power of 2019 for photovoltaic and 9 times for wind power, in Italy) [75]. Indeed the excess power could be used for the production of hydrogen that, if stored, would allow to produce electricity at a later time. It is therefore essential to decrease the enormous volume of the hydrogen gas; the available methods are (i) physisorption of molecular H_2 on materials, (ii) hydrogen (atomic H) intercalation on host metals, (iii) chemical

oxidation of metals with water and liberation of hydrogen, and (iv) complex compounds ($[\text{AlH}_4]^-$ or $[\text{BH}_4]^-$) [76, 77].

- Magnetic systems (superconducting magnetic energy storage): the energy storage occurs in a magnetic field. The system consists of a direct current that, flowing through a superconducting wire at cryogenic temperature, creates a magnetic field [74, 78].
- Thermal systems (thermal energy storage): thermal energy is stored within a storage medium through a temperature increase of the material (sensible heat-TES), through a phase transition (latent heat-TES), or through chemical reactions (thermochemical storage) [70, 74].

9.4 Thermal Energy Storage for Building Applications

Considering that the residential sector, in 2018, contributed for 17% of the total CO_2 emissions in the EU and that 78% of this contribution was due to space heating and domestic hot water, thermal energy storage seems to be a promising and critical technology for the next years [17, 72]. As previously mentioned, solar energy is variable and time-dependent, but also heat demand of buildings is usually time-dependent with a certain mismatch with respect to solar radiation. Thermal energy storage can adjust this mismatch to cover the energy needs at all times [72].

Depending on the way of storing energy, TES can be divided into three categories: sensible heat, latent heat, and thermochemical heat storage.

9.4.1 Sensible Heat Storage

SHS is performed by changing the temperature of the storage medium, and the stored energy is proportional to the temperature difference, as shown in Fig. 9.13. The performance of the storage medium is proportional to its mass/volume and specific heat that determines the slope of the curve. The most widely used materials are water, molten salts, rocks, concrete, and oils. The properties of some SHS materials are listed in Table 9.1.

Water is preferred as SHS material in the temperature range 0–100 °C due to the low cost, high specific heat, nontoxicity, and nonflammability [66, 72, 82]. SHS using water is usually implemented for short-term applications (less than 1 week), but in some cases seasonal systems are possible. A very common application is the use of solar collectors to charge a water tank taking advantage of the solar radiation in the daytime. The stored thermal energy can be used to satisfy the heat demand for a certain period (e.g., during the nighttime) instead of using boilers [82]. The duration of the energy storage depends on the size of the water tank, and this allows the implementation of long-term storage systems. In Switzerland, the company Jenny Energietechnik AG produces storage tanks with capacities of up to 350,000 liters,

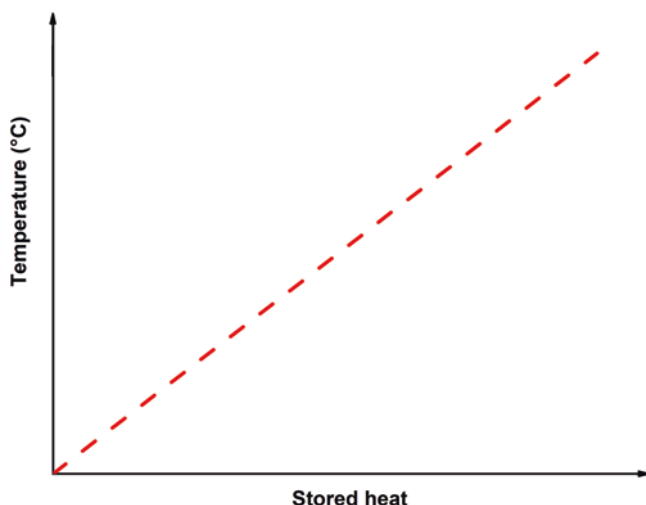


Fig. 9.13 SHS behavior during temperature change

Table 9.1 Properties of some SHS materials [72, 79–81]

Material	Density [g/cm ³]	Specific heat [J/kg·K]	Application range [°C]	Cost [€/kg]
Water	1	4190	0–100	0.0015
Molten salts	~2	~1500	200–700	0.3–1.3
Rock	~2.5	~880	<1500	~0.006
Concrete	~2.2	~650	<400	~0.03
Sunflower oil	0.93	2115	<250	0.25–0.4

using water as SHS medium, able to satisfy at least 50% of the annual heat energy demand of buildings using solar energy [83]. In Sweden, a house with a living space of 240 m² was equipped with a solar collector area of 50 m² [53] connected to a 200,000 liters storage tank. The solar system provides a power of around 35–40 kW, able to heat water during the summer period up to 90 °C. The heat pump of the heating systems is supplied with hot water that is able to cover almost the entire annual energy demand of the building [84]. During the summer period, hot water from solar collectors is charged into the top of the water tank. The stored thermal energy is then recovered by removing the hot water from the upper part of the tank, which is replaced by cold water entering the lower part. The efficiency of the energy storage process strongly depends on the thermal stratification occurring within the tank due to the density difference between hot water, accumulated at the top, and cold water, accumulated at the bottom. The thermal stratification is influenced by several factors, such as the tank geometry, the design of the inlet and outlet valves, and the operating conditions. The highest the stratification, the highest the hot water volume and the highest the efficiency of the system [66].

In the case of building applications, Facci et al. compared different solutions for the heating and cooling of buildings, considering a building with a surface of around

3000 m², composed of 31 apartments and 1 office [85]. The considered solutions were:

- (A) boiler + SHS (water tank) + air conditioning
- (B) boiler + SHS (water tank) + air conditioning + photovoltaic panels
- (C) heat pump + SHS (water tank) + air conditioning
- (D) heat pump + SHS (water tank) + air conditioning + photovoltaic panels
- (E) heat pump + air conditioning + photovoltaic panels.

They observed that solution D (followed by B) is the best one in terms of costs, both for cold and hot climates. In terms of CO₂ emissions, solutions B and D are equivalent in the case of cold climates, while solution B is much better in the case of hot climates due to the larger quantity of electricity fed into the grid. It was estimated that solution D, with respect to solution A, in the case of cold climates, allows a reduction of costs and CO₂ emissions of around 60% [85].

9.4.2 Latent Heat Storage

In LHS, the thermal energy is stored within a storage medium through the phase transition of the storage medium that, for this reason, is generally called “phase change material” (PCM). LHS systems are generally based on a melting-crystallization phase transition, with heat absorbed during melting and released during crystallization. The behavior of LHS as a function of temperature is shown in Fig. 9.14: the system initially behaves as SHS absorbing sensible heat and increasing its temperature. As soon as the phase transition temperature of the material is reached, the system absorbs heat at a constant temperature until the phase transition is completed: the amount of stored heat is equal to the latent heat of fusion (or crystallization, in cooling). When the phase transition is completed, the system behaves again as an SHS, absorbing sensible heat and increasing its temperature. The main advantages of LHS, compared to SHS, are the higher energy storage capability and the constant temperature of the material during the phase transition. On the other hand, the main disadvantages are represented by the higher cost, the necessity of encapsulation to avoid leakage in the molten state, the low thermal conductivity, the volume change associated with the phase transition, and the flammability of the most used organic PCMs [66, 82].

9.4.2.1 Phase Change Materials

Typical PCMs are water/ice, paraffin wax, fatty acids, polyethylene glycol (PEG), fatty alcohols, salt hydrates, metal alloys, and eutectic mixtures (some properties are listed in Table 9.2).

Paraffins are the most widely used organic PCMs thanks to their low cost, high heat of fusion, and a broad range of melting temperatures. They consist of a mixture

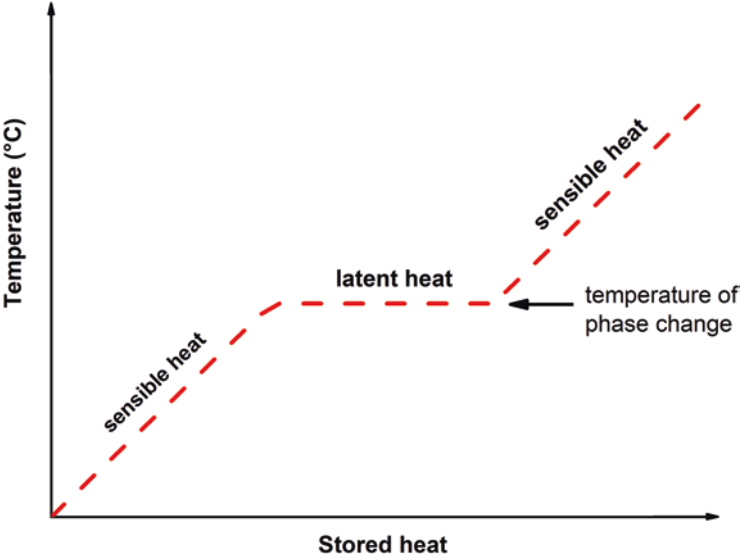


Fig. 9.14 LHS behavior during temperature change

Table 9.2 Properties of some PCMs [86–91]

Material	Density [g/cm ³]	Specific heat [J/kg·K]	Latent heat [kJ/kg]	Application range [°C]	Cost ^b [€/kg]
Water/ice	1	4190	334	0	0.0015
Paraffin wax	0.8	~2000	150–2550	–10 to 155	11
Fatty acids	0.8	~2100	170–270	–40 to 150	18
PEG	1.1	~2100	120–180	4–70	15
Salt hydrates	1.1	1000–4000	100–220	–50 to 120	2–5
Metal alloys ^a	> 2	120–900	25–350	30–660	2–10

^aProperties referred to most common alloys (gallium, bismuth, and aluminum)

^bPrice taken from manufacturers according to quotations available to the author

of mostly straight chain n-alkanes C_n-H_{2n+2} , whose melting point and melting enthalpy depend on the chain length (the longer the chain length, the higher the melting point and the melting enthalpy): from around $-9\text{ }^{\circ}\text{C}$ for n-dodecane ($C_{12}H_{26}$) to $109\text{ }^{\circ}\text{C}$ for n-heptacontane ($C_{70}H_{142}$). Commercial-grade paraffins are derived from the distillation of crude oil and are mixtures of saturated hydrocarbons with different chain lengths in order to obtain products with intermediate properties. Paraffins are safe, nonreactive, and stable for over 2000 cycles. The main drawbacks of paraffin waxes are their flammability and low thermal conductivity. The latter does not allow a good rate of heat transfer and often requires the incorporation of conductive particles in order to enhance the heat exchange [92–96].

Saturated fatty acids are bio-based organic PCMs such as capric acid [$\text{CH}_3(\text{CH}_2)_8\text{COOH}$], lauric acid [$\text{CH}_3(\text{CH}_2)_{10}\text{COOH}$], myristic acid [$\text{CH}_3(\text{CH}_2)_{12}\text{COOH}$], palmitic acid [$\text{CH}_3(\text{CH}_2)_{14}\text{COOH}$], and stearic acid [$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$] [97, 98]. Fatty alcohols can be synthesized from the triglycerides (fatty acid triesters), and the resulting methyl esters are then hydrogenated to give fatty alcohols. Various vegetable oils and animal fats are traditional sources of fatty alcohols [99].

Polyethylene glycol (PEG) is a polymer with the chemical formula $\text{H}-(\text{O}-\text{CH}_2-\text{CH}_2)_n-\text{OH}$, widely studied due to its high melting enthalpy, congruent melting, non-toxicity, hydrophilicity, and biodegradability. The phase change properties of PEG depend on the molecular weight that ranges from 400 Da (melting point around 4 °C) to 10^6 Da (melting point around 70 °C) [86, 100–102].

Salt hydrates are mixtures of salts and water forming a crystalline solid. The solid–liquid phase change of salt hydrates is a dehydration/hydration of the salt that decomposes into an anhydrous salt and water. The main problem related to salt hydrates is the incongruent melting due to the segregation of the anhydrous salt at the bottom of the container and the consequent hindrance of the hydration process. Examples of salt hydrates are $\text{CaCl}_2 \cdot 12\text{H}_2\text{O}$, $\text{LiNO}_3 \cdot 2\text{H}_2\text{O}$, $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, $\text{Ca}(\text{NO}_3)_4 \cdot 4\text{H}_2\text{O}$, $\text{Ca}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and many others [92].

Metal alloys are characterized by high melting enthalpy, high thermal conductivity, high thermal reliability, and repeatability, but, due to their high density, they have not been considered for real applications. Due to the wide range of temperatures, from 30 °C of gallium to 660 °C of aluminum, they can find several possible applications in the future. The most promising materials are gallium for low-temperature applications, zinc, magnesium, and aluminum for high-temperature applications, and binary/ternary alloys of these elements [92, 96].

Eutectic mixtures are PCMs constituted by two or more components able to melt and freeze congruently without segregation. Their properties can be therefore adjusted for specific applications. Examples of eutectic mixtures are triethylolthene + water + urea (melting point at 13.4 °C, latent heat of 160 J/g), $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O} + \text{NH}_2\text{CONH}_2$ (melting point at 52 °C, latent heat of 125 J/g), $\text{Mg}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O} + \text{NH}_4\text{NO}_3$ (melting point at 59 °C, latent heat of 132 J/g), $\text{Mg}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O} + \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} + \text{MgBr}_2 \cdot 6\text{H}_2\text{O}$ (melting point at 66 °C, latent heat of 168 J/g) [92].

9.4.2.1.1 Applications

Kondo et al. reported the use of a microencapsulated PCM, with a melting point of around 25 °C, in ceiling boards for the thermal management of offices. In particular, the panels were chilled during the nighttime using the cooling system and used in order to avoid temperature peaks during the hottest hours of the daytime. The energy demand for cooling was around 15% lower with respect to common offices insulated using rock wall panels and the running costs were around 10% lower thanks to the lower price of electricity during the night [103].

Zhang et al. studied the performance of a floor radiant heating system during the period from 2011 to 2014: the plant was driven by a PCM-based solar collector system and the adopted solution was able to maintain a room temperature of about 5–7 °C higher than that of the nonheated rooms. In particular, it was found that, compared to conventional solar heating systems, the use of PCMs improved the global energy efficiency of the combined plant by 30% [104].

Oro et al. and Gin et al. studied the effect of energy black-out on the internal temperature of conventional freezers and freezers insulated with panels containing a eutectic mixture of water and ammonium chloride, with a melting point of –15.4 °C. After a 3-hour black-out, the internal temperature of the conventional freezers increased from –16 °C up to –3 °C, while in the other case the presence of the PCM limited the temperature increase only up to –11 °C [105, 106].

Ahmed et al. investigated the effect of polyurethane insulation panels containing copper pipes filled with a PCM with a melting point of 4 °C applied on the internal side of a refrigerated truck. The results showed that the heat transfer from the external walls of the truck decreased by around 16% with consequent lower temperature oscillations in the load compartment [107].

Again, in the field of refrigerated trucks, Liu et al. studied the possibility of using an external unit containing a PCM with a melting point of –25 °C, connected to the cooling system of the truck: while driving the coolant was cooled by the compressor, whereas during stops it was cooled by the PCM unit. The system was able to guarantee a temperature of –18 °C for 10 hours, allowing a reduction of around 50% of the operating costs [108]. Similarly, Simard et al. demonstrated that a PCM with a melting point of –43 °C was able to guarantee a cooling power of 3.5 kW for 8 hours, occupying only 3% of the loading volume [109].

A commercial product is available on the market for the insulation of refrigerated trucks, presented at the “7th India cold chain show” in 2018 by the Indian company PLUSS Advanced Technologies Pvt. The “Thermotab” panel is constituted by an external plastic envelope, containing a coil immersed in a PCM with a melting point of –25 °C. The coil contains the coolant and is connected to an electric compressor powered by the electric grid in order to cool down the load compartment and by the alternator while driving. During stops, the load compartment is not refrigerated, but thanks to the presence of the PCM, the temperature is maintained constant. The operating costs are around 65% lower with respect to a conventional refrigerated truck, whereas the initial costs are only 5–10% higher [110, 111].

Other applications in the cold chain regard the possibility to store cold at night in the case of buildings characterized by very high cooling needs during the day and low during the night, such as hospitals, museums, shopping centers, etc. The presence of storage tanks containing PCM allows decreasing the size of the cooling systems by 30–70%, avoiding energy absorption peaks during the hottest hours of the day and keeping the working load of chillers constant, avoiding stress periods [112].

In the case of building applications, commercial products are present on the market with the name of *heat battery*, which store solar energy in a tank filled with a PCM with a melting point of 58 °C. The system, available with storage capacities

from 3.5 to 14 kWh, can be used both for the production of hot water and heat thanks to the integration of an electric heater that works in the case of necessity [113]. Similar products, but with storage capacities from 25 to 50 kWh, are also available and can be designed for cooling or heating applications, depending on the geographical area of the building. The storage tanks range from 700 to 1500 kg of PCM [114].

The integration of photovoltaic-thermal (PV-T) solar collectors with PCMs also finds interest thanks to the increased thermal and electrical gains due to the involvement of latent heat of fusion, which is greater compared to the specific heat of any other fluid. As investigated by Hasan et al., the adopted technology allows power production to increase by 5.5% due to the lower operating temperatures of the PV systems that increase the open-circuit voltage [115].

Other studies regard the heat recovery from foundry [116], from exothermic reactions during the production of surfactants [117], and from incinerators in order to contribute to the heating of public buildings [118]. The integration of TES in the automotive industry also finds some applications, such as engine cooling [119], thermal comfort of the passengers [120], and waste heat recovery [121, 122].

9.4.2.2 Encapsulation and Shape Stabilization

The main problem related to the use of PCMs is their leakage in the molten state, which requires the accumulation of the PCM in a tank (bulk storage) or the confinement either by encapsulation (micro- or macro-encapsulation) or by shape stabilization:

- *Bulk storage* consists in a tank heat exchanger equipped with fins or other metal structures intended to maximize the heat transfer between the PCM and the system [108, 109, 114, 123, 124]. Commercial products are already available at the market scale, e.g., the *UniQ heat battery* produced by Sunamp Ltd. (Tranent, UK) [113].
- *Macroencapsulation* consists in the confinement of a certain quantity of PCM (<1 kg) within specific containers (panels, spheres, or cylinders) properly sealed and designed in order to avoid corrosion phenomena and to resist the volume variations associated with the phase transition [105, 106, 110, 123]. Commercial products are available on the market, for example, the *compact storage modules* produced by Rubitherm GmbH (Berlin, Germany) [125].
- *Microencapsulation* refers to the confinement of small quantities of PCM within polymeric or inorganic capsules (in the micrometer range) that prevent leakage and allows the application of the PCM within other matrices (such as gypsum, plasters, concrete, polymers, etc.) in order to obtain multifunctional materials. The main advantages with respect to macroencapsulation are the higher specific surface area that maximizes the heat transfer between the matrix and the PCM capsules. The main disadvantage is the higher cost [123, 126, 127]. Commercial

products are available on the market, for example, the paraffin microcapsules produced by Microtek Laboratories Inc. (Moraine, United States) [128].

- *Shape stabilization* consists in the confinement of the PCM within a matrix able to retain the PCM without leakage or exudation. The most used materials are high-density polyethylene, polypropylene, poly(methylmethacrylate), polyurethane copolymers, acrylic resins, styrene–butadiene–styrene rubber, or inorganic materials such as clay [129–138]. The main advantage is the lower cost with respect to other encapsulation techniques. The main disadvantage is that leakage may occur after several working cycles [139–143]. Commercial products in the form of granulate and powder are produced by Rubitherm GmbH (Berlin, Germany).

9.4.3 Thermochemical Heat Storage

THS stores and generates heat through the combination of sorption and chemical reactions. The working principle, as shown in Fig. 9.15, involves the desorption of water (A) from the material (B) during the charging process by absorbing thermal energy from the surrounding, and then the absorption of water, with consequent temperature increase (due to chemical bond formation), during the discharging process. The total heat released depends on the reaction enthalpy (J/mol) and on the quantity of material (mol). THS allows heat storage in the long term thanks to the fact that energy is stored as a chemical potential between two reactants with zero heat losses as long as the reactants are separated. Other advantages of THS are the very high energy density and the low volume change during the hydration/dehydration process. Despite the theoretical enthalpies being very high, especially in the case of salt hydrates, the efficiency is much lower due to some reasons: during absorption, the volume increase inhibits the hydration process due to the closure of the pathways for the vapor; the low thermal conductivity of salts slows down the heat transfer; the aptitude of salt hydrates to sintering may lead to the formation of a crust on the surface that leads to further hydration impairment. Other disadvantages are the high cost, the fact that they can be corrosive for some metals, and that they can undergo sub-cooling phenomena. Typical materials used for THS are salt hydrates (such as CaCO_3 , MgSO_4 , CaSO_4 , SrBr_2), hydroxides, oxides, carbonates,

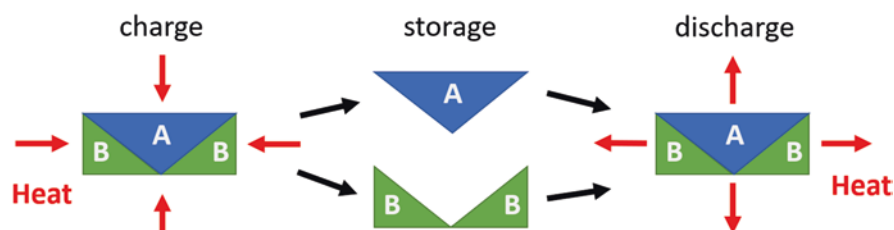


Fig. 9.15 Thermochemical heat storage process

Table 9.3 Properties of some materials used for THS [86–91]

Material	Density [g/cm ³]	Theoretical energy storage [kJ/kg]	Cost [€/kg]
MgSO ₄ ·7H ₂ O/MgSO ₄ ·0.1H ₂ O	~1.33	2500	~8.7
MgCl ₂	~1.56	794	0.18
Na ₂ S·5H ₂ O/Na ₂ S·1/2H ₂ O	~0.93	2900	~0.6
CaCl ₂	~1.84	836	0.3
Zeolites 13X	~0.74	535	~2.5
Microporous silica gel	~0.71	127	~18

and zeolites [66, 72, 82, 144–147]. In Table 9.3, the properties of some materials used for THS are listed.

Despite the interesting properties of THS, several aspects of this technology are currently under development due to the necessity to solve the above-mentioned problems (mainly the necessity to incorporate the material within a matrix to avoid sintering).

One application of THS on a real scale was reported in Germany and regarded the use of THS system based on zeolites in order to store the heat excess of the district heating during the night to be used during the day for the heating of a school. The system was composed of three cylinders containing 7 tons of zeolite with a discharging power of around 130–150 kW. The district heating was used as a desorption heat source that was used to heat up the school in order to avoid a peak of the heating demand in the early morning. The cooling was performed using the air dehumidification system of a club [66].

Another application was based on the use of 400 kg of SrBr₂ in a modular system with a power of around 1.5 kW. The system was tested for several months and a strong influence of the working parameters (moisture content of inlet air, temperature, pressure) on the reactor performance was reported by Michel et al. [148].

Mauran et al. tested a chemical heat pump based on SrBr₂ with expanded natural graphite as support material. The system contained 1 m³ of THS material and a power of around 2.5 kW. Different working conditions were tested in order to optimize the system and the positive effect of having a high ratio of reagent volume over the reactor volume was pointed out [149].

9.5 Conclusions and Future Perspectives

The concept of sustainability refers to a new approach based on the necessity of rethinking of our cities in order to harmonize them with the environment, technology, economy, society, and people [150]. Sustainability shows that the environment (the place where we live) and development (what we do to improve our future) are two inseparable concepts [151]. In particular, it becomes clear that nowadays energy is not only the world's growth engine but also one of the major limiting factors due to the use of fossil fuels for energy production [69]. It is therefore essential to find a

compromise between energy demand and energy resources in order to reduce greenhouse gas emissions and mitigate the consequences of climate change.

Current European strategies to reach the target of the European Green Deal for 2050 involve the use of natural gas to substitute coal in order to decrease GHG emissions, but in the second half of 2021, the rise of gas prices resulted in the coal-fired generation to grow by over 11% in Europe [60, 152–154]. Due to the current rise of gas prices and the increasing difficulties in gas import, it is crucial the identification of strategies able to increase European energy independence, such as the improvement of energy storage, energy efficiency in buildings and industry, and the increase of the market share of renewable energy sources [60, 62, 152, 155–157]. Other critical technologies will be electrification and batteries, hydrogen, fusion power, fuel cells, carbon removal technologies, circular economy, and bioeconomy [35, 158].

Thermal energy storage (TES) is a very promising technology since the energy that Earth receives from the sun is around 10,000 times higher than the total energy demand. TES may allow the accumulation of heat during the hot season to satisfy the heat demand during the entire cold season. Moreover, the use of insulating materials with TES capability may result in the compensation of energy absorption peaks caused by air conditioning or by space heating with a consequent reduction of energy consumption and related CO₂ emissions. Commercial technologies based on sensible-heat TES, consisting of solar collectors to heat-up water and of a storage system, allow satisfying at least 50% of the annual energy demand of buildings using solar energy. Similarly, the latent-heat TES can be used in PCM-based solar collectors (the so-called heat batteries) to store thermal energy from the sun with a significant volume reduction of the storing system compared to the sensible-heat TES. Latent-heat TES can also be used for the production of insulating panels to increase the storage capacity of the walls allowing the reduction of the energy demand of the investigated buildings by approx. 30%.

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