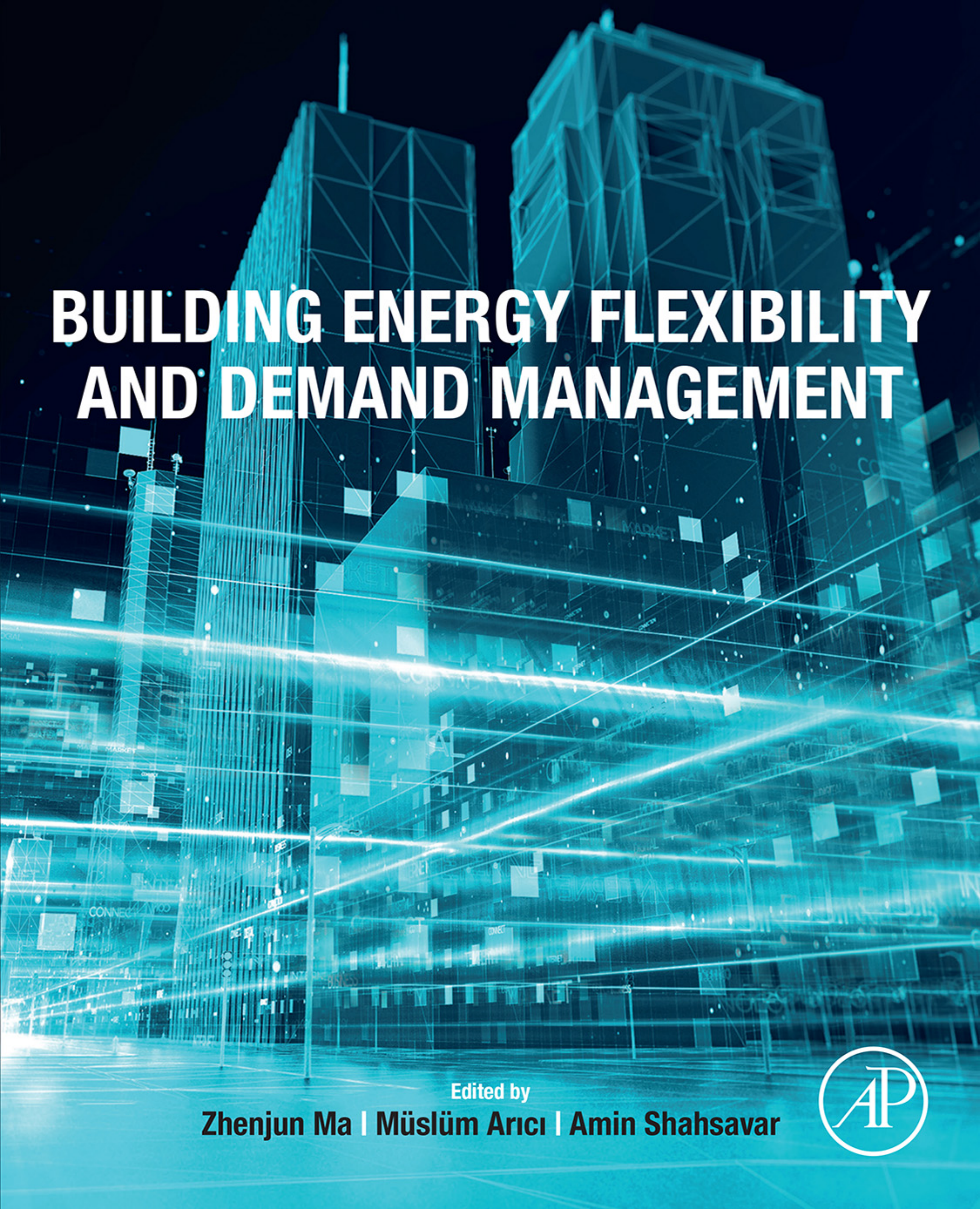

BUILDING ENERGY FLEXIBILITY AND DEMAND MANAGEMENT

Edited by
Zhenjun Ma | Müslüm Arıcı | Amin Shahsavar

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Edited by

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Preface

Global warming, climate change, and the shortage of conventional fossil fuels are among the main challenges to creating a more sustainable future and achieving many of the United Nations' Sustainable Development Goals. The implementation of a worldwide commitment to achieve the net-zero emissions target will call for a range of innovations to address these global imperatives and stringent environmental standards related to increased energy efficiency, resilience, and sustainability and demonstrate how we can build a more sustainable society. According to the 2021 Global Status Report for Buildings and Construction [1], buildings are responsible for 36% of global final energy consumption and 37% of energy-related CO_2 emissions. Building energy consumption is expected to continuously increase due to the rising population, improved living standards, wide access to air-conditioning systems in developing countries, and growing ownership of smart appliances. This increasing energy demand and the likelihood of extreme weather events will pose significant challenges to existing electricity infrastructure.

On the other hand, buildings can be a part of the solutions to address these challenges and achieve deep decarbonization. Building energy flexibility, which is the ability of a building to manage and modify its energy demand profile, has been highlighted as a distributed resource showing great promise at the level of the end users to provide grid support services and significantly reduce building energy costs, and it is an emerging strategy allowing more active engagement of buildings in the operation and control of electrical power systems. High penetration of intermittent renewable energy sources in buildings has created a great need for increased demand flexibility and has intensified the calls for effective demand response programs to mitigate the mismatch between energy supply and demand. However, this approach will require new technologies and innovative solutions to identify, quantify, model, optimize, and manage demand flexibility to effectively engage with customers and interact with the power grids and will also require a deep understanding of mechanisms governing demand flexibility. Previous investigations into the energy flexibility of electrical grids from the supply side are numerous and extensive. Nonetheless, there is significant research and information gap on the demand side although significant efforts have been made to accelerate building demand flexibility over the last several years, and this concept has recently started to draw increasing attention and is becoming an increasingly viable strategy to assist in shifting from conventional supply-side management to demand response and demand-side management. The increasing use of this concept and the lack of a suitable reference in this field are the main drivers that encouraged us to prepare this book.

This book consists of two sections (i.e., Section I and Section II), which include a total of 11 chapters. Section I consists of four chapters that present the foundational information and methods associated with building energy flexibility and demand management. In Chapter 1, an attempt has been made to describe the relationship between building energy consumption and the concept of sustainability and to explain why building energy flexibility is an essential need in today's world. Chapter 2 mainly introduces the concept of building energy flexibility, energy-flexible sources in buildings, and energy flexibility indicators as well as energy flexibility quantification. A case study was also presented as an example to demonstrate how to calculate building energy flexibility potential. In Chapter 3, the main modeling methods (i.e., traditional building performance simulation and emerging data-driven modeling) are first introduced. How to use optimization methods to determine cost-effective energy-flexible systems is then discussed. Demand response is a change in the consumption profiles of end users to balance energy supply and demand and is becoming an integral part of demand-side management. Chapter 4 is, therefore, dedicated to building demand response and demand-side management and provides insights into main demand-side management options commonly used in practice to encourage end users to actively participate in managing their consumption. Section II of the book is dedicated to emerging technologies and case studies for enhanced building energy flexibility, and it consists of seven chapters. Thermal energy storage, which can store heat or cold and use it later when needed, can play a significant role in increasing building energy flexibility. Hence, Chapter 5 discusses different forms of thermal energy storage and how thermal energy storage can contribute to building energy flexibility. Potential limitations associated with the use of thermal energy storage are also discussed. The role of renewable energies such as solar, wind, and geothermal in building energy flexibility is discussed in Chapter 6. Chapter 7 provides an overview of heat pumps and discusses how heat pumps can be integrated with heat sources or heat storage at the building level and how they can contribute to improving building and network operating flexibility. Chapter 8 introduces district heating and cooling systems and discusses the relationship between energy flexibility and district heating and cooling. A smart grid is a digitally enabled electrical grid and has shown great advantages to provide timely, efficient, and uninterrupted electric power to consumers. The flexibility concept of smart power grids and the most crucial challenges and opportunities related to smart grids and flexibility are discussed in Chapter 9. A case study is also introduced to evaluate the role of energy flexibility in the smart grid energy system. Chapter 10 presents a case study to quantify the energy flexibility potential of a net-zero energy office building using photovoltaic panels and an electric storage system. The potential of using other energy-flexible measures implemented in the building to enhance energy flexibility is also discussed. Finally, the market mechanisms and flexible interaction between buildings and power grids are discussed in Chapter 11. The application characteristics and key technologies used to increase the energy flexibility of a nearly zero energy building are also presented in this chapter.

The chapters presented in this book have a chain relation from the first to the last chapter, and we hope that this book can be a useful reference for potential readers who wish to work on this new concept to develop and support a highly electrified, renewables-based clean energy future, generate significant economic and environmental benefits through facilitating high penetration of renewable energy in buildings to mitigate global warming and climate change, and accelerate the transition to a low carbon energy future.

Zhenjun Ma
Müslüm Arıcı
Amin Shahsavar

Reference

[1] United Nations Environment Programme. 2021 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector. Nairobi; 2021.

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SECTION I

Foundational information and methods

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CHAPTER

1

Building energy and environmental sustainability

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Despite repeated warnings about the warming of planet Earth and the ensuing problems and calamities, the statistics show rising global energy demand and consumption. In addition, levels of carbon dioxide in the atmosphere, as well as other key greenhouse gases such as methane and nitrous oxide, are all rising. If these trends continue unchecked, the problems arising from global warming, such as the changes in climatic conditions and the melting of glaciers and ice caps, will intensify and the planet Earth will eventually turn into an inhabitable place. To deal with these problems, a global resolution and endeavor are needed to reduce the per capita consumption of energy and to cut down on the burning of fossil fuels, which are the main source of carbon dioxide emissions. Buildings can play a significant role in this issue because they use about 40% of global energy and they emit approximately 33% of greenhouse gas emissions. This chapter examines the environmental impact of buildings and describes how environmental sustainability can be considered during the design, construction, and operation of buildings. This issue is very important and this chapter can be a guide for engineers and designers to consider the issue of environmental sustainability when designing a building and selecting its equipment.

1.1 Introduction

According to the estimates in 2019, energy used in the construction sector comprising residential and commercial sectors, accounts for 35% of global energy consumption

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(Fig. 1.1) [1]. The Energy Information Administration (EIA) predicted that global energy consumption in buildings will grow by an average of 1.3% per year from 2018 to 2050 [1]. The EIA also predicted that in non-OECD (Organization for Economic Co-operation and Development) countries, electricity consumption in buildings would increase by more than 2% or roughly 5 times the growth of building electricity consumption in OECD countries (Fig. 1.2) [1].

Electricity, as the primary energy source for lighting, air conditioning, tools, and equipment, has the fastest growth among the other energy sources in residential and commercial buildings. The EIA expected that population growth and rising living standards in non-OECD countries would increase the demand for electricity consumables and personal appliances [1]. The EIA expected that in the first years of the 2020s, the total electricity consumption in buildings in non-OECD countries would exceed that in OECD countries [1]. In 2019, building thermal and electrical energy consumption led to the emission of

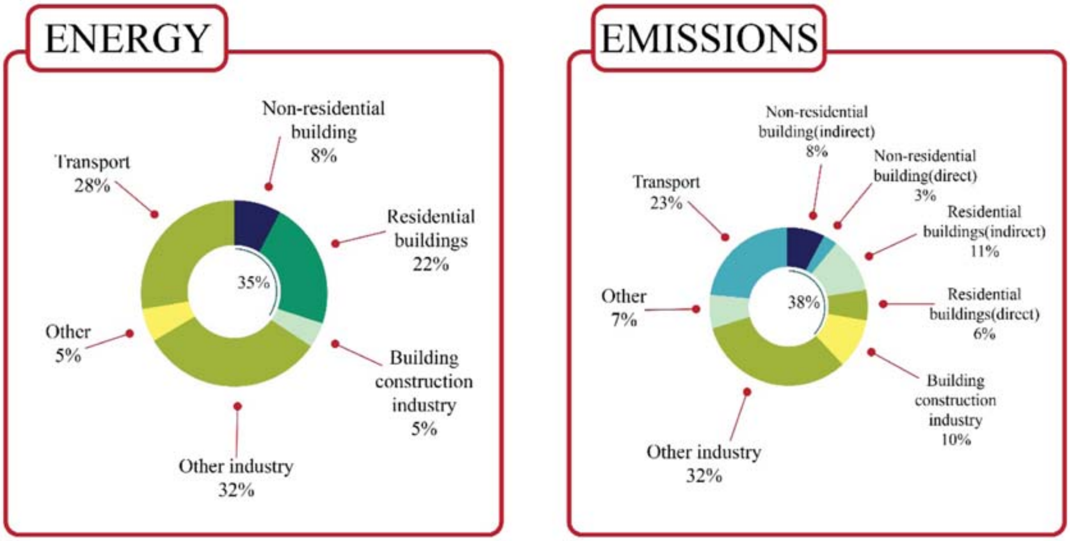

FIGURE 1.1 Global share of building and construction final energy and emissions, 2019 [1].

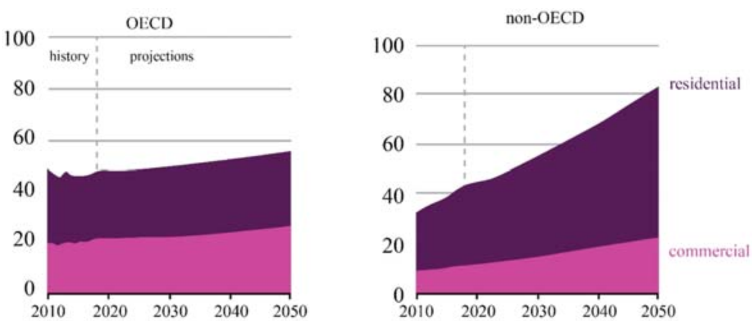

FIGURE 1.2 Building sector energy consumption (quadrillion British thermal units) [1].

10 Gt of carbon dioxide, directly and indirectly, the highest amount ever recorded [2]. The main factors involved in this issue were the increase in air conditioners and extreme hot and cold climates in different parts of the world. Of course, this increase in carbon dioxide emissions could have been avoided if there had been a solid determination to adopt effective policies on energy efficiency and appropriate investment in sustainable buildings and renewable energy sources. In 2020, energy-related carbon dioxide emissions from buildings were reduced to 9 Gt due to the impact of the Covid-19 pandemic [2]. The pandemic led to teleworking and the closure of schools, universities, hotels, and restaurants, which reduced energy demand and thus carbon dioxide emissions in the services sector. Studies have shown that the impact of the pandemic on greenhouse gas emissions has been limited to one break, and its efficiency has been largely lost. The greenhouse gas emissions in 2021 returned to the prepandemic levels [2].

The situations mentioned above confront us with alarming facts. If this trend continues, it cannot be imagined that the earth will be a good place for human life for the next few decades. A global decision must be made to reform energy consumption patterns in all sectors, especially the building and construction sector, and all countries should adhere to this. In this regard, paying more attention to implementing sustainability in building design, construction, and utilization would pave the way.

1.2 Sustainability concept

Sustainability refers to a situation in which human societies and other live ecosystems on the planet can maintain the possibility and capacity to sustain a long-term presence in a cohesive, pluralistic, and fertile manner. In a more general sense, sustainability indicates the bearing capacity of systems or processes. The concept of sustainability usually encompasses various areas such as ecology, economics, politics, and culture, and achieving it requires considering inherent or desirable characteristics.

The term sustainable development was introduced into the environmental literature in a report entitled "Our Common Future," or the "Brundtland Report" [3], in April 1987. However, the first use of the term sustainable development was attributed to Barbara Ward in the mid-1970s. This general concept was widely used in the global conservation strategy to manage the protection of natural resources and the environment to better role-play in human welfare. Sustainable development is, in fact, the balance between development and environmental protection. Sustainability can exist in four aspects: society, environment, culture, and economy. The concept of sustainable development focuses not only on the environmental dimension but also on social and economic sustainability. Furthermore, sustainable development is a crossroads between society, economy, and environment.

1.3 Sustainable building design

New concepts have emerged in the architecture and construction industry in recent years, including sustainable architecture, green architecture, and zero energy buildings. As a result, terms such as sustainable and green buildings have become common. Although these concepts differ from a professional perspective, many sources emphasize their similarities and are sometimes used interchangeably. The reason for the semantic similarity of these concepts is the emphasis of all energy efficiency and environmental friendliness. This section examines the concept of sustainable design, its principles, advantages, and its role as a human ecosystem.

The concept of sustainability in the form of sustainable architecture can date back to more than three decades ago, in the mid-1980s, by the World Environment Committee. The principle of sustainable architecture emphasizes humans and the environment and believes that the building, as part of nature's ecosystem, should be included in the life cycle. Thus, sustainable architecture does not only focus on construction but also considers nature's various cultural, social, economic, and environmental dimensions simultaneously. For sustainable buildings, we must pay attention to various aspects of construction in the life cycle of the building.

1.3.1 Sustainable buildings, green buildings, and zero energy buildings

Despite many similarities between sustainable and green architecture, green architecture is based on the environment, while sustainable architecture, besides environmental factors, also considers human existence and coexistence with the interior and exterior of the building from different dimensions. According to the US Environmental Protection Agency and the World Green Building Council, a green building is environmentally friendly, socially responsible, and economically justifiable throughout its life cycle. Although, according to the existing definitions, the concept of green buildings is very close to sustainable buildings, in green buildings and zero energy buildings, more emphasis is placed on the environment and energy consumption. On the contrary, the principle of building design for humans is also considered in sustainable buildings, except for environmental and energy consumption considerations. In this case, if human needs are not considered as a formative and sustainable element of this ecosystem, even with criteria such as reducing energy consumption and environmental issues, sustainable construction will remain unused and does not make sense.

1.3.2 Principles and features of sustainable buildings

At least the following three steps are required to develop a sustainable building:

- Save resources.
- Designed to return to the life cycle.
- Design for humans.

In this regard, sustainable building design contributes to resource efficiency, minimal energy expenditure, flexibility, and longevity. According to these prerequisites, in a sustainable building, the following principles and characteristics should be considered:

- Meeting the physical and mental needs of building occupants: The most distinctive feature of a sustainable building that sets it apart from other modern buildings is the emphasis on meeting human needs.
- Fuel efficiency: Sustainable construction should minimize fossil fuel utilization, use alternative energy sources such as solar energy, and reduce visual and noise pollution to some extent.
- Reduce the use of new resources: A sustainable building should be designed to be used as a new resource for the new building after its useful life.
- Climate-friendly: A sustainable building must be compatible with the energy and climatic resources of the construction site.
- Coordination with the site and environment: The consistency of a sustainable building with its surroundings is essential.
- Totalitarianism: In all its principles, sustainable construction must have a holistic approach to creating a healthy environment and move in this direction.

1.3.3 Methods of realizing sustainable construction

The question now is how can these principles be achieved? How can sustainable construction be realized in practice? How can this increase the useful life of a building? To answer these questions, we must pay attention to sustainable buildings from different perspectives and take appropriate actions for each section.

- Energy: Use of renewable energy sources, mainly sun and wind, and the least possible consumption of fossil fuels.
- Materials: Using nonchemical, durable, and locally sourced recyclable materials whose production, consumption, and destruction are compatible with the environment while reducing the production of construction waste.
- Insulation: Thermal and acoustic insulation.
- Lighting: Proper lighting and design of windows as well as efficient lighting without wasting energy.
- Nature and the environment: Respect for nature and use of its potential, noninterference, nonenvironmental damage, reducing carbon dioxide emissions, and using natural plants as inspiration for the living design.
- Quality and cost: Increasing the life of the building using new technologies despite increasing initial costs, having a long-term investment attitude rather than short-term vision and intermediation, saving costs in the long run due to energy efficiency optimization, damage less against accidents, and increased building security.
- From a human point of view and a sense of the environment: a positive sense of place, avoidance of disturbance, attention to human life, and improvement of physical and mental condition and regional and cultural identity.

1.3.4 Advantages of sustainable buildings

At first glance, the use of new technologies in the construction industry, including innovative materials for sustainable building design and increasing the cost of the building due to the uncommon use of these technologies, can be justified. According to experts and designers of sustainable buildings, these buildings, because of principles of optimized energy utilization and the employment of recycled or reusable materials, in addition to creating a positive and pleasant feeling in today's modern living space, in general, increase the life and quality of the building.

1.4 Sustainable energy technologies

This section evaluates sustainable energy technologies that fall into two categories: energy production and energy conservation. Energy production considers potential green energy sources that are environmentally friendly, long-term, and safe for people and the environment. Energy conservation is one of the oldest architectural issues in history, and it remains crucial for all buildings.

1.4.1 Energy production

The following resources, which are not reliant on fossil fuels, stabilize rather than degrade the ecosystem and inspire a solid dedication to architecture:

- Bioenergy
- Solar energy
- Geothermal energy
- Wind energy
- Hybrid energy systems

1.4.2 Energy conservation

Energy conservation in buildings is the decline in building energy consumption without compromising occupant thermal comfort and affecting building key functional requirements. This refers to but is not limited to the reduction in electric power, heating, and cooling energy, replacing incandescent and other old bulbs with new and energy-efficient LEDs, installing light and thermal sensors and timers, regulating and rethinking HVAC usage, deploying building automation and control, and engaging the occupants to realize the outcome of the solutions. These energy conservation measures have been frequently deployed to existing buildings to improve operational performance.

1.5 Government policies

Many nations are now struggling with implementing and adopting integrated measures, programs, and policies to incorporate resource efficiency, adaptation, and climate change mitigation into their built environment. President von der Lahne, for example, launched the New European Bauhaus (NEB) project in his 2020 statement in January 2021 [4].

The NEB is an economical, environmental, and cultural initiative that aspires to produce a European green contract by combining design, sustainability, cost-effectiveness, accessibility, and investment. Sustainability, esthetics, and inclusivity are the main objectives of the NEB. Despite these exciting efforts, one of the most significant challenges in constructing this new model of sustainable buildings is the ongoing concerns about taxes, finance, and long-term depreciation. Nevertheless, stockholders have difficulty in constructing sustainable buildings due to high initial capital expenses and lower market value than traditional buildings. Furthermore, the dispersion of capabilities across multiple levels of government, central, regional, and local authorities, and numerous players in this process may delay the effective creation of sustainable structures. Many governments worldwide are putting policies in place to encourage sustainable construction. These drivers are generally either monetary (obliging the user to implement specified sustainability requirements) or voluntary (offering incentives via subsidies or other sustainable construction methods).

European governments, like Spain, have set up loans and subsidies to build new buildings and update existing ones. A project called the New Green Savings Program, in the amount of CZK 2 billion, was paid to 9088 projects for reconstructing buildings in the Czech Republic [5]. In Finland, the rules are that the owner must obtain an Energy Certificate when someone wants to buy or rent a building [6]. The Land and Building Use Act (Finland) also assures that water and land regions and building operations produce favorable living standards and develop environmentally, socially, culturally, and economically sustainable development. While there are no special incentives for the building itself, the U.K. government pays the total amount for purchasing qualified devices to reduce energy consumption [7]. There are several incentives for green construction in France. For instance, buildings certified to be low in energy consumption will receive a 100% or less tax exemption. The Dutch government encourages entrepreneurs to buy sustainable equipment through the environmental investment allowance and arbitrary depreciation environmental investments (Vamil) incentive plans. These plans are in the field of environmental investment and depreciation of sustainable equipment, respectively. Poland's national fund for water management and environmental protection provides incentive programs for buildings or buying energy-efficient homes [8]. In Portugal, improving the sustainability of a property can lead to the cancellation of the property's transfer tax [9]. Switzerland's "Building Program" encourages home renovations to enhance walls, windows, roofs, and floors. Regional programs have been introduced in Canada, like in Hamilton, where a new, sustainable building will be eligible for a property tax exemption of up to 75% [10]. New buildings in Colombia must save a certain amount of water and energy each year, depending on the location of the building [11]. The government encourages municipalities to pay incentives to save water and energy. In Mexico, the government does not provide financial support for sustainable construction, which is the municipalities' responsibility. For example, in Mexico City, certified sustainable structures are eligible for property tax savings [11]. The same situation is valid for New Zealand, with the difference that the Building Council of New Zealand, instead of paying financial aid, shows its support by providing tools and systems [12].

1.6 Relevant codes, regulations, and standards

This section reviews some of the most important certificates and standards in the green building field. The reviewed standards are the most popular worldwide, in countries with different climatic conditions and continents. These standards include BREEAM from the United Kingdom, LEED and WELL from the United States, Green Globes from Canada, and Comprehensive Assessment System for Built Environment Efficiency (CASBEE) from Japan (Table 1.1).

1.6.1 BREEAM standard

The BREEAM rating system is the most common system for assessing the sustainability of buildings in the United Kingdom and more than 70 other countries, which was established in 1990 and has issued more than 555,000 certificates [13]. This standard places a building based on the type of use in eight groups: residential, office, commercial, educational, industrial, medical, court, and prison. Some of the main characteristics of measuring sustainability in the BREEAM system are comprised of recycling and reuse of materials, building hygiene, use of low carbon or zero-carbon energy production technologies, quality and air conditioning, water protection and wastewater recycling, lighting, security, and easy access to public transportation.

1.6.2 LEED standard

One of the institutions active in the field of green construction is the United States Green Building Association, which was established in 1994 under the sponsorships of the Environmental Committee of the American Institute of Architecture, and developed a LEED (leading standard in environmental and energy design) green building ranking system. LEED is one of the most prominent ranking systems with the required standard for green buildings and has been used in 82,000 projects in 162 countries, including Asia and Oceania [14]. From 1994 to 2015, the LEED changed from a building standard operating institute to a comprehensive system covering all aspects of large buildings' design, construction, maintenance, and operation. LEED started with a committee of 6 volunteers and currently consists of 120,000 employees and professional volunteers and has certified for

TABLE 1.1 Certificates and standards are reviewed in the order of year of operation.

Standard	Main country (continent)	Year of operation
BREEAM	United Kingdom (Europe)	1990
LEED	United States (America)	1994
Green Globes	Canada (America)	2000
CASBEE	Japan (Asia)	2001
WELL	United States (America)	2014

7.1 billion square meters of buildings worldwide. The ability to design in the form of LEED certification standards is critical and has been raised as one of the conditions of employment, especially in the United States. This certificate was issued in 2000 by the American Green Building Association for any building type and dimensions. LEED can be used for all building types, including new and newly constructed buildings, existing buildings, commercial spaces, building blocks, schools, and homes. It should be noted, however, that this certification is also being tested on several neighborhood unit projects, sanitary facilities, and retailers.

1.6.3 Green Globes building standard

Green Globes is an online rating and certification system for green buildings, first established in 2000 by the Energy and Environment Agency of Canada and in 2004 by the GBI (Green Building Initiative) complied with ANSI (American National Standard Institute) standards and has been used in the United States [15]. The emergence of the Green Globes standard was similar to the LEED system and many other systems worldwide. The Green Globes system can be used to evaluate new constructions for a wide range of buildings, including offices, schools, hospitals, hotels, scientific and industrial facilities, warehouses, laboratories, sports venues, and residential buildings. The goals of setting up this system include the following:

- Evaluating energy and environmental performance of the building.
- Encouraging careful inspection of design and management methods.
- Increasing awareness of environmental issues among building owners, designers, and managers.
- Providing practical plans for improvement in different stages of project delivery.
- Presenting certificates and awards for designing and managing green buildings.

1.6.4 Comprehensive Assessment System for Built Environment Efficiency building standard

A research team established the CASBEE in 2001 in collaboration with the universities, industrial groups, and the government of Japan [16]. This system was created to increase people's quality of life and reduce the use of life cycle resources and environmental burdens. The Japanese government has now extended various schemes of this assessment standard throughout its cities. According to the definition of the Japan Architects Association, a sustainable building is a building that is designed with the following characteristics: (1) saving energy and resources, recycling materials, and minimizing the release of toxic substances during their lifetime; (2) compatibility with local climate, customs, culture, and environment; and (3) be able to improve the quality of human life while maintaining the capacity of global and regional ecosystems. The Institute for Building Environment and Energy Conservation implemented CASBEE cities for the first time in Japanese municipalities to develop agenda plans and support an understanding of regional features. The program started in 2008, and the first version was released in 2011. Subsequent editions were published in 2012 and 2013 after re-editing. The recent CASBEE program in the Future Cities Initiative project, launched by the Government of Japan, was used to monitor the development of future cities, through which all municipalities were evaluated, and the results were published as a research paper. Following these results, a pilot version for use by all world cities was presented in 2015 at the Paris City Conference - the 21st Conference of the Member States of the United Nations Framework Convention on Climate Change.

1.6.5 WELL (IWBI) building standard

During the last decade, especially in the standardization of green buildings, significant steps have been taken towards the evolution of the construction industry and the expansion of environmentally friendly buildings worldwide, although relatively fewer standards were in the field [17]. There has been an increase in human health and well-being. The time has come for significant activities to be carried out to improve the health of communities in the construction industry. In addition to its essential role in reducing land pollution, it also leads human lives to greater welfare. Americans spend more than 90% of their time at home, work, schools, stores, sports centers, and healthcare. Therefore, they are most often exposed to the interiors of buildings. However, most people are unaware that these buildings and everything in their interior can affect well-being and health. That is why Delos, a leading building health company, established the WELL Building Standard. The WELL standard is the product of a 7-year study on the sanitation of the interior of buildings, which was officially launched in October 2014 after a comprehensive review by some experts and was awarded IWBI (International WELL Building Institute) certification. This standard is one of the first of its kind that focuses only on the health of the occupants of the building. The WELL building standard measures certifies and performs building features that affect human health and well-being. To achieve better standards, a process should be performed to evaluate the spaces in a location designated by a third party. Delos, in collaboration with Mayo Clinic, one of the most prestigious centers and universities in the world of medicine, has launched the WELL Laboratory Center intending to study building environments and create healthier interiors for living, working, and having delight.

1.7 Global imperatives

Some global measures and guidelines are complementary to the sustainable building definition and objectives. The core of them are Sustainable Development Goals (SDGs) announced by United Nations and adopted by 193 countries in the Paris Accord (COP21). U.N. SDGs are a list of 17 goals calling and guiding the nations to preserve our planet while stimulating human prosperity. Accordingly, the goals interlink primary social demands comprising equality, education, job opportunities, and health with environment preservation by handling global warming. These goals are at the core of the 2030 Agenda for Sustainable Development, which U.N. members adopted in 2015. The 17 goals of U.N. SDGs are shown in Fig. 1.3.

FIGURE 1.3 17 SDGs of United Nations [18]. *SDGs*, Sustainable Development Goals.

Achieving sustainable buildings can contribute to meeting the above goals. Strictly speaking, the SDGs are solidly interwoven with the building sector so that sustainable buildings can pave the way to achieve them. Although there is an interlinkage between all of the goals and sustainable buildings, the following ones are the most achievable goals in line with sustainable buildings.

SDG 3: Good health and well-being

This goal aims to "ensure healthy lives and promote well-being for all ages" [18]. There is currently clear evidence that sustainable buildings can contribute to achieving this goal. According to the World Health Organization statistics, lung and respiratory diseases due to deficient indoor air quality are among the primary causes of death. Sustainable building characteristics comprising improved lighting, air quality, and greenery have been confirmed to improve health and well-being.

SDG 6: Clean water and sanitation

This goal "ensures availability and sustainable management of water and sanitation for all" [18]. The construction and building sectors affect clean water and sanitation significantly. It is reported that building operations comprise about 12% of total water use in the US. Sustainable buildings have the potential to save resources like water through appropriate plumping and wastewater management.

SDG 7: Affordable and clean energy

This goal is "ensure access to affordable, reliable, sustainable and modern energy for all" [18]. Sustainable buildings can affect to achieve this goal in two ways. The first one is deceased energy use through energy savings from efficient equipment. The second is a result of employing renewable resources in a sustainable building as local resources. Energy efficiency combined with local, distributed, and renewable energy resources also improves energy security and resilience. It can be stated that sustainable buildings are at the forefront of achieving this goal.

SDG 8: Decent work and economic growth

This goal addresses "promoting sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" [18]. In line with the steady growth of worldwide demand for sustainable demand, providing the staff, employees, and workers need to design, construct, inspect, and maintain them is a mandate. Strictly speaking, the whole cycle life of a sustainable building, from its conception to construction, operation, and even renovation, necessitates a broad diversity of skills and workforce, defining more opportunities for inclusive employment. In this way, sustainable buildings can improve economic growth through local jobs.

SDG 11: Sustainable cities and communities

This goal searches for "making cities inclusive, safe, resilient and sustainable" [18]. Buildings are the pillars of cities, and sustainable buildings are crucial to their long-term sustainability. Irrespective of the building type—homes, offices, schools, shops, or outdoor spaces—the built environment contributes to forming communities that necessitate their sustainability.

SDG 13: Climate action

This goal is to "take urgent action to combat climate change and its impacts" [18]. Sustainable buildings are a fundamental part of tackling climate change since the construction and building sectors are the primary producers of CO_2 emissions. Addressing a circular economy in building material usage and reliance on local and renewable resources are vital measures that sustainable buildings can contribute to climate action.

1.8 Summary

In this chapter, first, an introduction was given to the situation of energy consumption in the world, and it was concluded that there is no choice but to turn to sustainable development. Then, the concept of sustainability was introduced and described, and how to apply this concept in building designs was discussed. Finally, government regulations, policies, codes, and standards used in the field of sustainability were reviewed. As mentioned earlier in this chapter, adopting on-site generation to achieve a sustainable building is indispensable. These local resources are mainly based on renewables, primarily solar and wind energy. These systems' relatively lower capacity factor may be handled by hybridizing different hourly potential renewable resources or employing energy storage systems. On the other hand, the electrification of residential heating systems using heat pumps and the ongoing adoption of electric vehicles are steadily increasing. These factors have constituted an additional reason for the onward interest in the concept of energy flexibility of buildings besides their considerable share in the total energy consumption. Accordingly, harmonization between buildings and associated energy systems can offer more flexibility. Building energy flexibility is the ability to strategically modify energy usage from the typical consumption profile by responding to price signals or monetary incentives provided by the grid operators or aggregators. Building energy flexibility lacks a specific and widely-acknowledged definition primarily due to the diverse requirements and characteristics of an energy flexible building. This has been addressed in the subsequent chapter by providing concepts, indicators, and quantification methods for building energy flexibility.

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CHAPTER

2

Building energy flexibility: definitions, sources, indicators, and quantification methods

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High penetration of intermittent renewable energy resources has created a great need for increased flexibility on the demand side that would allow buildings and power grids to adapt to increasingly dynamic energy supply and demand conditions. Failure to adapt may carry serious electrical blackouts, particularly during summer heat wave episodes. To support the transition to a renewable energy future with fluctuating power generation, demand can be adjusted to the available power by incorporating energy flexible systems. The building sector accounts for a significant amount of global energy usage and offers great opportunities for energy flexibility. This chapter will introduce several aspects of building energy flexibility including energy flexibility definitions, sources, indicators, and quantification methods and discuss the importance of energy flexibility in reducing building operational costs and facilitating the penetration of renewable energy in buildings. The main elements of building energy flexibility will be discussed, and an overview of energy flexibility indicators and major energy flexibility quantification methods developed to date will be provided. The energy flexibility indicators will be categorized in terms of fundamental variables including time (i.e. duration or response time), capacity (i.e. the amount of energy that can be shifted or shed), cost, energy, and efficiency of the systems used. Lastly, a case study will be provided to demonstrate how to calculate the energy flexibility potential of a building that was conditioned by an air source heat pump and a thermal energy storage system.

Building Energy Flexibility and Demand Management
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2.1 Introduction

The foreseen reduction of available fossil fuels, the continued increase in global energy demand, and the irrefutable evidence of global warming and climate change along with the implementation of a worldwide commitment to reach the net-zero emissions target have greatly sharpened commercial interest in using renewable energy. The share of renewable energy resources in the global energy mix climbed up to 29% in 2020 [1] and it is expected that this number will continuously increase in the next several decades. The rising penetration of renewable energy resources will pose great challenges and uncertainty for the electrical grid in planning and optimizing power production, transmission, and distribution due to the intermittent nature of renewable energy generation. A strategic response to this challenge requires a shift from generation on-demand to consumption on-demand [2], and thus a bidirectional communication between end-users and power grids.

Bidirectional communication between the demand and supply sides is an emerging topic and has received significant applications in the building sector. The challenge of stabilizing the energy flow among consumers, power generators, and grids can be mitigated by exploring the energy flexibility of buildings. Buildings offer great flexible services and can provide unique opportunities for effective demand-side management and thermal comfort of occupants, particularly under extreme weather conditions when peak electricity demand occurs. It can also assist in reducing building energy costs and CO_2 emissions and accelerate the transition to a low-carbon energy future.

Depending on the electricity generation and consumption profiles and the requirement of the power grid operation, different levels of flexibility are required at different times and different time scales (duration) to support power grid operation. For instance, the Australian Energy Market Operator introduced Frequency Control Ancillary Services to maintain the frequency of the electrical power systems. It consists of different regulations and responses such as fast response (6 seconds), slow response (60 seconds), and delayed response (5 minutes) to handle the drop or rise in frequency of the power generation system because of the change in generation and consumption ratio. Similarly, other ancillary services such as Network Support and Control Ancillary Services, and System Restart Ancillary Services were also introduced to ensure the safety of the supply side [3]. Building energy systems including self-generation, energy storage and controllable loads can help meet the targets set by the electricity providers according to different flexibility requirements such as load covering, load shedding, load shifting, and load modulation.

The domain of building energy flexibility can be divided into eight categories as shown in Fig. 2.1 [4]. These categories include driving forces (i.e., why energy flexibility is needed or what benefits a building energy flexibility plan can offer), definitions (i.e., how building energy flexibility can be defined, and what characteristics can be considered to represent the interaction of systems and personals in defining building energy flexibility), methods (i.e., how to characterize and quantify building energy flexibility), energy demand, infrastructure (i.e., type of buildings and power systems), stakeholders, technologies (e.g., electric vehicles, building energy and storage systems, power generation systems), and control (i.e., type of control schemes to modulate energy systems to achieve optimized flexibility).

FIGURE 2.1 Categorization of building energy flexibility domain.

2.2 Building energy flexibility: definitions, driving forces, and stakeholders

2.2.1 Energy flexibility definitions

Building energy flexibility, also named building demand flexibility, is a progressive form of demand-side management techniques. It has been receiving increased attention due to its capability to manage dynamic demand and renewable-based power generation. It can also facilitate the usage of modern controllers such as model predictive controllers to achieve building optimized operation. However, due to the lack of an international framework for building energy flexibility, several different definitions have been reported, which were mainly focused on specific tasks rather than a standardized definition.

In the report of the International Energy Agency (IEA) Annex 67, building energy flexibility was defined as the ability of a building to manage its demand and generation according to user needs, energy network requirements, and local climate conditions [2]. In a report published by the International Renewable Energy Agency: Demand-side flexibility for power sector transformation, demand flexibility was defined as part of the demand that could be altered (i.e., reduced, increased, or shifted) in a specific period of time via reshaping the load profiles to match renewable energy generation or via load shifting and peak demand reduction [5]. In a report prepared by the European Smart Grids Task Force, demand flexibility was categorized into implicit demand flexibility and explicit demand flexibility. Implicit demand flexibility was defined as the reaction of consumers to price signals by adapting their behaviors to save energy costs, while explicit demand flexibility was defined as the committed, dispatchable flexibility that can be traded on different energy markets, which needs to be facilitated and managed by an aggregator [6]. Although the above three definitions were slightly different from each other, they all focused on the same principle to change the demand profile in a specific period of time by using different flexibility types (e.g., on-site generation, load shifting, load shedding, peak demand reduction, and load modulation) to meet the requirements of power grids and reduce building operational costs.

2.2.2 Driving forces

The main task of a building energy flexibility plan is to ensure that a building adapts to the power generation pattern without jeopardizing occupants' thermal comfort and other functional requirements while reducing building operational costs and facilitating power grid optimization. The following factors make building energy flexibility plans attractive for different stakeholders.

2.2.2.1 *Decarbonization*

Global temperature rise is one of the leading challenges of the 21st century. Environmental pollution has resulted in extreme weather conditions such as droughts, floods, heat waves, and heavy storms. It will also likely hit the world economy with a loss of 18% by the mid-century if no action is taken [7]. The Paris Agreement set a target to keep the world temperature rise preferably below 1.5°C and strictly below 2.0°C by the mid-century as compared to the preindustrial level to mitigate the adverse effects of environmental changes [8]. Considering that a large share of global emissions is from the building sector, it is important to significantly reduce building emissions to help achieve this target [9]. Research has shown that the implementation of a building energy flexibility plan can greatly help mitigate building emissions without significant investment [10].

2.2.2.2 *Grid safety*

Grid safety is critical to ensuring a continuous supply of electricity to consumers. The rising trend of solar systems has switched end-users from consumers to prosumers, that is, consumers not only buy electricity from the grid but may also sell electricity to the grid [4]. To stabilize the supply from the grid to buildings and from buildings to the grid, it is important to have a management plan that can effectively create a balance between supply and demand without affecting grid or building operations.

2.2.2.3 *Cost-saving*

Another main driving force behind the need for a building energy flexibility plan is the energy cost reduction for consumers. Rising utility prices pose economical pressure on consumers, and it can also have an impact on the economic development of a country [11,12]. For instance, the Australian Energy Regulator recently announced that the benchmark electricity prices will increase by up to 18.3% for New South Wales residential customers, largely due to a significant increase in wholesale electricity costs over the past year [13]. Hence, the cost-saving factor generates another exigency for the implementation of a building energy flexibility plan. Building operational costs can be greatly reduced by effectively using building energy flexibility via demand management strategies such as load shifting, load shedding, and load regulation.

2.2.2.4 *Decentralization*

Decentralized power plants are considered more resilient and environmentally friendly, less expensive because of the low infrastructure cost, low operational cost, and more efficient because of low line losses, reliability, and flexibility [14]. Moreover, decentralization of power generation systems can help avoid a complete nationwide blackout. To achieve decentralization, optimized management of building energy and storage systems is vital that can be effectively achieved by using building energy flexibility plans.

2.2.3 Interactions between different stakeholders

Different stakeholders including government, service providers/aggregators, and consumers are involved in the successful implementation of a building energy flexibility plan. Consumers can be divided into residential and nonresidential classes. The residential class further includes single-family and multifamily spaces, whereas the nonresidential class can be divided into the industrial and nonindustrial sectors. A report published by Expert Group 3 (EG3) of the European Smart Grids Task Force further characterized service providers as Balance Responsible Party, Balance Service Provider, Congestion/Grid Capacity Management Service Provider, Distribution System Operator and Transmission System Operator [6].

Fig. 2.2 shows an implementation plan for demand flexibility by considering the interactions among different stakeholders. The government body is responsible for suggesting a demand flexibility plan and approving the respective budget. The budget and plan are shared with the aggregators. Consumers are directly linked with aggregators or service providers, and the stability of a demand flexibility plan highly depends upon the

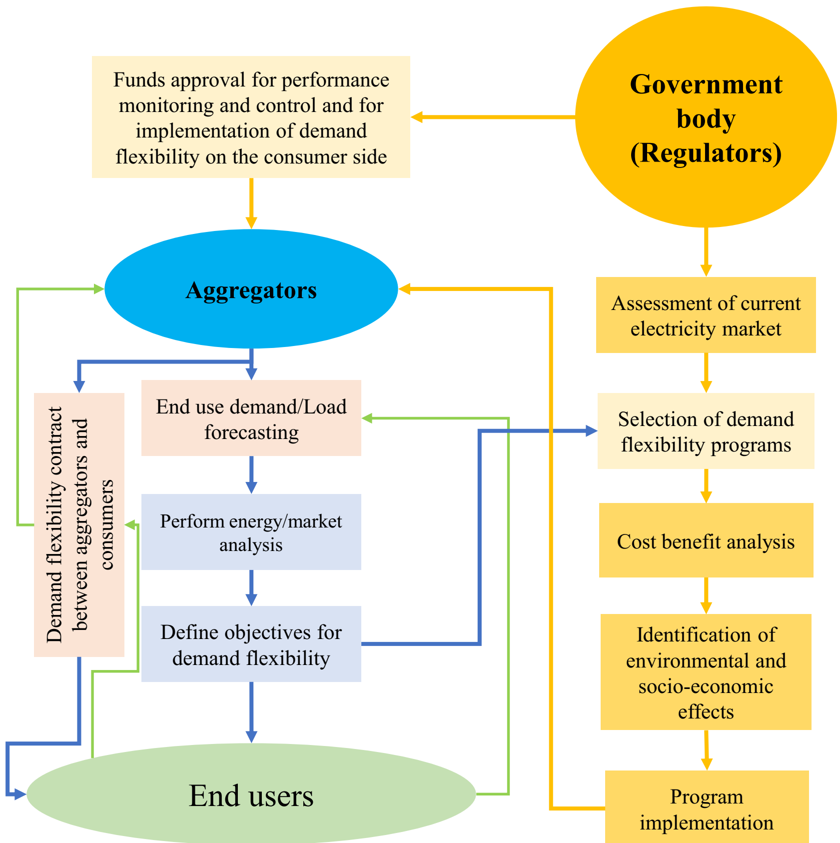

FIGURE 2.2 Role of different stakeholders in implementing a building energy flexibility plan.

consumers and aggregators. With the constantly rising energy demand, complex patterns of energy consumption, and renewable energy-based generation, the demand flexibility plan needs to be updated regularly. For that purpose, the aggregator has the responsibility to closely monitor external variables such as weather conditions, end-user demand trends, and generation patterns. Based on this data, energy and market analysis needs to be performed to help fine-tune building energy flexibility objectives. Sharing this information with the government authority will help achieve increased flexibility and future improvements in the generation and transmission infrastructure.

Fig. 2.3 illustrates a general procedure to implement a building energy flexibility plan on the consumers/end-users side. This six-step strategy includes defining desired objectives, load categorization, data collection, identification of energy flexible measures, quantification of energy flexibility, and optimization of energy flexible measures.

Different objectives including grid stability, increased share of renewable energy in the total energy mix, cost reduction, increased self-consumption, load reduction, load shifting, and emission reduction can be used to form an energy flexibility plan on the demand side. For example, distributors may be interested in improving grid stability and achieving peak-load reduction, while regulators may be interested in reducing emissions and increasing the renewable energy share in the national energy mix. On the consumer side, an increase in self-consumption, cost reduction, and load reduction can be considered to be the leading objectives. To meet all these objectives, building load categorization is necessary to better understand the load characteristics. A building can have different types of loads including shiftable and nonshiftable loads, thermostatically and nonthermostatically controlled loads, and curtailable and noncurtailable loads. Load categorization can help

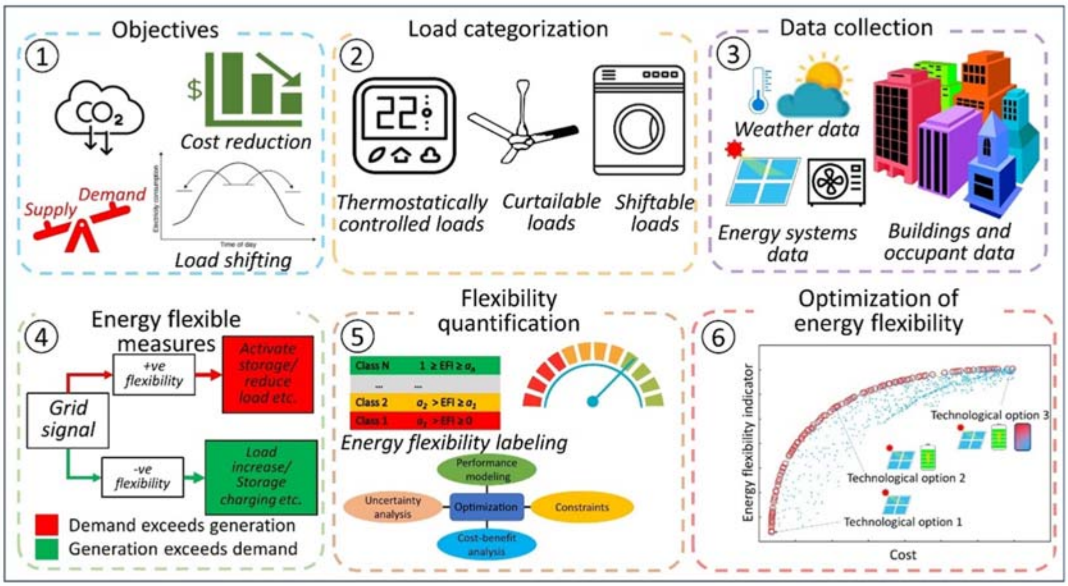

FIGURE 2.3 Implementation plan of demand flexibility for end-users. *EFI*, Energy flexibility indicator.

identify flexible sources inside a building. This step can also help identify different energy flexible measures in Step 4. The next step is to collect data related to buildings and building energy systems. The main data can include but is not limited to weather data, building materials data, energy bill data, occupancy schedule, equipment usage data, electricity usage profiles, gas usage profiles, hot water consumption data, desired thermal comfort temperatures, and share of renewable and nonrenewable consumption/generation. Once data collection is completed, energy flexible measures such as optimal controllers, storage in building thermal mass, storage in the sensible/latent thermal energy storage tanks, electrical energy storage, setpoint changes, delayed operation, and preheating/precooling can be applied. To gauge the effectiveness of energy flexible measures, quantification of the applied energy flexible measures is an important process. Various energy flexibility indicators suitable for a particular application can be used for quantification purposes. Details about energy flexibility indicators and quantification methods are presented in Section 2.3.2 and Section 2.4, respectively. Lastly, optimization can be carried out to identify and determine the optimal sizes of energy flexible systems. Different technological options and combinations can also be compared to optimize the flexibility potential of a building [15]. It is noted that this optimization is focused on the design and sizing of energy flexible systems during the design stage. How to optimize the use of energy flexibility offered by the energy flexible systems during the building operation stage is a different issue and is often achieved by the optimization embedded in demand management strategies. Data can also be shared with the aggregators to ensure grid stability under dynamic generation and consumption patterns and facilitate better energy demand forecasting.

2.3 Building energy flexibility: sources and indicators

2.3.1 Sources of energy flexibility in buildings

Identification of energy flexible sources in buildings is essential to unlocking the flexibility potential of a building. Different types of buildings and building energy systems offer different levels of flexibility. Both residential and nonresidential buildings have several different sources of energy flexibility. However, residential buildings can provide more tolerance and susceptibility to an energy flexibility plan [16]. For instance, load shifting in the industrial sector can disrupt production but in residential buildings, it will not cause much disruption. Potential sources of building energy flexibility are illustrated in Fig. 2.4. Buildings can supply flexible services in different ways such as the utilization of building thermal mass, changes in the operating schedules and set points of heating, ventilation, and air conditioning (HVAC) systems, optimization of charging and discharging of electrical and thermal energy storage, and shifting of plug loads (e.g., electrical appliances). This adaptable behavior is an important element to provide unique opportunities for effective demand-side management and thermal comfort of occupants, particularly under extreme weather conditions.

Building energy flexible sources can be divided into three categories including generation sources, consumption sources (loads), and storage sources. The potential energy

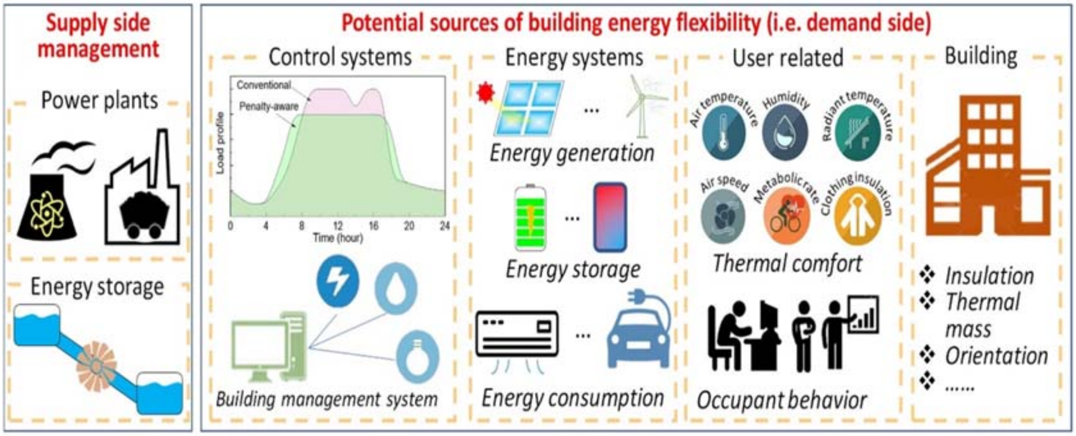

FIGURE 2.4 Potential energy flexible sources from buildings for demand-side management.

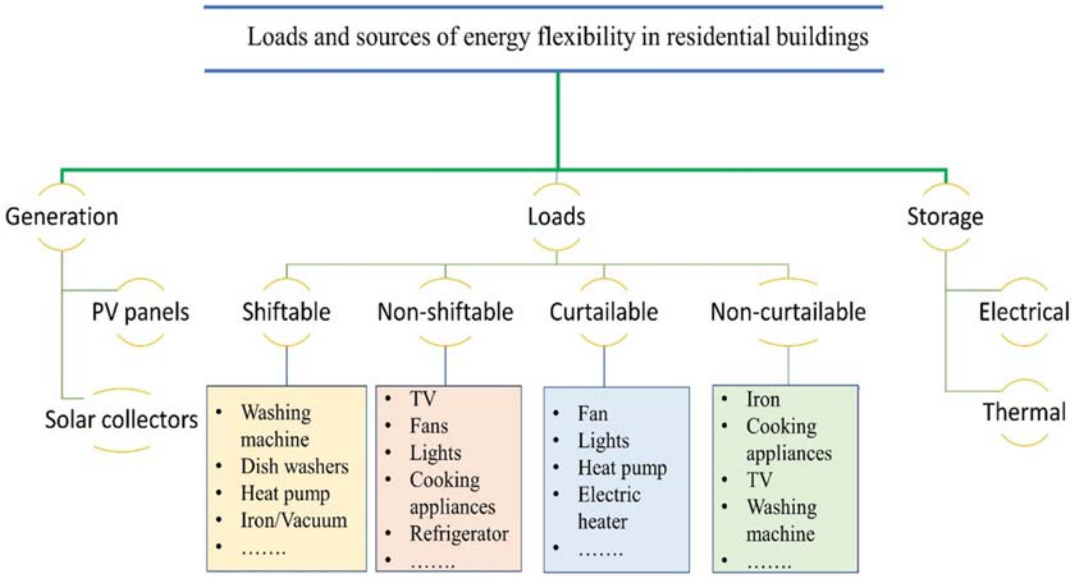

FIGURE 2.5 Categorization of energy flexible sources in residential buildings.

flexible sources for residential buildings are illustrated in Fig. 2.5. Shiftable loads are the loads that can be completely or partially shifted from the peak demand period to the off-peak demand period without significantly compromising the thermal comfort of occupants and impacting the operation of essential equipment and facilities, while nonshiftable loads are the loads that cannot be shifted to the off-peak demand period without disrupting the occupants' thermal comfort and other building functional requirements. Similarly, curtailable loads are the loads that can be reduced during peak demand periods, while noncurtailable loads are the loads that cannot be modulated during peak demand periods without disrupting the thermal comfort of building occupants and the operation of essential equipment. Building loads identified either as shiftable or curtailable can be considered part of a flexibility plan in business as usual case, that is, no thermal or electrical energy storage and/or no self-generation available for the building. Other energy flexible sources presented in Fig. 2.5, such as energy generation by using solar photovoltaic panels and solar thermal collectors, and energy storage technologies such as thermal energy storage in building thermal mass, sensible and latent heat storage tanks, and electrical energy storage can be used to provide flexibility to the nonflexible loads. Nonshiftable or partially shiftable loads could be made shiftable by using thermal or electrical energy storage technologies. For instance, heat pumps can be used to charge thermal energy storage systems during the off-peak demand period, and the building cooling/heating load during the peak demand period can be covered by discharging thermal energy storage. In general, the use of energy storage and on-site energy generation systems can significantly enhance the flexibility potential of a building. These systems are essential for reducing building emissions and supporting grid operation and optimization. An energy flexibility plan for a residential building without storage and self-generation can often compromise the comfort of the occupants.

2.3.2 Energy flexibility indicators

Energy flexibility indicators are considered to be an important component in a flexibility plan to gauge the performance and effectiveness of an energy flexibility measure and provide insights for better decision-making. A building energy flexibility plan includes cross-sectoral and multisystem interaction. Many energy flexibility indicators have been formulated and used to evaluate the flexibility potential of various energy flexible systems involved in an energy flexibility plan. As presented in Section 2.3.1, the flexibility on the building side is dependent on three main sources, including energy generation, energy storage, and shiftable and/or curtailable loads. Hence, the formulated energy flexibility indicators should be able to evaluate the performance of these sources and the effect of these sources on the overall flexibility potential of a building. Five key factors including time, power/energy, capacity/amount, cost, and efficiency/effectiveness have been frequently used in the formulation of building energy flexibility indicators. Each of these factors can be used to present several aspects of building energy flexibility. For instance, the capacity factor can be used to estimate the amount of energy shifted and it can also be used to estimate the charging state of a thermal energy storage system after providing flexibility to a building. To gauge the success of a flexibility plan, all of these factors should be evaluated by using appropriate energy flexibility indicators. Among these five key factors, time is the most important parameter to formulate energy

TABLE 2.1 Summary of key factors used in the formulation of building energy flexibility indicators.

Key factor	Description
Time	• Demand response period, that is, flexibility activation period • Response time • Charging period • Discharging period, etc.
Power/energy	• Energy-saving potential • Self-generation potential • Self-consumption potential • Power reduction potential • Power shifting/shedding potential, etc.
Capacity/amount	• Storage capacity • Amount of emissions reduced • Comfort compromised • Maximum hourly surplus • Maximum hourly deficit, etc.
Cost	• Cost reduction potential
Efficiency/effectiveness	• Effectiveness of a flexibility plan • Flexible energy efficiency • Storage efficiency, etc.

flexibility indicators, as a flexibility plan is highly dependent on the response time, activation time, and demand response period. Hence, to formulate an energy flexibility indicator, the temporal domain of the flexibility plan should be considered. Details about these factors are presented in Table 2.1.

These key factors can be used to formulate different energy flexibility indicators such as optimum cost factor, available structural storage capacity, rebound energy, flexibility index of aggregated demand, power shifting capability, loss of load probability, and many other energy flexibility indicators as those reported in [4,17]. Table 2.2 summarizes the major flexibility indicators that can be used to evaluate the flexibility potential of a building and building energy flexible systems and the interaction with the power grid.

Although energy flexibility indicators developed to date can represent the flexibility potential of a building or building energy systems under dynamic conditions and specific flexibility plans, some of them have limitations in terms of providing collective information related to the interactions among different stakeholders. Under an energy flexibility plan, if an energy flexibility indicator is just to provide information about a single objective such as cost reduction or load reduction, it may then only provide limited opportunities for operational improvements. Furthermore, a specific value of flexibility obtained in a building cannot guarantee similar results in other buildings because of disregarding external variables such as weather conditions, occupant behavior, and state of energy systems in formulating the energy flexibility indicators. Hence, energy flexibility indicators should be further developed to rationally and reliably evaluate the energy flexibility offered by buildings or building energy systems.

TABLE 2.2 Summary of main energy flexibility indicators developed for building demand flexibility.

Application	Indicator	Factors covered					Formulation and description
		Time	*Power*	*Cost*	*Capacity*	*Efficiency*	
Building level	Demand response potential [18]	✓	✓		✓		$DR_i = \frac{P_{i,b} - P_{i,DR}}{P_{i,b}}$ where i represents the ith appliance, $P_{i,b}$ is the average baseline power during a DR event, and $P_{i,\ DR}$ is the power consumption by using flexible measures.
	Self-sufficiency [19]	✓	✓		✓		$\gamma_l = \frac{\int_{t1}^{t2} \min[G(t) - S(t) - \zeta(t), l(t)]dt}{\int_{t1}^{t2} l(t)dt}$ where ζ represents energy losses, G is the generation, l is the building demand and S is the storage.
	Self-consumption [19]	✓	✓		✓		$\gamma_s = \frac{\int_{t1}^{t2} \min[G(t) - S(t) - \zeta(t), l(t)]dt}{\int_{t1}^{t2} G(t)dt}$
	Flexibility factor [20]	✓	✓		✓		$FF_{f,e} = \frac{E_{f,e}^{+} - E_{f,e}^{-}}{E_{f,e}^{+} + E_{f,e}^{-}}$ $FF_{d,\ e} = \frac{E_{d,e}^{+} - E_{d,e}^{-}}{E_{d,e}^{+} + E_{d,e}^{-}}$ where f and d are forced and delayed, respectively; $+$ and $-$ indicate the system operated with and without using energy flexible measures, respectively.
	Flexibility index [21]	✓	✓	✓	✓		$FI = 1 - \frac{C^1}{C^0}$; $C^1 = \sum_{t=0}^{N} \sigma_t \quad u_t^1$; $C^0 = \sum_{t=0}^{N} \sigma_t \quad u_t^0$ where C represents the cost, u_t^1 and u_t^0 respectively represent energy consumption at time t under the penalty aware control and penalty-ignorant control, and σ_t is the penalty on the energy consumption at time t.
	Flexibility indicator of aggregate demand [22]		✓		✓		$\mathrm{F}_{\Delta t_s}^{(a)} = 2 \times \min_{\forall \omega_{\Delta t_s}^{(a)}} (\omega_{\Delta t_s}^{(a)}, (1 - \omega_{\Delta t_s}^{(a)}))$, *with* $\mathrm{F}_{\Delta t_s}^{(a)} \epsilon \quad [0, 1]$ where $\omega_{\Delta t_s}^{(a)}$ and $(1 - \omega_{\Delta t_s}^{(a)})$ represent the binomial probability of increase and nonincrease in demand respectively, and a represents the number of aggregating customers.
	Percentage flexibility level [22]		✓		✓		$\psi_{\Delta t_{s\%}}^{(a)} = \frac{\overline{\Delta p}_{\Delta t_s +}^{(a)} - \overline{\Delta p}_{\Delta t_s -}^{(a)}}{\overline{p}_{\Delta t_s}^{(a)}} \left(\frac{\mathrm{F}_{\Delta t_s}^{(a)}}{2} \right) \times 100$ where $\overline{\Delta p}_{\Delta t_s +}^{(a)}$ and $\overline{\Delta p}_{\Delta t_s -}^{(a)}$ are the mean load variations for the increase and nonincrease in demand respectively, and $\overline{p}_{\Delta t_s +}^{(a)}$ is the mean aggregate demand.
	Energy flexibility [23]	✓	✓		✓		$EF_d(t) = \int_{t1}^{t2} (P_{inflex}(t) - P_{min}(t))dt$
	Power shifting flexibility [24]	✓	✓		✓		$r_{shift} = \frac{P_{shifted}}{P_{demand}}$

(*Continued*)

TABLE 2.2 (Continued)

Application	Indicator	Factors covered: Time	Power	Cost	Capacity	Efficiency	Formulation and description
	Rebound energy [25]	✓	✓		✓		$E_{rb} = \int_{-\infty}^{t_{DR,start}} (P_{DR} - P_{ref})dt + \int_{t_{DR,end}}^{+\infty} (P_{DR} - P_{ref})dt$ where DR represents the demand response event.
	Flexible energy efficiency [25]		✓			✓	$\eta_f = \left\lvert \frac{E_f}{E_{rb}} \right\rvert \times 100\%$
Grid	Grid interaction index [26]	✓	✓		✓		$f_{grid} = STD\left[\frac{E_i}{Max\lvert E_i \rvert}\right]$ where E is the net energy export to the grid at time interval i, and STD is the representation of standard deviation.
	One percent peak power [27]	✓	✓		✓		$OPP(kW) = \frac{P_{1\%Peak}}{\Delta t(h)/100}$
	Absolute grid support coefficient [28]	✓	✓		✓		$GSC = \frac{\sum_{i=1}^{n} P_{el}^i G^i}{P_{el}\overline{G}}$ where P_{el}^i and G^i respectively represent the electricity consumption and value of the grid signal at the time step i, n represents the total number of time steps, and P_{el} and $\overline{G}$ are the average values in a period of interest.
Building energy systems	Flexibility of building thermal mass [29]	✓	✓		✓	✓	$F_{TM} = \frac{\sum_{i=1}^{n} \alpha_i C_i \Delta T}{t_{DR} COP_{HVAC}}$ where α_i is the heat release ratio of thermal mass, ΔT is the thermal comfort temperature range, C_i is the total heat capacity of thermal mass, and COP is the HVAC coefficient of performance.
	Flexibility of HVAC systems [29]	✓	✓		✓	✓	$F_{HVAC} = F_{TM} + \frac{\left[k_0 P_{lights} + \left(\frac{\rho_a V_r c_a}{t_{DR}} + U_A + \dot{m} c_a\right)\Delta T\right]}{COP_{HVAC}}$ where $k_0 P_{lights}$ is the heat gain reduction from lights, and ρ_a, V_r, c_a, U_A *and* $\dot{m}$ represent the air density, volume of the thermal zone, air-specific heat, overall heat transfer coefficient, and mass flow rate of fresh air, respectively.
	Shifting efficiency of building thermal mass [30]				✓	✓	$\eta = \frac{\Delta Q_{discharged}}{\Delta Q_{charged}}$
	Flexibility of thermal storage tanks [29]	✓	✓		✓	✓	$F_{T.S} = \frac{\left[\frac{\rho_w V_{tank} c_w \left(T_{tank,t_0} - T_{tank,t_{DR}}\right)}{t_{DR}}\right]}{COP_{HVAC}}$ where T_{tank} represents the temperature of the tank.

Flexibility of electrical battery-based load [31]	✓		✓		$F_{ES} = \frac{(t_{use} - t) - (t_f - t)}{t_{use} - t}$ where t, t_{use} and t_f respectively represent the current time, the time when the fully charged battery will be used, and the expected time to complete charging based on charging status.
Flexibility of lights [29]		✓	✓		$F_{lights} = k_0 P_{lights}$ where P_{lights} represents the lights load and k_0 represents the lights' dimming rate with the value of one indicating that lights can be completely turned off.
Flexibility of appliances [29]	✓	✓	✓		$F_{app} = \sum_{i=1}^{n} P_i(t).K_i(t)$ where $P_i(t)$ and $K_i(t)$ respectively represent the power and flexibility state of the appliance.
Flexibility of occupant behavior [29]	✓	✓	✓	✓	$F_{OB} = \frac{\Delta T_{extra}\left(\sum_{i=1}^{n}\frac{\alpha_i C_i}{t_{DR}} + \frac{\rho_a V_r c_a}{t_{DR}} + U_A + \dot{m} c_a\right)}{COP_{HVAC}}$ where ΔT_{extra} represents the difference between the upper limit of the recommended temperature range and the maximum temperature that occupants can accept for cooling applications.
Flexibility index of combined cooling, heating, and power system [32]		✓	✓		$FI = \left(w_{gas}\frac{U_{gb}^{no} - U_{gb}}{U_{gb}^{no}} + w_{grid}\frac{P_{grid}^{no} - P_{grid}}{P_{grid}^{no}}\right) \times 100$ where w represents weight, U_{gb} and P_{grid} respectively represent natural gas usage of the boiler and interactive power (i.e., sum of power purchased from and sold to the grid) between the system and grid, and U_{gb}^{no} and P_{grid}^{no} respectively represent the fuel consumption of the gas boiler and interactive power without storage devices.
Flexibility of wind power-based system [33]	✓	✓	✓		$F_{E.A} = \sum_{i \epsilon A}^{n}\left[\frac{P_{max}(i)}{\sum P_{max}(i)} \times \frac{0.5[P_{max}(i) - P_{min}(i)] + 0.5[Ramp(i).\Delta t]}{P_{max}(i)}\right]$ where $P_{max}(i)$ and $P_{min}(i)$ respectively represent the maximum capacity and the minimum stable generation of the conventional generator i. $0.5[Ramp(i)]$ represents the average value of ramp up and ramp down.

2.4 Building energy flexibility: quantification methods

Quantification of building energy flexibility is vital to assign a numeric value to the performance of an energy flexibility plan. A standardized quantification method can be used to evaluate and optimize the flexibility potential of a building and it can also be used to compare the performance of a building with other buildings under similar energy flexibility plans. As shown in Fig. 2.6, there are eight main factors, including power grid requirement, utility tariff, flexibility types, demand response strategies, energy flexible measures, constraints, uncertainties, and the selection and aggregation of energy flexibility indicators, that are governing the development of a quantification method.

To support power grid operation, an energy flexibility plan must control the kVA demand of the building according to the requirement of the power grid. kVA is a measure of apparent power and helps maintain the frequency of the power generation system according to the preset limits. To maintain the frequency, a grid-responsive building should be able to increase or decrease its consumption according to the grid needs which can be achieved by optimizing and controlling the operation of building energy flexibility sources. Service providers monitor and predict generation and demand patterns and develop different tariffs accordingly with the main focus on cost penalties and benefits for consumers. These tariff profiles are then used to facilitate the development of different demand response programs and flexibility types such as load shifting, load shedding, and load covering. Buildings working under a flexibility plan can respond with different capacities and at different periods of time to these demand response programs by controlling the operation of energy flexible systems while considering system constraints and uncertainties. The performance of energy flexible measures needs to be evaluated by using appropriate energy flexibility indicators in relation to other factors. Furthermore, aggregation is required if multiple energy flexibility indicators are used to quantify the overall response of the building to the grid requirement.

A number of building energy flexibility quantification methods or frameworks have been reported in the open literature, which were mainly developed to quantify the

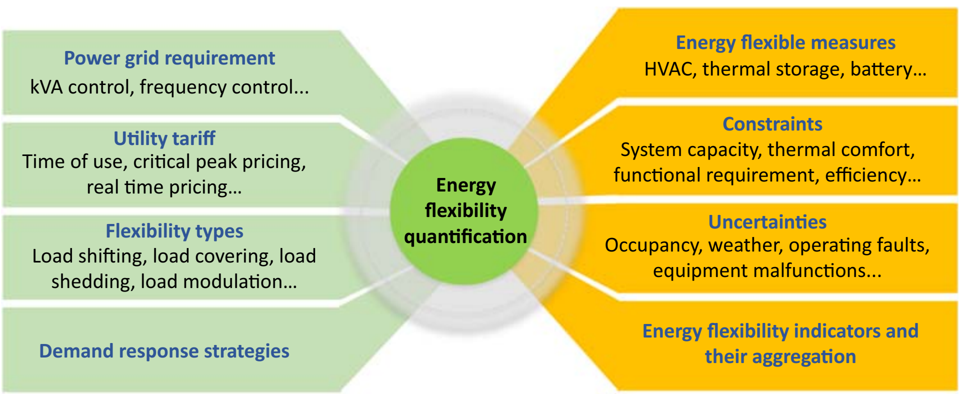

FIGURE 2.6 Factors for quantification of building energy flexibility.

flexible response of buildings or building energy systems according to the need of a specific study. For instance, Yin et al. [18] proposed a demand response estimation framework to quantify the flexibility potential of residential and commercial buildings by using setpoint changes. Based on the physical models developed, the demand response potential of thermostatically controlled loads was first determined and a simplified strategy based on a set of regression models which used an hour of the day, setpoint change, and outside air temperature as the inputs was then developed and used to estimate demand response potential. Stinner et al. [23] developed a methodology to quantify the flexibility potential of building energy systems with integrated thermal energy storage. The developed method can compare different flexibility options for building energy systems via the calculation of temporal flexibility, power flexibility, and energy flexibility through simulations. It was claimed that one of the main features of this methodology was the aggregation potential of the flexibility measures. Tang and Wang [24] presented a methodology, as shown in Fig. 2.7, to quantify the flexibility potential of grid-responsive buildings. The flexibility capacities and flexibility ratios were proposed and used as the flexibility indicators, which eventually resulted in generating a five-dimensional flexibility performance map. The results from a case study showed that this strategy can help achieve up to a 21% reduction in electricity costs.

Chen et al. [29] presented the quantification of energy flexibility offered by building thermal mass, HVAC systems, lighting, appliances, and occupant behaviors based on their mathematical expressions and by using the flexibility ratio as the indicator. Zhou et al. [32] developed a strategy, as shown in Fig. 2.8, to quantify and optimize the flexibility potential of combined cooling, heating, and power system by using a new flexibility index, which can reflect system design and operational performance. The flexibility

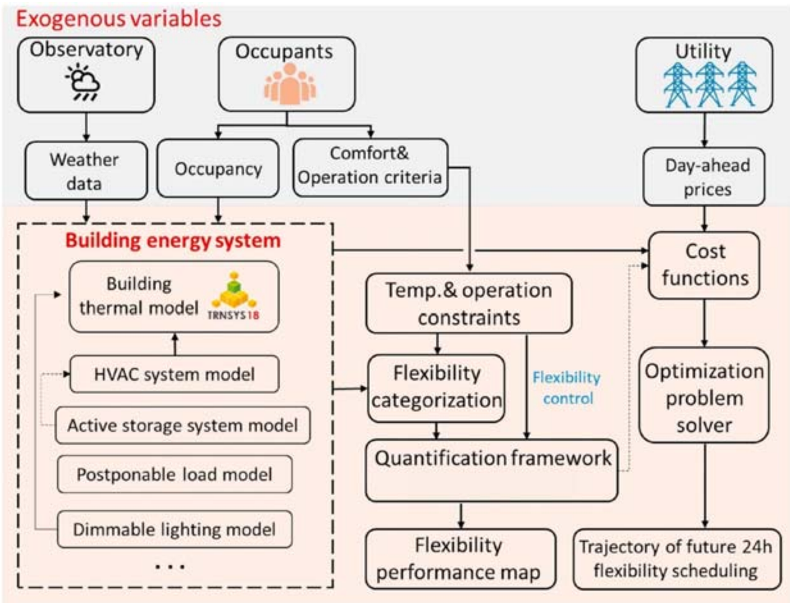

FIGURE 2.7 A strategy for energy flexibility quantification and schedule optimization [24].

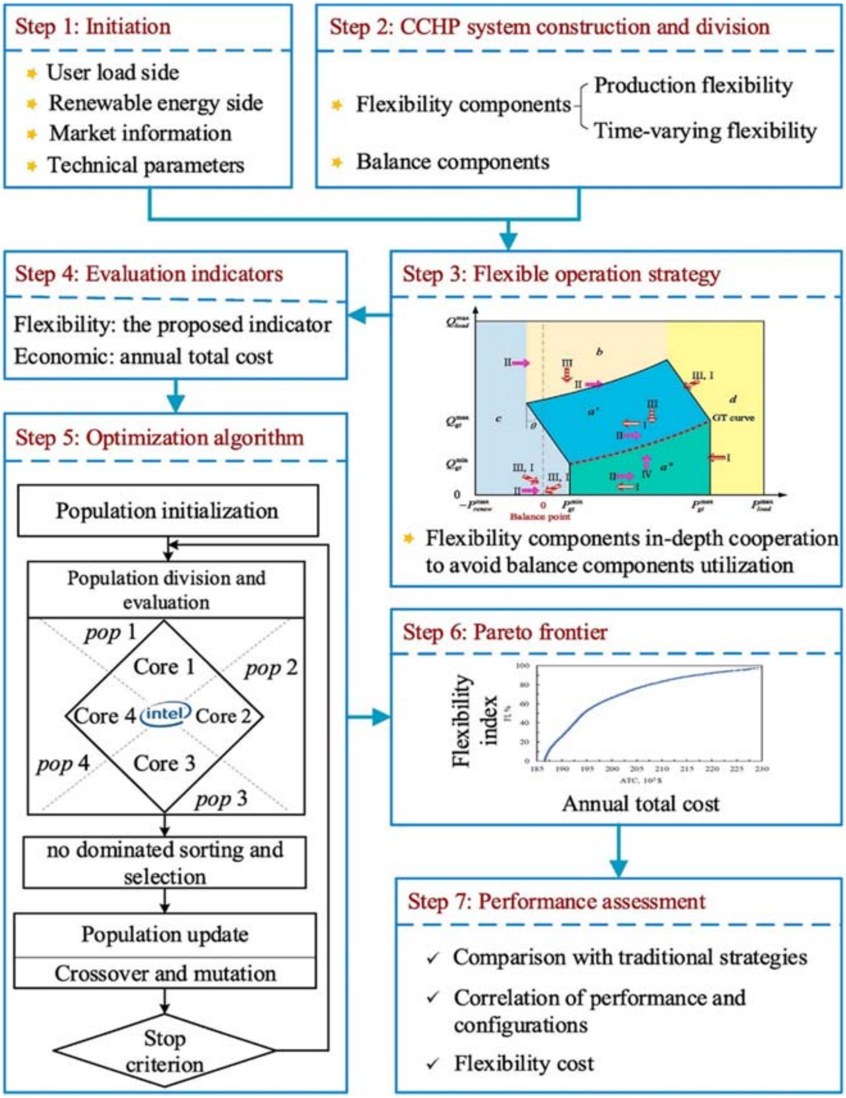

FIGURE 2.8 A strategy to evaluate and optimize the flexibility potential of a hybrid combined cooling, heating, and power system [32].

enhancement was achieved through optimization of system configuration and the use of appropriate operation strategies. It was shown that the uncertainties due to renewable energy generation and power demand can be well handled by the flexible components in the system.

Perera et al. [34] introduced a quantification method, as shown in Fig. 2.9, to evaluate the system's flexibility. A multicriteria decision-making method was used to aggregate different flexibility indicators to develop a single quantification function. A number of

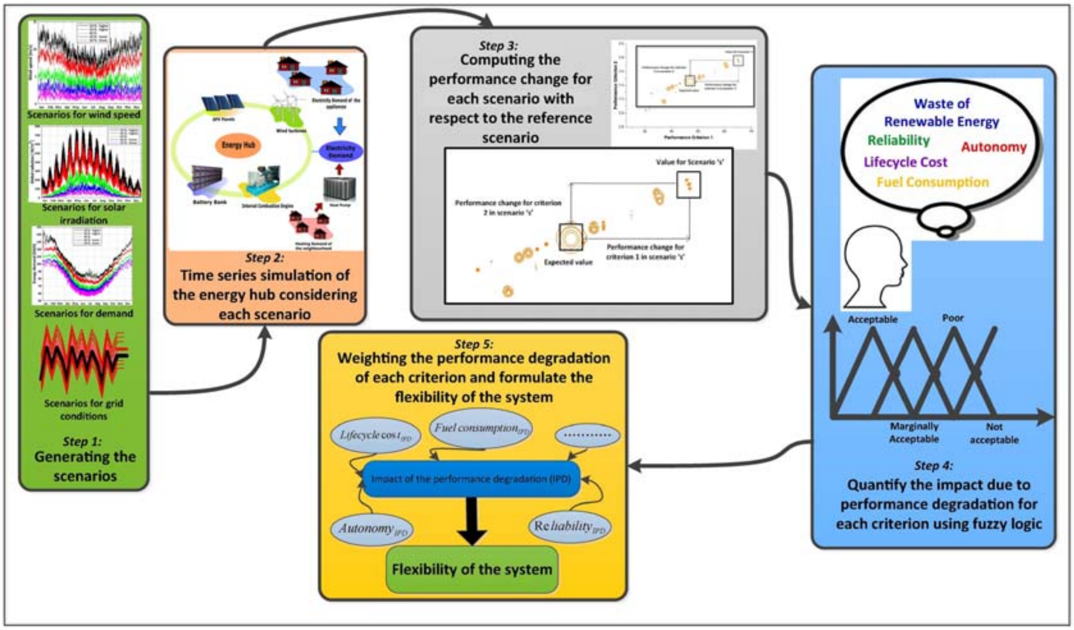

FIGURE 2.9 A method to evaluate system flexibility for distributed energy system design [34].

probabilistic scenarios for different grid conditions, energy demand, and renewable energy generation were simulated. It was concluded that more than 45% renewable energy covering with respect to the annual demand can be achieved. However, a decrease in the flexibility level was observed if the renewable energy penetration level was above 30%.

Bampoulas et al. [35] presented a framework to characterize and quantify the energy flexibility of residential buildings by taking into account possible interactions among different energy systems. Storage capacity, storage efficiency, and self-consumption were used as the energy flexibility indicators to generate daily energy flexibility maps, which can be used to quantitatively compare and evaluate the energy flexibility potential of different energy flexible options. De Coninck and Helsen [36] used a bottom-up approach to quantifying building energy flexibility, in which the range of flexibility was graphically represented in a cost curve. This method can quantify both the amount of energy that can be shifted and the cost associated with the energy shift. Homaei and Hamdy [37] introduced an energy flexibility quantification method by taking into account the trade-off between survivability and energy flexibility under the time of use tariffs. Different building flexibility indexes including the cost-effective flexibility index, survivability, savings index, and passive survivability index were used in the formulation of the quantification method.

Although a range of methods has been developed to quantify building energy flexibility, the majority of these methods were developed for a particular application and used different energy flexibility indicators to meet the demand for that particular application. There is no one-size-fits-all method that can be applied to different types of buildings and various energy flexible systems. Therefore, a generic quantification method is needed but the development of such a method in principle is quite challenging due to the unique characteristics of each building and its energy flexible systems and flexibility types required, as well as various constraints imposed for different applications.

2.5 Demonstration of building energy flexibility quantification

2.5.1 Description of the case study

A case study was designed to illustrate the significance of building energy flexibility in supporting power grid operation and reducing the operational cost of the building. The energy flexibility potential of a grid-connected building, which participated in the Middle East 2018 Solar Decathlon Competition was quantified under the weather conditions of Dubai, United Arab Emirates (UAE) through a simulation exercise. Fig. 2.10 illustrates the case study building and the air source heat pump and thermal energy storage system (i.e., two storage tanks) used for space cooling. The total floor area of the building is 92 m^2, which includes a conditioned space of 79 m^2. The thermal energy storage system was filled with a phase change material with a melting temperature of 10°C and its total storage capacity is 33.5 kWh, The HVAC system consists of an air source heat pump with a cooling capacity of 7.4 kW at the design conditions, a fan coil unit system, a dehumidification heat pump to deal with the latent load, and an enthalpy recovery ventilator.

In this demonstration, only the thermal energy storage system was considered in the flexibility plan to provide flexibility to the operation of the air source heat pump. A brief introduction to the main assumptions and parameters used in the simulation is presented as follows.

- During off-peak demand hours (7:30 p.m. to 9:30 a.m. of the next day), the HVAC system was used to condition the house and also charge the thermal energy storage system by using the air source heat pump.
- During peak demand hours (9:30 a.m. to 7:30 p.m.), the thermal energy storage system was used instead of the air source heat pump to condition the house along with other components of the HVAC system.

FIGURE 2.10 Illustration of the case study building, heat pump, and thermal storage tanks.

- The unit cost of electricity during off-peak demand hours was 0.14 USD/kWh and it was increased by 2.5 times during peak demand hours.
- The latent load of the building was handled by using the dehumidification heat pump, and hence the air source heat pump and thermal energy storage system were only used to handle the sensible load.
- For cooling applications, during inflexible operation mode (i.e., thermal energy storage system was not used), the air source heat pump was operated at a temperature setpoint of 10°C, whereas under flexible operation conditions, that is integration of the thermal energy storage system with the air source heat pump, the temperature setpoint of the air source heat pump was reduced to 5°C when it is used to charge the thermal energy storage tank. The supply air temperature for both scenarios was set at 16°C.
- Indoor air temperature and relative humidity were set at 24°C and 50%, respectively.
- In the simulation, the house was always occupied by two occupants. Hence, less energy consumption will be consumed in real applications, as compared to the simulation exercise.

2.5.2 Methodology

Fig. 2.11 shows the methodology used to quantify and calculate the energy flexibility potential of the case study building. Initially, the objective to implement an energy flexibility plan was identified, which was to reduce the operational cost of the building by reducing HVAC energy consumption during peak demand hours. The system variables

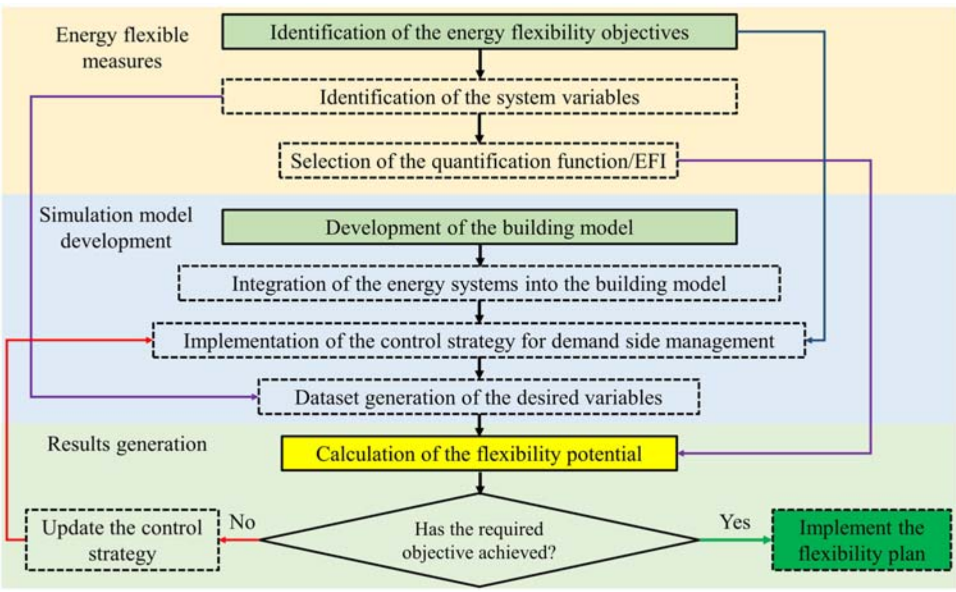

FIGURE 2.11 Illustration of quantifying/calculating flexibility potential of the case study building and its HVAC system.

including the power consumption and unit costs of electricity during peak and off-peak demand hours were then identified. Lastly, a quantification function was selected. In this case, cost-based and peak-load reduction-based flexibility indexes were calculated by using Eq. (2.1) and Eq. (2.2), respectively.

$$FI_C = 1 - \frac{\sum_{i=1}^{n} |P_i \times C_i|_{flex}}{\sum_{i=1}^{n} |P_i \times C_i|_{ref}} \quad \begin{cases} C = 0.14\dfrac{USD}{kWh}\text{during off} - \text{peak period} \\ C = 0.35\dfrac{USD}{kWh}\text{during peak period} \end{cases} \tag{2.1}$$

$$FI_{P_{peak}} = 1 - \frac{\sum_{i=1}^{n} |P_i|_{flex_{peak}}}{\sum_{i=1}^{n} |P_i|_{ref_{peak}}} \tag{2.2}$$

where C represents the unit cost of electricity, which is different for peak and off-peak times, and the subscripts i, *flex*, and *ref*, respectively represent the timestep, flexible operation, and inflexible operation.

In the second step, a building model was developed in SketchUp and was then imported into TRNBuild of the TRNSYS simulation program to define the internal loads, operational schedule of the building, and building energy systems, as well as other necessary building parameters. The simulation system was then developed in TRNSYS by integrating the HVAC system into the building model. Lastly, a control strategy was implemented to control the operation of building energy systems according to peak and off-peak schedules. The thermal energy storage system was used to handle the sensible cooling load of the building during the peak demand period, and during the off-peak demand period, the air source heat pump was used to handle the building's sensible cooling load and was also used to charge the thermal energy storage tanks. Lastly, the simulation system was used to generate a dataset of the desired variables based on the assumptions and parameters presented in Section 2.5.1. The dataset was generated based on the 24 h electricity consumption of the HVAC system during both peak and off-peak demand hours.

In the third step, the flexibility potential of the building was calculated based on the generated dataset of the HVAC power consumption with flexible and inflexible operations. The flexibility potential of the HVAC system was then quantified in terms of the flexibility indexes. Optimization of the flexibility potential can also be achieved by updating the control strategy but which was not considered in this case.

2.5.3 Results

The simulation was run for 24 hours from 7:30 p.m. to 7:30 p.m. of the next day. During the simulated period, the total sensible cooling demand was around 32 kWh, and hence the thermal energy storage tank was able to provide the desired cooling demand during the peak demand hours without compromising the comfort of the occupants as it has a maximal cooling capacity of 33.5 kWh. Fig. 2.12 shows the advantage of using thermal energy storage as an energy flexible system, which was generated by using the Flexibility

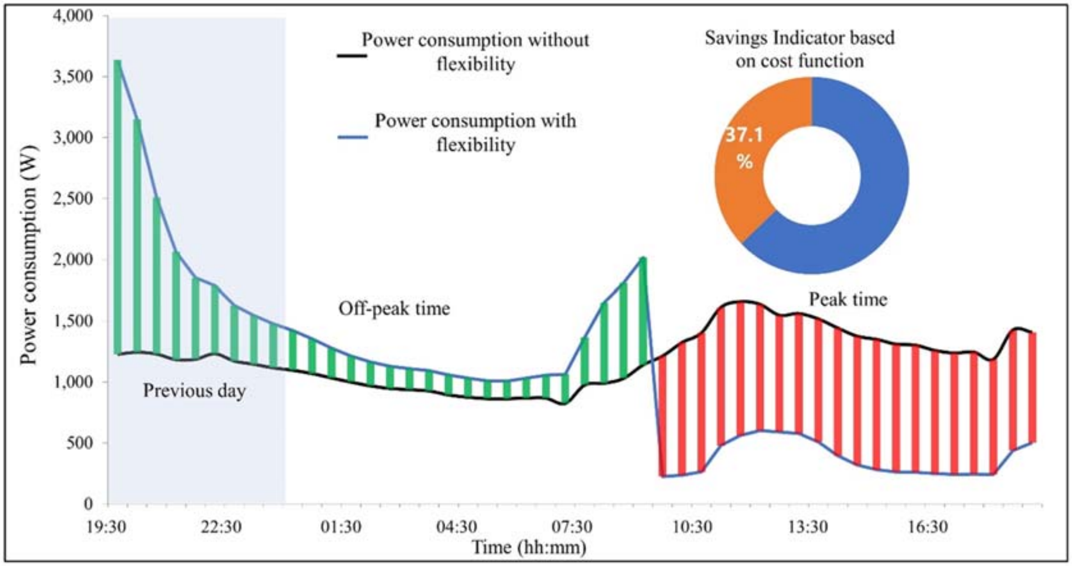

FIGURE 2.12 Power consumption profiles and cost savings under the flexibility plan.

Evaluation Tool developed through the IEA Annex 67 project [2]. The flexibility indexes in terms of cost savings and peak-load reduction were 0.371 and 0.73, respectively, which showed that the thermal energy storage system helped reduce the HVAC energy costs by 37.1% and reduced 73% of the peak electricity consumption, while the rest 27% of electricity was consumed by the water pump, fan, enthalpy recovery ventilator and the dehumidification heat pump during the peak demand period.

It is worthwhile to note that the purpose of the simulation exercise was to demonstrate the effectiveness of an energy flexibility plan to reduce building energy costs by decreasing energy consumption during peak demand periods. Optimization of the energy flexible sources was not considered in this study. Hence, further savings can be achieved by optimizing the operation of the building and its HVAC system. Moreover, a rebound effect was observed from 7:00 a.m. to 9:30 a.m., which can be avoided by terminating the charging of the thermal energy storage system before 7:00 a.m. Similarly, to avoid the rebound effect after 7:30 p.m., optimal control strategies can be used to modulate the charging rate so that charging of thermal energy storage can be more effectively distributed during the whole off-peak demand period.

2.6 Summary

This chapter first introduced the definitions and domain of building energy flexibility. Four main driving forces including decarbonization, grid safety, cost savings, and decentralization were identified for the need for a building energy flexibility plan. Furthermore, the role of different stakeholders was identified for the successful implementation of a building energy flexibility plan. A six-step strategy was then introduced to implement the energy flexibility plan on the consumer side. The sources of energy flexibility were identified and categorized into three categories including energy generation sources, energy storage sources, and building loads. To implement the energy flexibility plan, curtailable load and shiftable load should be identified, which can be used as potential sources of energy flexibility. Moreover, on-site energy generation and storage technologies are among the main sources of enhancing building energy flexibility. Energy flexibility indicators were also summarized based on their application type and in terms of key factors including time, power/energy, capacity/amount, cost, and efficiency/effectiveness. It was concluded that the available energy flexibility indicators can be used to assess the performance of buildings or building energy systems at the individual level but the utilization of these indicators as standardized functions needs further improvements, as most of the indicators developed to date were output based and mainly focused on the power consumption profiles, and ignored external variables such as environmental conditions, state of the systems, occupant behavior, and interactions among different systems.

Some of the available quantification methods were also reviewed, and factors considered in the development of a quantification method were identified. A case study was also performed to analyze the flexibility potential of an HVAC system integrated with a phase change material-based thermal energy storage system implemented in a grid-connected building. The effect of thermal energy storage on building energy flexibility was analyzed in terms of energy cost savings. The thermal energy storage system proved to be effective in not only reducing building energy costs but also reducing load during peak demand hours. The thermal energy storage system helped to achieve a total of 37.1% energy cost savings and 73% of the HVAC electricity consumption was also reduced during peak demand hours.

Conclusively, building energy flexibility can greatly support the penetration of renewable energy sources in buildings without affecting the stability of the power grid and the comfort of occupants if it is properly used and optimized. Appropriate energy flexibility indicators and quantification methods are essential for cost-effective optimization and utilization of energy flexibility in buildings.

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CHAPTER

3

Building energy flexibility: modeling and optimization

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Demand flexibility has been highlighted as a distributed resource showing great promise at the level of the end-user to provide grid support services and is an emerging strategy allowing more active engagement of the demand side in the operation and control of electrical power systems. Buildings can provide different levels of energy flexibility depending on the nature of the energy flexible systems used. How to appropriately model and optimize energy flexible systems is essential to providing cost-effective solutions for building energy management. This chapter will first introduce the main simulation methods, including traditional building performance simulation methods and emerging data-driven modeling methods. How to use these methods to appropriately simulate building energy flexibility will be discussed. An optimization process is generally required to determine and size the cost-effective energy flexible systems in order to meet different levels of energy flexibility with different capital costs. Therefore, both single-objective and multiobjective optimization methods used to determine cost-effective energy flexible solutions to support demand-side management and grid optimization will be introduced and their pros and cons will be discussed.

3.1 Introduction

With the increasing penetration of intermittent renewable energy, the grid is facing major challenges to absorb renewable energy without damaging grid stability. The energy flexibility of buildings has been considered a key contributor that can help improve grid stability [1]. A variety of systems and technologies can be deployed on the demand side to improve the energy flexibility of buildings at very different cost levels [1,2]. It is vital to accurately evaluate the performance of energy flexible systems with different

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configurations and sizes, to quantify the cost-effectiveness of the energy flexible systems. Optimization will be critical to determining the right size and appropriate system configurations to ensure that sufficient and cost-effective flexibility can be provided to support demand-side management and grid operations.

Modeling and simulation of building energy flexibility are one of the most effective tools to evaluate the performance of energy flexible systems, which has been extensively investigated in existing studies [3]. Many simulation methods and simulation tools have been developed to assist this process [4,5]. Meanwhile, extensive simulation-based optimization methods for energy flexible systems have been developed [6,7]. They have been proven as effective approaches to improving energy flexibility via optimized system design and sizing [8].

3.2 Simulation methods for building energy flexibility

Simulation of building energy flexibility is a key premise to the optimization of energy flexible systems. Simulation can provide quantitative results of energy flexibility. Existing simulation methods can be categorized into two main groups, that is, traditional physics-based building performance simulation methods and emerging data-driven simulation methods. Traditional building performance simulation methods rely on physics-based models which are derived from the first principles using mass, momentum, and energy equations. Data-driven simulation methods usually adopt black-box models that are developed by learning hidden relationships from a massive amount of performance data. This section introduces the common approaches and techniques used to model the performance of building energy systems for evaluating building energy flexibility.

3.2.1 Traditional physics-based simulation methods

Traditional physics-based simulation methods are formulated by physics-based modeling of key components in a building energy system, mainly including building space, Heating, Ventilation, and Air Conditioning (HVAC) systems, and on-site energy generation and storage systems, for example, photovoltaic (PV) panel, wind turbines, battery storage. Fig. 3.1 presents a schematic of the modeling structure of physics-based simulation methods. The modeling of the building space is to predict the cooling and heating load of different thermal zones in the building. The internal load of the indoor space can be evaluated based on the modeling of the appliances and occupancy. The energy demand of the HVAC system can be evaluated using the HVAC system models based on the cooling and heating load of the building. The modeling of the on-site energy generation and storage systems is to predict the power generation of the on-site energy generation devices such as rooftop PV and wind turbines, and states of energy storage such as battery energy storage and thermal energy storage, through which the energy exchange with the grid can be determined.

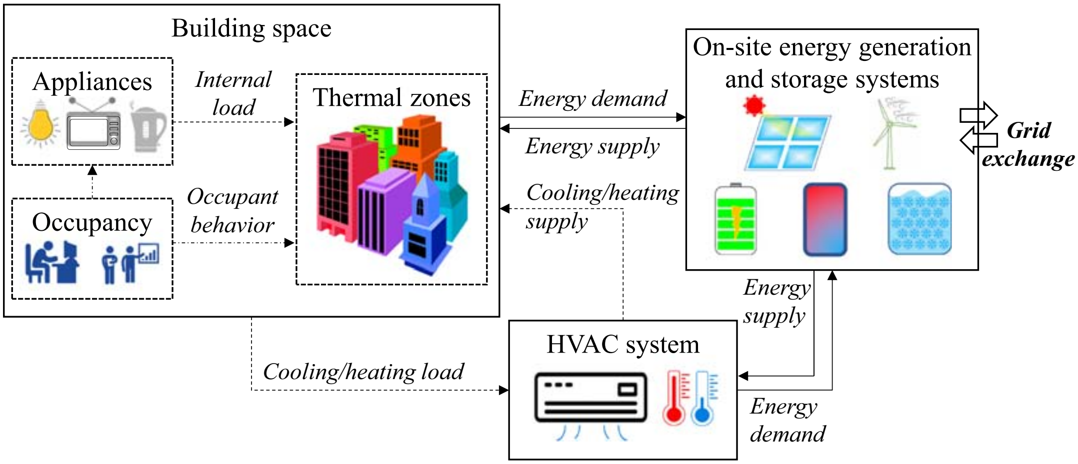

FIGURE 3.1 Schematic of the physics-based simulation method.

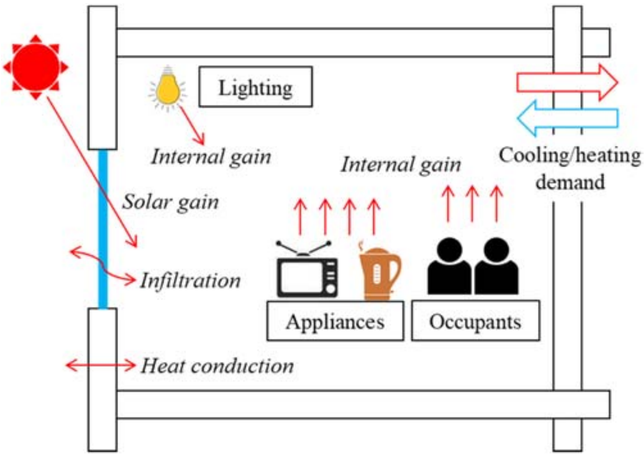

FIGURE 3.2 Heat and mass transfer process for modeling of building space.

3.2.1.1 *Modeling of building space*

The key objective for the modeling of building space is to predict the cooling/heating load and thermal comfort of the indoor environment. Based on the energy and mass balance of the building space, the cooling/heating load can be determined by evaluating the heat gain/loss of the space [9]. This is achieved by characterizing the heat and mass transfer process that occurs in the indoor space, as presented in Fig. 3.2. The physics-based simulation of the building space requires detailed information about the building as input, including location, the geometry of the building, building envelope parameters, internal heat gains, appliances, occupancy schedules, and weather data. In existing studies of building energy flexibility, a common practice of modeling building space is to use building simulation software such as EnergyPlus [10] and TRNSYS [11], which will be introduced later in this section.

3.2.1.2 *Modeling of Heating, Ventilation, and Air Conditioning systems*

This section introduces two modeling approaches for HVAC systems as examples, including a simplified modeling approach based on the coefficient of performance (COP) for general HVAC systems and an empirical model of split air-conditioners and heat pumps.

The simplified modeling approach evaluates the energy consumption of HAVC systems using Eq. (3.1). The energy consumption is determined based on the cooling/heating load (i.e., Q_{load}) handled by the HAVC system and the COP of the system. The COP of the HVAC system can be considered as a constant or evaluated based on performance maps. The COP of split air-conditioners and heat pumps is typically in the range of 2.0−4.0 [12,13], and the COP of centralized chiller plants could be higher [14]. The performance map is usually provided by manufacturers. It determines the COP by performance map interpolation based on operating conditions such as part load factor, outdoor air temperature, and/or cooling water temperature [15,16].

$$P_{\text{HVAC}} = \frac{Q_{load}}{COP} \tag{3.1}$$

The empirical model to be introduced here was adopted by EnergyPlus for modeling split air-conditioners and heat pumps, which has been extensively used in building energy simulation. It predicts the power consumption based on system performance under rated conditions in a combination of fitted curves to simulate performance at off-rated conditions. The model is presented in Eq. (3.2)−Eq. (3.5) [17,18]. $EIR_{f(T)}$ and $EIR_{f(FF)}$ are the fitted curves that modify the EIR (energy input ratio) based on outdoor and indoor air conditions and the flow fraction of indoor fans, respectively. Similarly, $Q_{f(T)}$ and $Q_{f(FF)}$ are to modify the rated total capacity (i.e., $Q_{total,\ rated}$). The RTF (runtime fraction) is calculated with Eq. (3.5), which accounts for part load losses of the system. PLR (part load ratio) is the ratio of the actual sensible load to total sensible capacity, and PLF (part load fraction) is a fitted function of the PLR. Detailed descriptions of the model can be found in [17,18].

$$P_{HVAC} = EIR \times Q_{total} \times RTF \tag{3.2}$$

$$EIR = EIR_{rated} \times EIR_{f(T)} \times EIR_{f(FF)} \tag{3.3}$$

$$Q_{total} = Q_{total,rated} \times Q_{f(T)} \times Q_{f(FF)} \tag{3.4}$$

$$RTF = \frac{PLR}{PLF} \tag{3.5}$$

3.2.1.3 *Modeling of on-site energy generation and storage systems*

This section introduces the modeling of solar PV panels, wind turbines, battery energy storage, and thermal energy storage, which have been extensively used to provide energy flexibility in buildings as energy flexible systems.

The solar PV converts solar irradiance into electricity and its conversion efficiency can be predicted using Eq. (3.6) [19]. The conversion efficiency of PV cells deteriorates with the increase in cell temperature. The temperature coefficient is used to include the performance deterioration under off-rated conditions. Fig. 3.3 presents the modeling results of a

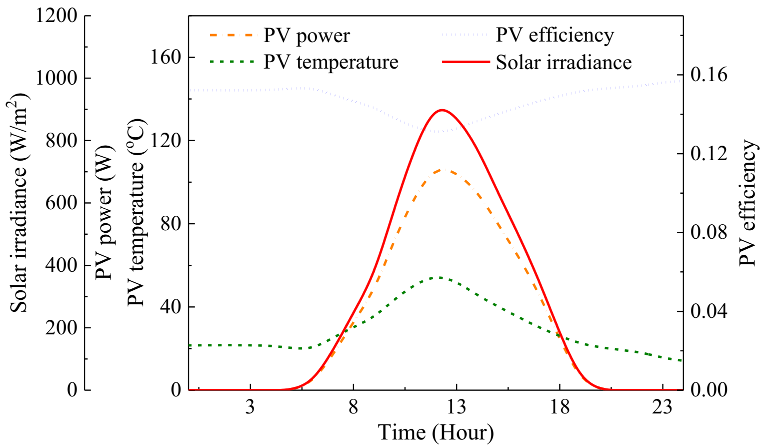

FIGURE 3.3 Modeling results of a 1-m^2 exemplary PV panel in a day.

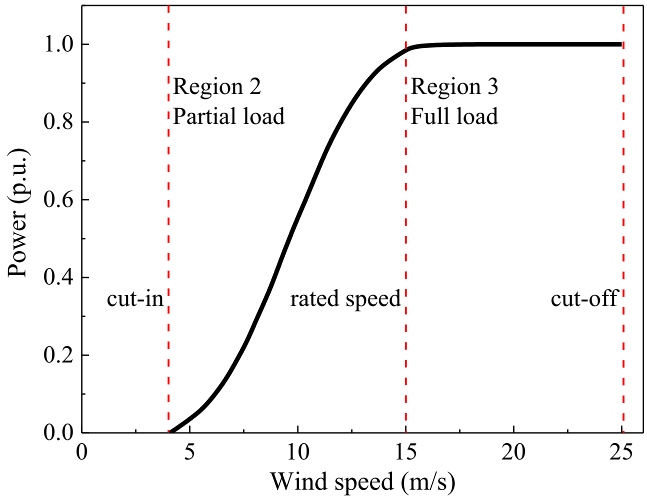

FIGURE 3.4 Exemplary wind turbine power curve.

1-m^2 exemplary PV panel in a day. The PV temperature increased at midday, thereby reducing the PV efficiency.

$$\eta_{PV} = \eta_{PV,rated} \times (1 - \eta_{T,coef}(T_{PV} - T_{rated})) \tag{3.6}$$

where η_{PV} is the conversion efficiency of the PV cell, $\eta_{PV,\ rated}$ is the conversion efficiency of the PV cell at rated conditions, $\eta_{T,\ coef}$ is the temperature coefficient, T_{PV} is the PV cell temperature, and T_{rated} is the reference temperature at rated conditions.

The power generation of a wind turbine depends on the wind speed at the height of the wind turbine hub. It can be described by a power curve such as Fig. 3.4. A piecewise function as presented in Eq. (3.7) [20] can be used to predict wind turbine power based on wind speed. The wind turbine power under partial load operations (when the wind speed is higher than the cut-in speed and lower than the rated speed) can be fitted from the power curve.

$$P_{WT} = \begin{cases} 0 & \left(V_{wind} < V_{CutIn} \quad or \quad V_{wind} > V_{CutOff}\right) \\ f(V_{wind}) & \left(V_{CutIn} \leq V_{wind} \leq V_{rated}\right) \\ P_{WT,rated} & \left(V_{rated} < V_{wind} \leq V_{CutOff}\right) \end{cases} \tag{3.7}$$

The battery storage system can be used to buffer the mismatch between renewable power generation and demand. It is capable of both filling valleys and shedding peaks [1]. The battery storage system can be modeled using Eq. (3.8) [21]. It predicts the amount of energy stored in a battery, that is, state of energy based on the charging and discharging operations.

$$SOE^{t+1} = SOE^{t} + \Delta t \times \left(\eta_{ch} P_{ch} + \frac{P_{dis}}{\eta_{dis}}\right), \tag{3.8}$$

where Δt is the duration of charging/discharging, η_{ch} and η_{dis} are the charging and discharging efficiency, respectively, and P_{ch} and P_{dis} are the charging and discharging power, respectively. The battery should not be charged and discharged at the same time.

Similar to the battery storage system, the thermal energy storage system can provide flexibility by charging/discharging the storage medium. The medium can utilize sensible heat and/or latent heat to store thermal energy. Based on the storage medium used, thermal energy storage systems for energy flexibility can be generally categorized into sensible storage systems and latent storage systems [22]. The hot water tank is one of the most commonly used sensible thermal energy storage systems. It utilizes the sensible thermal capacity of fluids such as water and oil to store thermal energy. One-dimensional models considering thermal stratification of the storage medium have been widely used to simulate the performance of hot water tanks [23]. The tank was divided into isothermal temperature nodes to model thermal stratification. The temperature of the storage medium was predicted by evaluating the heat loss to the ambient, the heat exchange with the internal heat exchanger and/or the heater, and the heat and mass balance of the inlet fluid and the outlet fluid [24,25].

Latent storage systems utilize phase change materials such as salt hydrates, paraffin, eutectics, and ice as the storage medium. It is charged/discharged via heat transfer between the storage medium and heat transfer fluid. The phase change process can be modeled via the enthalpy method [26,27] or the effective heat capacity method [28,29].

3.2.1.4 Simulation tools

There are various software tools that can be used to model building energy systems and evaluate building energy flexibility. Software that has been commonly used in existing studies, including TRNSYS [11], EnergyPlus [10], Modelica [30], and ESP-r [31], will be introduced below.

TRNSYS (Transient System Simulation Tool) is a transient system simulation program that was developed based on a modular structure. A TRNSYS simulation system generally consists of multiple TRNSYS components similar to an actual system. TRNSYS includes a variety of component models for simulations of building energy systems, such as PV model, battery energy storage model, and hot water tank model. It can be also used to simulate building space. The modular structure of TRNSYS makes it easy to include user-developed models into a simulation system. TRNSYS can be used to carry out co-simulation of building space and associated energy systems, which makes it a powerful tool for modeling building energy systems. It has been extensively used to evaluate energy flexibility for building energy systems [2,32,33].

EnergyPlus is a free and open-source building energy simulation program provided by the US Department of Energy. It is a console-based program that reads input and writes output to text files. Graphical user interfaces for EnergyPlus are provided by other software such as OpenStudio and DesignBuilder. EnergyPlus includes a comprehensive library of components including but not limited to HVAC systems and on-site energy generation and storage systems.

Modelica is an equation-based, object-oriented modeling language for component-oriented modeling of complex systems. It is not specialized for energy system simulation but is a generic modeling tool. Some recent studies adopted Modelica to model building energy systems and evaluate their energy flexibility [34,35]. An open-source library of Modelica for buildings and district energy and control systems [36] was developed by Lawrence Berkeley National Laboratory. It mainly includes the building space model, the HVAC system model, and the energy storage model.

ESP-r is an open-source building energy simulation software that was created by the University of Strathclyde [37]. It was mainly used for modeling building space and HVAC systems. Some attempts were made to integrate ESP-r with other modeling tools such as TRNSYS and MATLAB to simulate buildings with complex energy systems [38,39].

3.2.2 Data-driven simulation methods

Data-driven simulation methods have been frequently reported in recent studies to predict the performance of building energy systems and cooling/heating demand. The data-driven simulation methods are generally developed based on black-box models without the guidance of physical laws. They require less or no physical information about the modeled system, as compared to physics-based models. The black-box models are generally built upon historical performance data of the modeled system, using statistical or machine learning models to learn and describe the hidden correlations between input parameters (e.g., weather conditions, temporal information) and output parameters (e.g., energy consumption, indoor temperature) [4]. This section introduces typical black-box models and their applications in building energy simulation and energy flexibility evaluation, including artificial neural networks (ANNs), support vector regression, and decision trees.

3.2.2.1 Artificial neural networks

ANNs are a major subset of machine learning techniques. The structure of the ANN is inspired by the human brain, which mimics the signal transmission approach of biological neurons. Fig. 3.5 presents a schematic of a single feedforward neuron of an ANN. It predicts the output based on a weighted sum of the inputs and an activation function, for

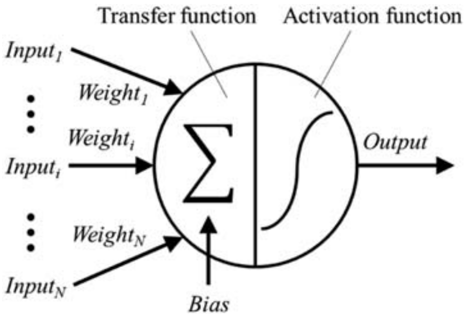

FIGURE 3.5 Schematic of a single neuron in artificial neural networks.

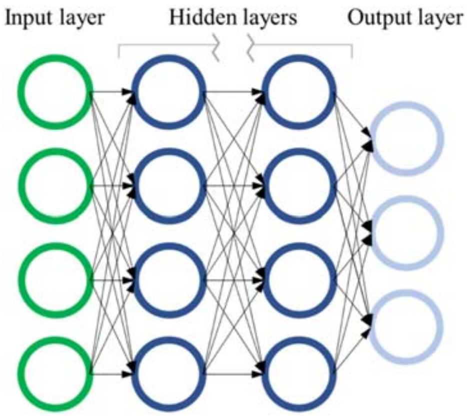

FIGURE 3.6 Schematic of a feedforward neural network.

example, linear function, sigmoid function, rectifier function. The weights are determined based on performance data via a training process [40].

Feedforward neural network (FFNN) is a classic form of neural network. Fig. 3.6 presents a schematic of an FFNN. It mainly consists of an input layer, an output layer, and hidden layers (or a hidden layer). Each layer includes multiple neurons. In the network, information moves in only one direction from the input layer, through the hidden layers, and to the output layer. There are no cycles or loops in the network [41]. FFNNs have been extensively used in the data-driven simulation of building energy systems, including individual components [42] and complex building energy systems [43]. Hu et al. [43] adopted a single-layer FFNN model to predict heating/cooling load and HVAC system energy consumption based on inputs including the outdoor temperature, indoor zone temperatures, ground-source temperature, and occupancy. The model was used to evaluate the energy flexibility of the modeled building under a time-of-use tariff.

A recurrent neural network (RNN) includes recurrent units to receive outputs from previous steps as the input of the current step. This feature allows RNNs to consider both the current input and information from previous steps, which makes it suitable for handling time series data such as cooling/heating load, indoor temperature, and solar irradiance. Fig. 3.7 presents a schematic of a long-short-term memory network. It is a type of RNN capable of learning

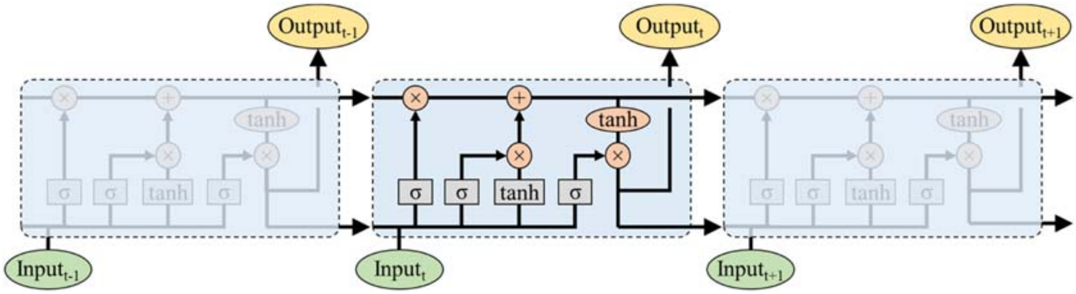

FIGURE 3.7 Schematic of a long-short-term memory network.

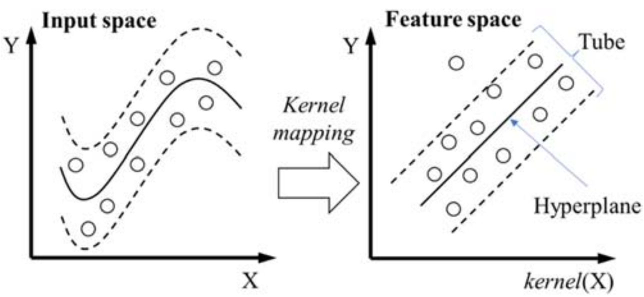

FIGURE 3.8 Schematic of support vector regression.

long-term information and developing associated correlations [44], which showed promising performance in predicting building cooling/heating load and building energy consumption.

3.2.2.2 *Support vector regression*

Support vector regression (SVR) is a kernel-based machine learning technique that is derived from a support vector machine (SVM) [45]. It can effectively handle the regression of high-dimensional nonlinear data with a relatively small amount of training data [46]. SVR introduces kernel functions that map input space into high-dimensional feature space to transfer nonlinear problems into linear ones. Fig. 3.8 presents a schematic of the SVR. The regression attempts to identify the narrowest tube around the hyperplane while containing most of the training samples [47]. The SVM-based approach has been considered one of the most robust and accurate machine learning techniques [48].

Due to its advantage in handling nonlinear regression with a relatively small amount of data and its robust performance, SVR has been extensively used as a data-driven technique for predicting building heating/cooling load and energy consumption, predicting occupant behavior, forecasting renewable energy resources, and performance prediction of energy systems.

3.2.2.3 *Decision trees*

A decision tree is a machine learning technique for classification and regression problems, which is featured by its tree-shaped structure. A decision tree model consists of

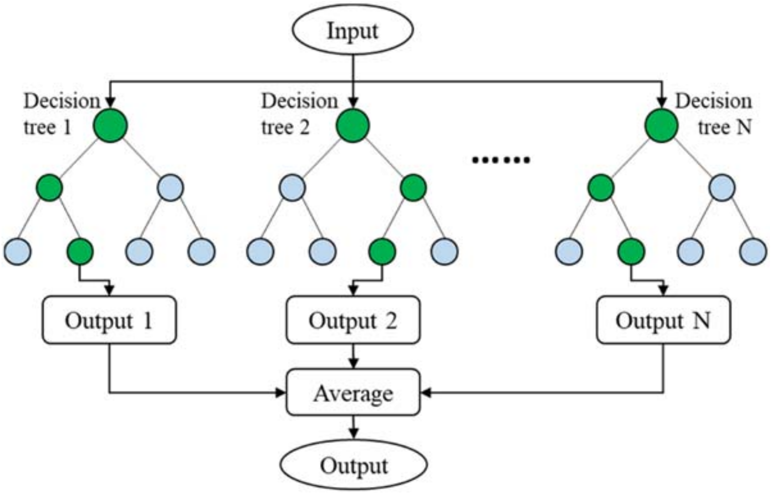

FIGURE 3.9 Schematic of a random forest model.

internal nodes and leaves which are essentially a set of rules for dividing a large heterogeneous dataset into smaller and more homogenous classes [49]. Among different decision tree models, random forests [50] and gradient boosting trees [51] have been frequently used as data-driven simulation methods for building energy systems.

Random forests are an ensemble learning method incorporating multiple decision trees which are simultaneously used for data regression and prediction. Fig. 3.9 presents the schematic of a random forest model. The average of the individual trees is the outcome of a random forest. Random forests can tackle overfitting issues of decision trees by assembling multiple trees [4]. It has been extensively adopted as a data-driven simulation method for HVAC systems and building energy consumption prediction. Gradient boosting trees is an ensemble learning method with a similar structure as the random forest, while the individual trees are trained sequentially via a gradient-based approach [52]. It is a relatively new method, showing promising performance in predicting cooling/heating load and building energy consumption.

3.2.3 Summary of simulation methods

The traditional simulation methods are featured by the physics-based models with good interpretability, and the models can be transferred to different simulation scenarios. The methods require detailed parameters of the modeled systems to set up the physics-based models. The development of new physics-based models can be time-consuming and needs expert knowledge.

The data-driven simulation methods have the key advantage of being free of expert knowledge, and rapid development of the models can be achieved. However, the quality of the data-driven model is highly dependent on the training data and hyperparameters, and the modeling results generally lack interpretability.

3.3 Optimization methods for building energy flexibility

Optimization is an essential process to fully exploit the energy flexibility potential offered by energy flexible systems. For new buildings and existing building retrofits, optimization can be used in the design stage to determine the optimal size and effective configurations of energy flexible systems. This is often achieved in combination with cost-benefit analysis and uncertainty analysis. It is usually expected to achieve high energy flexibility at reasonable costs. During the building operation stage, optimization can be used to explore energy flexibility potential and optimize the operation of energy flexible systems, which forms the core part of a demand response strategy. This chapter will introduce the optimization methods for building energy flexibility at the design stage.

Fig. 3.10 presents the schematic of a general procedure for optimization of building energy flexible systems, which has been extensively adopted in existing studies. It usually starts with the selection of parameters to be optimized such as the area of PV panels, the size of a battery energy storage system, and the size of a thermal energy storage system. At the same time, the objective function (e.g., energy saving, peak shaving, cost saving) and constraints (e.g., initial cost, peak export, storage capacity) will be determined based on specific demands. The selection of the parameters to be optimized is determined based on multiple factors including expert knowledge, specific objective(s) of interest, and the significance of the parameters to the objective function. The parameter selection can be evaluated via sensitivity analysis and/or existing practices.

Optimization of building energy flexible systems can be categorized into single-objective optimization methods and multiobjective optimization methods depending on the number of objective functions used. The single-objective optimization method usually only concerns one objective function (e.g., energy consumption, operational cost, thermal comfort), while the multiobjective optimization maximizes/minimizes two or more objective functions which are contradictory to each other. Both methods can follow the general procedure as presented in Fig. 3.10 to achieve optimization, while different optimization algorithms suitable for different applications are used.

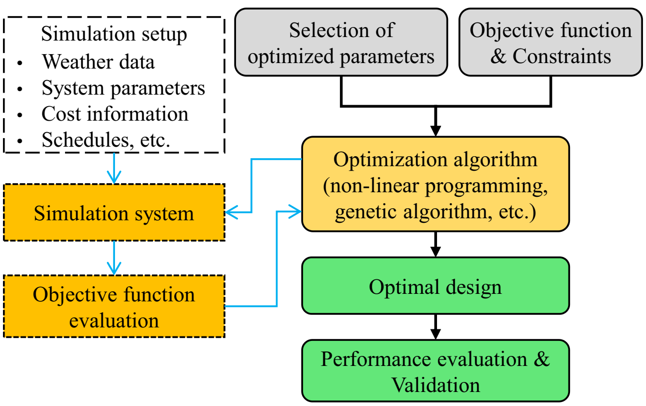

FIGURE 3.10 Schematic of a general procedure for optimization of building energy flexible systems.

3.3.1 Single-objective optimization methods

3.3.1.1 Direct search

Direct search is a method for solving optimization problems that do not require any information about the gradient of the objective function [53]. A direct search algorithm searches a set of points around the current point and looks for a surrounding point with performance better than that of the current one. It can be used to solve problems for which the objective function is not differentiable, or is not even continuous. Direct search can be easily implemented for simulation-based optimization. However, it has two major disadvantages, that is, slow asymptotic convergence and difficulties in handling high-dimensional problems [54]. Worse ever, it may fail to obtain optimal solutions for complex problems [55].

A recent study showed that the direct search provided poor performance for the optimization of a heat pump system with thermal energy storage [56]. On the other hand, hybrid optimization methods which integrate direct search with global search methods such as the Hooke-Jeeves algorithm-particle swarm optimization (PSO), and direct search-linear programming, to improve the effectiveness of global optimization have been used for the optimization of energy flexible systems.

3.3.1.2 Linear and nonlinear programming

Linear programming is a mathematical programming technique for the optimization of a linear objective function, subject to linear equality and linear inequality constraints [57]. It solves the optimization problem using algorithms such as the primal simplex algorithm, the dual simplex algorithm, and the interior-point algorithm. Linear programming can efficiently handle a large number of continuous variables and constraints, providing exact solutions. It can be modified into mixed-integer linear programming via branch and bound methods to include integer variables [58]. Linear programming techniques have been used for the optimization of energy flexible systems, for example, residential energy systems, and battery energy storage systems.

Formulation of linear programming requires an explicit form of the optimization problem and the objective function must be evaluated via linear models. Therefore, when applying linear programming to optimize energy flexible systems, the models usually need to be simplified, and thus complex physics-based models or nonlinear black-box models are generally not applicable.

Nonlinear programming handles optimization with nonlinearities in the objective function and/or constraints [57]. Similar to linear programming, it can handle continuous and/or integer variables depending on the algorithm adopted for problem-solving. Nonlinear programming covers a wide range of algorithms/methods for nonlinear optimization problems, for example, sequential quadratic programming, and interior-point algorithm. It has been used for optimal sizing of complex energy systems such as PV-battery systems and combined heat and power systems.

Many software tools can be used to solve linear and nonlinear programming problems such as open-source tools (e.g., COIN-OR Linear Programming, GNU Linear Programming Kit) and commercial solvers (e.g., CPLEX, GUROBI, MATLAB).

3.3.1.3 Meta-heuristic optimization

Meta-heuristic algorithms are a type of optimization method for complex problems, which are generally inspired by a natural process, a physical process, or social behaviors. Meta-heuristic optimization cannot guarantee the optimal solution while it could provide near-optimal solutions within a reasonable time [59]. It is a derivative-free approach and can be used for various types of optimization problems using different kinds of models (i.e., physics-based and data-driven). Meta-heuristic optimization can be easily integrated with simulation software (as introduced in Section 3.2), and this integrated approach has been extensively used for the optimization of energy flexible systems. A few meta-heuristic algorithms that have been extensively used for the optimization of energy flexible systems are introduced below, along with their applications.

A genetic algorithm (GA) was proposed by John Holland [60] as early as 1975, originally inspired by the idea of natural evolution and the survival of the fittest principle [61]. It is one of the most popular meta-heuristic algorithms. In general, GA is a population-based stochastic optimization algorithm that utilizes mechanics of natural evolution such as inheritance, mutation, selection, and crossover [62]. The GA usually starts with population initialization that generates a population in the search space randomly. It then improves the fitness function of the population via the selection, crossover, and mutation operators as an iterative process until the termination criteria are met.

GA has been extensively used for the optimization of energy flexible systems. For instance, Li et al. [63] conducted optimal sizing of grid-connected PV-battery systems for residential houses using a GA. The sizes of the PV panels and the battery energy storage system were optimized to minimize the annual operating cost under a time-of-use tariff. Huang et al. [64] developed a design optimization of a coupled PV-heat pump-thermal storage-electric vehicle system for a residential building cluster using a GA. The sizes and location of the PV panels and the size of the battery energy storage system were optimized to maximize the lifetime self-consumed electricity of the building cluster.

PSO is inspired by the social behavior of bird flocking and fish schooling, which was proposed by Eberhard and Kennedy in 1995 [65]. The searching for the optimal solution is mimicked by the searching for the best position (i.e., fitness function) conducted by a particle swarm. The positions of the particles in the searching space are improved by iteratively modifying the moving directions and velocities of the particles based on information sharing in the swarm. The movement of a particle is determined based on the best-known position of the particle itself (i.e., individual best) and the best-known position of all particles (i.e., global best) [66]. PSO is a rather new meta-heuristic algorithm and also a popular one thanks to its advantages of easy implementation, robustness to control parameters, and computational efficiency [67].

PSO has been frequently used for the optimization of energy flexible systems [68,69]. For instance, Yang et al. [69] utilized PSO for optimal sizing of key components of a solar hybrid combined cooling, heating, and power (CCHP) system. The sizes of the CCHP system, PV panels, solar thermal collectors, and a hot water tank were optimized to maximize a weighted-sum performance indicator concerning energy savings, carbon emission reduction, and cost reduction.

Simulated annealing (SA) is a meta-heuristic algorithm inspired by the annealing process in metallurgy, which is a heat treatment technique that alters the physical properties of materials via iteratively heating and cooling [61]. SA searches for the optimal solution by iteratively moving from the current state to a neighboring state based on an acceptance probability function, which ultimately leads the system to move to states of lower energy. SA has been increasingly adopted for optimization problems thanks to its simplicity in implementation and robust performance, while its final solution could be largely influenced by the initial state and may require high computational costs [70]. Applications of SA for design optimization of energy flexible systems in buildings are still limited. A few instances can be found in [71,72], such as optimal sizing of wind and solar energy systems with integrated energy storage.

3.3.2 Multiobjective optimization methods

3.3.2.1 Multiobjective optimization and Pareto optimality

Multiobjective optimization maximizes/minimizes two or more objective functions simultaneously, while they conflict with each other. This means that the optimal solution is a compromise of the objective functions instead of searching for the only best solution to the problem such as the single-objective optimization.

It is defined that a solution is considered Pareto optimal if one of the objective functions cannot be improved without compromising another one. The set of all Pareto optimal solutions formulates the Pareto front. For instance, Fig. 3.11 presents the Pareto front of a hypothetical bi-objective optimization concerning the energy flexibility and initial investment of a PV-battery system. The initial investment and the energy flexibility are the two conflicting objective functions. For the Pareto optimal solutions, energy flexibility is increased with the increase in the initial investment thanks to the larger capacities of the PV panel and the battery (from technological option 1 to technological option 3). A Pareto optimal solution can be selected from the Pareto front to formulate an optimal solution, while a compromise of the initial investment and energy flexibility must be established.

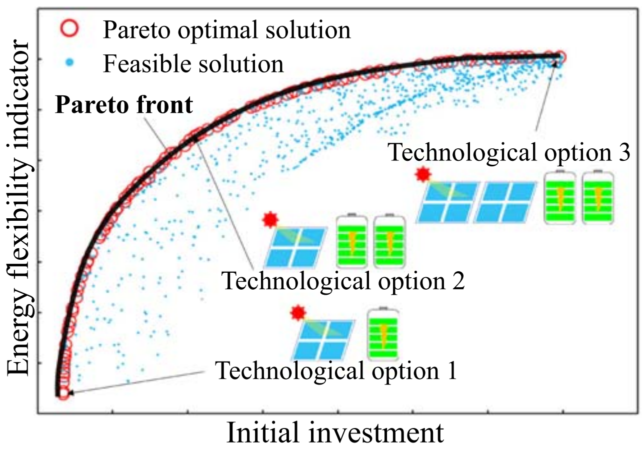

FIGURE 3.11 Pareto front and three technological options of a multiobjective optimization problem (for illustration only).

3.3.2.2 Weighted-sum method

Searching for the exact Pareto front of a multiobjective optimization problem could be complex, and, therefore, many approximation approaches have been developed for multiobjective optimization [73]. A widely used approach is the weighted-sum method which considers the sum of individual objective functions multiplied by weighting factors as the overall objective function. This transforms the multiobjective optimization problem into a single-objective optimization problem which can be solved by the methods introduced in Section 3.3.1.

The weighted-sum method has been widely adopted for multiobjective optimization of energy flexible systems [74,75] as it is easy to understand and apply in engineering practices. However, this method has a major disadvantage that it cannot identify all Pareto optimal solutions when the true Pareto front is nonconvex. This makes it difficult to find the solutions on a nonconvex trade-off front/surface [76]. Meanwhile, changing the weighting factors could largely alter the identified optimal solution, while the determination of the factors heavily relies on user preference and/or expert knowledge.

Apart from the weighted-sum method, there are also some other approximation methods for multiobjective optimization such as the ε-constraint method, the objective programming method, and the normal boundary intersection method. Detailed reviews of these methods can be found in [73,77]. This chapter will not elaborate on them due to their limited applications in the optimization of energy flexible systems.

3.3.2.3 Pareto front–based methods

Meta-heuristic algorithms have been extensively adopted to search for the Pareto front due to the high complexity of the problem. The nondominated sorting genetic algorithms (NSGAs), and multiobjective PSOs (MOPSOs) have been frequently used for multiobjective optimization of energy flexible systems. These algorithms and their applications will be introduced in this section.

NSGA is a variation of GAs for multiobjective optimization, and there are three versions, that is, NSGA, NSGA-II, and NSGA-III that have been developed by Deb et al. [78–80]. The key difference between the NSGAs and GAs is the selection operator while the crossover and mutation operators remain as the conventional GAs [78]. In NSGAs, all individuals in a generation can be sorted into different nondomination levels, and the individuals are ranked based on an individual's nondomination. Through this approach, individuals close to the true Pareto front can be identified via the iteration of the GA.

NSGAs are the most popular group of multiobjective optimization algorithms for optimal sizing of energy flexible systems. For instance, Wang et al. [81] conducted multiobjective optimal sizing of an integrated energy system including PV panels, solar thermal collectors, an internal combustion engine, an absorption chiller/heater, a heat pump, and a thermal storage unit. The capacities of the key components were optimized to maximize the primary energy savings, the cost saving (including levelized initial cost, operating cost, and fuel cost), and the carbon emission reduction simultaneously, using the NSGA-II. Fig. 3.12 presents the Pareto front considering the three objective functions. It can be observed that there was a clear trade-off between carbon emission reduction and cost savings. The carbon emission could be reduced with the increase in the capacity of the

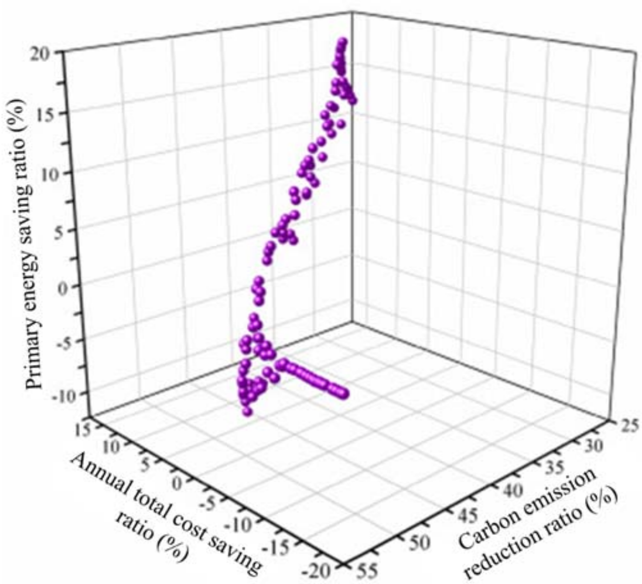

FIGURE 3.12 Pareto front considering primary energy savings, cost savings, and carbon emission reduction [81].

integrated energy system, while this also increased the levelized initial cost, thereby decreasing cost savings.

Similar to NSGAs, MOPSOs are modified from the PSO to realize multiobjective optimization. The performance of the particles is evaluated based on their nondomination levels. A set of leaders (i.e., nondominated solutions) are stored in an external archive to guide the movements of the particles [82]. MOPSOs have been used for multiobjective optimization of energy flexible systems. For instance, Azaza and Wallin [83] optimized the installation capacities of the PV panels, wind turbines, and diesel generators and the autonomy days (representing the battery capacity) of a hybrid micro-grid system, taking the reliability of power gird, cost of electricity, and renewable factor as the objective functions.

It is noteworthy that Pareto front–based methods search for the true Pareto front instead of a single optimal solution. However, a specific solution is still needed in practice to guide the design and planning of energy flexible systems. This can be achieved by multicriteria decision-making methods that have been well covered in many existing studies [84].

3.3.3 Cost-effectiveness improvement via optimization

Cost-effectiveness is a key aspect of the optimization of building energy flexible systems. In general, improving the energy flexibility of buildings needs to include energy flexibility sources, such as PV panels, electric and thermal energy storage systems, and advanced control for HVAC systems. These energy flexible systems will result in increased costs of installation, operation, and maintenance. It is, therefore, vital to consider the cost-effectiveness of energy flexible systems during the design stage via optimization.

A common approach to considering cost-effectiveness in optimization is to include cost factors in the objective functions, such as life-cycle cost, net-present cost, and energy bills. For instance, Shen et al. [85] developed an optimal planning method of energy storage in multienergy microgrids. This method adopted a weighted-sum objective function including investment cost, gas purchase cost, electricity purchase cost, maintenance cost, and carbon emissions. The installation capacities of energy storage devices were optimized to minimize this objective function.

Multiobjective optimization is another effective approach to including the cost-effectiveness analysis in the optimization of energy flexible systems. The cost (or cost-related indicators) of energy flexible systems can be considered as one of the objective functions in multiobjective optimization. The trade-off between energy flexibility and cost can be revealed by the Pareto front identified by the multiobjective optimization algorithm, and comprehensive analysis of the trade-off between energy flexibility and cost can be conducted. For instance, Arabkoohsar et al. [86] conducted multiobjective optimization for PV-based systems with integrated battery energy storage and heat pumps. The initial cost and the energy purchased from electricity/heat/cooling networks were considered as the objective functions, and the sizes of the PV thermal/cooling panels, heat storage capacity, and cold storage capacity were optimized. A Pareto front as presented in Fig. 3.13 was identified. The trend of the Pareto optimal solutions showed that the purchased energy was reduced with the increase in the initial cost, due to the increased size of the PV and storage.

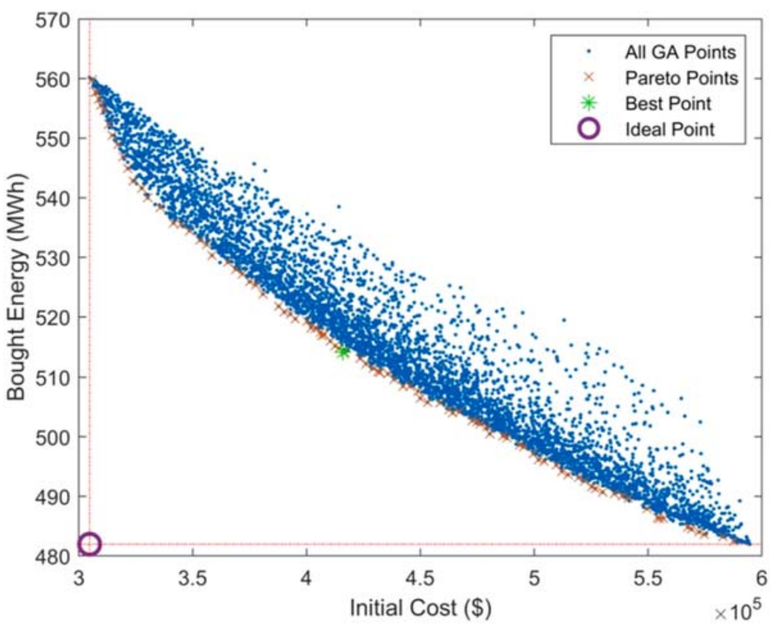

FIGURE 3.13 Pareto front of multiobjective optimization of PV-based systems with integrated battery energy storage and heat pumps [86].

3.3.4 Summary of optimization methods

A summary of the optimization methods introduced in this section is presented in Table 3.1. For single-objective optimization problems, extensive methods have been developed in previous studies. Direct search is easy to be implemented while it cannot guarantee good performance. Linear and nonlinear programming methods can efficiently solve optimization problems while they require explicit forms of models, which makes them difficult to be integrated with building simulation software, for example, TRNSYS, and EnergyPlus. The meta-heuristic algorithms are a powerful tool for the optimization of energy flexible systems, while they require high computational costs.

Multiobjective optimization of energy flexible systems is a rather new topic and it can provide useful trade-off information to guide the design of energy flexible systems. The weighted-sum method is easy-to-be-implemented by utilizing single-objective optimization algorithms. This largely simplifies the multiobjective optimization problem while the method may miss some Pareto optimal solutions when the true Pareto front is nonconvex. The Pareto front–based methods can provide the Pareto front of the multiobjective optimization problem, which makes it a powerful tool to support the optimization of energy flexible systems. However, the Pareto front–based methods require extensive computational costs as they are usually based on meta-heuristic algorithms.

3.4 Summary

This chapter provided an introduction to building energy flexibility modeling and optimization. The simulation methods for building energy flexibility were introduced, including

TABLE 3.1 A summary of optimization methods for energy flexible systems.

	Method	Advantages	Disadvantage
Single-objective optimization	Direct search method	• Easy to be implemented • Derivative-free	• No guarantee of the optimal solution • Slow convergence • Cannot handle many variables
	Linear and nonlinear programming	• High computational efficiency • Good convergence	• Difficult to implement • Need explicit forms of models
	Meta-heuristic optimization	• Easy to be integrated with simulation software • A powerful tool to provide near-optimal solutions	• High computational cost
Multiobjective optimization	Weighted-sum method	• Easy to be implemented • Can utilize single-objective optimization algorithms	• May miss Pareto optimal solutions
	Pareto front–based method	• Can provide multiple Pareto optimal solutions • Can provide Pareto front to assist decision-making	• Extensive computational cost

traditional physics-based simulation methods, and emerging data-driven simulation methods. The component modeling of the physics-based simulation methods was further described, including modeling of building space, HVAC systems, and on-site energy generation and storage systems. Meanwhile, simulation tools for physics-based simulation were overviewed. Typical data-driven simulation methods including ANNs, SVR, and decision trees and their applications in modeling building energy flexibility were introduced. The pros and cons of the simulation methods were summarized. The general procedure of optimizing building energy flexibility was presented and two key categories of optimization methods including single-objective optimization and multiobjective optimization were introduced. Single-objective optimization methods were represented by direct search methods, linear and nonlinear programming, and meta-heuristic algorithms. Multiobjective optimization was represented by the weighted-sum method and the Pareto front−based methods. Further discussions on the cost-effectiveness improvement via optimization revealed that there was usually a trade-off between building energy flexibility and the cost of energy flexible systems when considering the different configurations and sizes of the systems. The pros and cons of the optimization methods were also summarized in this chapter.

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CHAPTER

4

Building energy demand management strategies and methods

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Nomenclature

CCHP Combined Cooling, Heating, and Power
CPP Critical Peak Pricing
DR Demand Response
DSF Demand Side Flexibility
DSM Demand Side Management
IBR Inclining Block Rate
MPC Model Predictive Control
PCM Phase Change Material
PTR Peak-time Rebate
RBC Rule-based Control
RES Renewable Energy Source
RTP Real-time Pricing
T&D Transmission & Distribution
TES Thermal Energy Storage
TOU Time-of-Use Pricing

Demand-side management offers great opportunities to use building energy flexibility to significantly reduce building operational costs. Various management strategies can be applied to mitigate the energy demand of buildings and improve their energy efficiency. The key strategy is to move to on-demand consumption instead of on-demand generation. This strategy is usually based on some types of energy storage, such as the thermal mass of a building (e.g., building structures, building parts, or modules), where excess energy is stored and released on demand to the interior. To improve the energy efficiency of buildings, this chapter provides valuable insights into different management options and

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methods suitable for different types of buildings. This will be an important source of the information for future research and professionals in this field.

4.1 Introduction

Economic challenges, limited resources, and environmental concerns are some of the main triggering reasons for many countries to invest in energy management activities. Energy management involves all the activities that aim to optimize the use of energy, either from the energy generation side or demand consumption side. Traditional on-demand generation is accepted to be unsustainable. The grid is overloaded during the peak demand period while it oversupplies during the off-peak period. The mismatch between peak and off-peak loads ultimately leads to energy loss causing an inefficient and potentially unreliable energy system [1]. On the other hand, global energy demand is growing and is bringing lots of challenges where space heating and cooling can play a significant role in the demand [2].

To control and optimize energy consumption levels, it is necessary to shift the focus from on-demand generation to Demand Side Management (DSM) activities [3]. The goal of bringing the demand and supply closer to each other is to minimize the costs of energy usage, the cost of risks, and the cost of inefficiency and to enable buildings to operate more flexibly. The increasing technological advances, especially in smart grids, provide more flexibility in DSM methods and result in more efficient strategies and solutions.

Building energy flexibility can be defined as the capability of a building to operate flexibly to support the electrical grid, while the occupants' thermal comfort and overall building function are not compromised [4–6]. In other words, it is the way that a building operates according to its energy demand by adapting and managing the discrepancy between energy supply and demand to ultimately reduce energy costs while keeping the same level of building functionality and occupants' thermal comfort [4,7]. However, to further understand how energy flexibility is achieved through which strategies and technologies specifically, it is important to understand flexibility resources. For electrical grids, there are two categories of flexibility resources [8], including supply-side flexibility and demand-side flexibility (DSF).

When referring to supply-side flexibility, solar energy with power plants, wind power, and waste heat in combination with different storage systems, are the main terms used to define it. Power plants, which can be either conventional or combined heat and power ones, respond fast to the discrepancy between the generation of electricity and its consumption [9]. Essentially, on the supply side, this means that flexible buildings have their energy generation and storage systems. DSF-imposed loads are categorized into thermostatic loads and nonthermostatic loads. Thermostatic ones are often referred to as the loads from the systems such as heating, ventilation, and air conditioning (HVAC) systems, and refrigerators, which can automatically respond to the temperature changes of the interior environment, while nonthermostatic ones are often considered as load of lighting and plug loads [10]. Therefore, building DSF is mainly focused on the application of smart devices to control these loads. Smart devices are controlled by certain algorithms that enable load shifting in building appliances such as washing machines and dishwashers

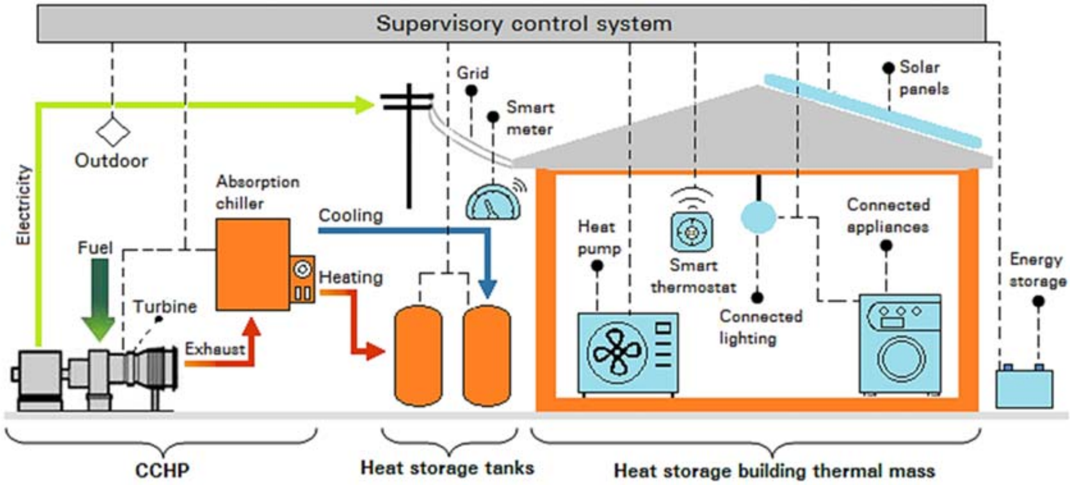

FIGURE 4.1 General scheme of building demand management.

[11], or controlling the air-conditioning load [12]. The application of a certain algorithm such as Model Predictive Control (MPC) and Rule-based control (RBC) depends on the scope, that is whether it is system-level, building-level, or service level [13]. The objective function of the algorithms can target different factors, such as economic factors, energy consumption, or CO_2 emissions, with constraints keeping occupant's thermal comfort. The load is controlled by implementing certain energy carriers suitable for buildings such as: building thermal mass, heat storage tanks (heat bank), batteries, photovoltaics, combined cooling, heating, and power (CCHP), which play a key role in facilitating the future energy systems [14] and are illustrated in Fig. 4.1.

Most of the DSM options can be grouped under two main concepts: energy efficiency and demand response (DR). Energy efficiency includes all types of activities that result in using less energy to perform the same or improved energy service, which includes a wide range of activities such as: better designed and smarter infrastructure, better insulation, and renewable resource utilization. DR, on the other hand, allows end-users to change their energy consumption behavior as a response to power grid status or some other factors such as emergencies. This helps balance the load on the power grid and results in freed capacity, and a more reliable power supply, as well as less energy costs for the users [15].

In the past, massive, centralized power generation units within power systems were used to meet building demand. However, with the introduction of renewable energy sources (RESs), it is advocated that the end user demands should be adapted to accessible power generation [16]. As a consequence of variability of RESs by natural factors, disbalance is created between inconsistent supply and demand causing instability of the grid. At the same time, it represents a great challenge for modern society toward creating an electric supply that is at the same time cost-effective as well as trustworthy [13,17].

The research scope including common strategic options, methods, and technologies is illustrated in Fig. 4.2.

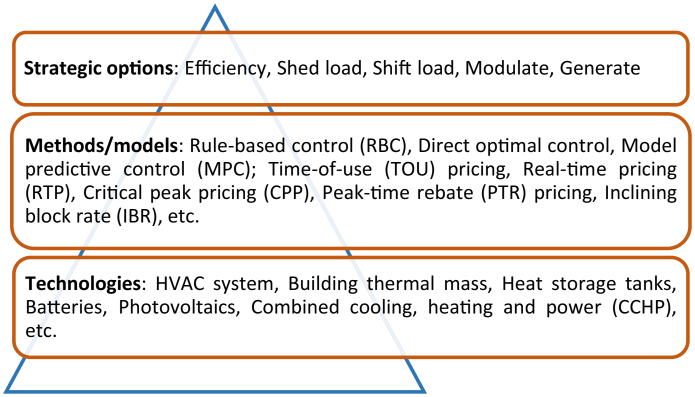

FIGURE 4.2 Scope of research—hierarchical illustration.

This chapter aims to provide a deeper insight into DSM through the use of energy flexibility options in buildings. Large industrial buildings have been traditionally targeted but today due to technological developments, commercial and residential buildings are involved. To address this research gap and provide the state of the art on this topic, significant aspects of different flexibility options, methods, and technologies were considered. In terms of technologies, a brief discussion was provided on thermostatic energy carriers such as building thermal mass, heat storage tanks, and CCHP.

4.2 Demand side flexibility and management options

The electricity demand is constantly growing, so the stress on the grid becomes more significant over time. In addition, DSF is required since renewable energy has an increasing share in total energy generation. By applying smart technologies within the built environment, the loads can be dynamically shaped, and costs and disruptions associated with peak demand can be reduced [18]. Depending on the type of the electrical grid, different load management options can be used to reduce base load demand, such as energy efficiency, load shifting, load shedding, load modulation, and power generation [19]. The most popular one mentioned in the literature is load shifting (60%), load shedding (19%), power generation (16%), and load modulation (5%) [13]. Fig. 4.3 shows common building DSM options.

Efficiency is to achieve the long-term and permanent building energy demand reduction, which is continuous and repeated and not time-dependent. It can be achieved by using an effective HVAC system and energy-efficient building envelopes [18]. The main benefit of this option is to reduce the burning of fossil fuels and CO_2 emissions while maintaining the same level of functionality.

Load shedding is to achieve short-term building energy demand reduction, which is implemented only during the peak demand period or in any case of emergency. This means that energy consumption from the grid can be reduced quickly for a short period (usually up to 1 hour) by scaling down consumption. It can be achieved by setting prices

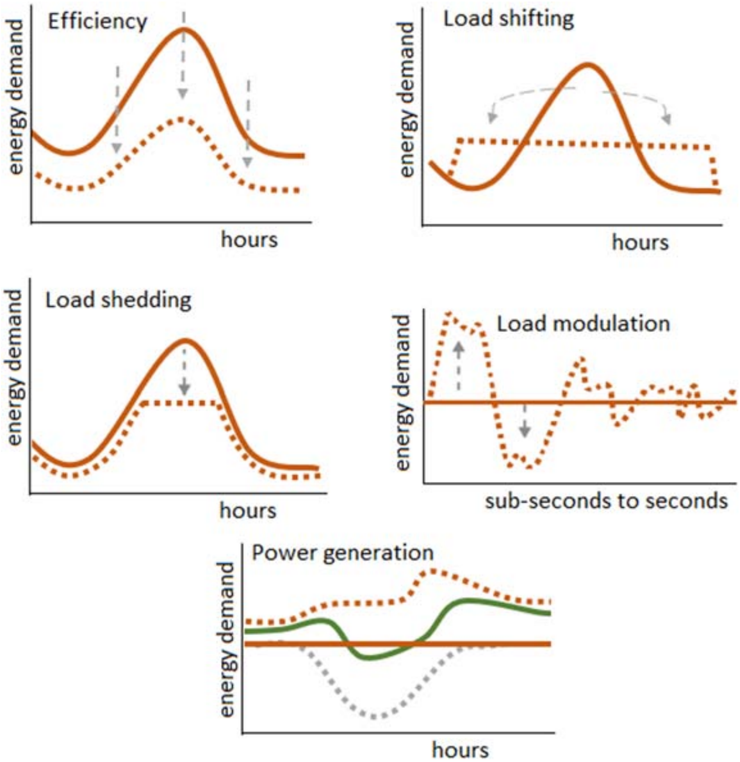

FIGURE 4.3 Demand side management options.

or by controlling equipment or setting up a market where aggregators can convince consumers to stop using electricity during peak demand hours. The electricity demand is reduced in a matter of minutes (only on short notice) after the signal is acknowledged [13]. The system is directly connected to the electrical grid and reacts by responding to signals received from the grid. The occupant's thermal comfort can be maintained by implementing this option for such a short time. During load shedding, the secondary energy source is activated either by thermostatic or nonthermostatic. For instance, *Load Shedding* with Thermal energy storage (TES) technology can reduce peak load by up to 90% [20]. The major benefit of lowering demand in peak demand hours is the cost reduction of transmission and distribution (T&D).

Load shifting is to achieve the short-term building energy demand reduction during peak demand hours and it usually lasts from two to up to 4 hours. The building shifts the timing of the electricity use during the peak period to the off-peak period. Electricity is used to charge TES during off-peak hours while the stored energy is used during peak hours. Therefore, TES technologies are proved to be flexible solutions for load shedding and shifting. Since the building is programmed to use electricity from the grid during off-peak hours, the main benefit of this option is the cost reduction. The most effective technology in this option is the HVAC system, which is connected to energy storage during peak hours [18]. Sometimes there are very low periods of load where the generators cannot back down enough to keep supply and demand in balance. It can be cheaper to raise demand during these periods and keep generation to avoid the startup cost or ramping cost that is associated with running a generator at a very low level.

Load modulation is to achieve short-term building energy demand reduction that has a variable duration. The shift of load management response time is rapid and the demand is reduced by seconds or even subseconds. The signal is received directly from the electrical grid, so the adjustments to the electricity demand can be made rapidly. Batteries and inverters work well with this option. The voltage of the system is controlled based on the modulation provided by the batteries and inverters [19].

Power generation is an option to reduce building energy demand during peak demand hours in which electricity is generated on-site for building utilization or dispatching to the grid. The demand has to be reduced from seconds to minutes and can last for 2–4 hours. The main benefit of this option is the cost reduction of T&D [13].

Each of these options corresponds to a certain technology applied for their implementation to provide certain benefits. A summary of the main benefits of each option and per area of application is provided in Table 4.1.

TABLE 4.1 Building demand side flexibility and management options.

Flexibility option	Characteristics	Benefits	Example of technology applied
Efficiency	• Reduced overall energy use. • Reduced consumption. • Permanent change.	• Energy consumption reduction. • Reduction in fossil fuels consumption. • CO_2 emissions mitigation.	• HVAC system. • Insulated envelope.
Load shedding	• Reduced load during peak demand hours. • Reduced consumption. • Temporary change. • Usually, last for up to 1 h.	• Transmission and distribution cost reduction.	• Lighting system.
Load shifting	• Reduced load during peak demand hours. • No change in consumption. • Temporary change. • Lasts for 2–4 h.	• Financial benefits; reduction of costs.	• HVAC system. • Water heaters.
Load modulation	• Modulation of power demand in terms of seconds or subseconds. • Control of the voltage system. • Response time from subseconds to seconds.	• Financial benefits include the potential integration of RES.	• Batteries and inverters.
Power generation	• On-site electricity generation. • On-site electricity utilization. • Excessive electricity is dispatched to the grid. • Rapid response time within minutes. • Lasts up to 4 h.	• Transmission and distribution cost reduction.	• Solar photovoltaics systems on the rooftops. • Small-scale wind turbines.

4.3 Energy carriers

Energy carriers can be defined as a substance or system that possesses stored energy, which can be converted or used later to operate certain processes such as HVAC and appliances. Therefore, various types of fuels, energy storage systems, electricity, and heat, are considered energy carriers. Technologies associated with energy carriers are those for transmission, storage, and conversion to useful forms for end-users [21,22].

In this section, the focus will be on certain energy carriers that support building energy flexibility [23]. Refereeing to Fig. 4.1, particularly building thermal mass, heat storage tanks and CCHP will be briefly discussed. Table 4.2 shows the common benefits and drawbacks of the considered thermal energy carrier systems for building applications.

TABLE 4.2 Benefits and drawbacks of energy carrier systems.

Energy carrier (scope of application)	Benefits	Drawbacks	References
Building thermal mass (building level)	• Heating/cooling during peak hours. • Building energy demand reduction. • Cost reduction. • Interior temperature fluctuation smoothing. • Peak temperatures reduction. • CO_2 emission reduction by reducing fuel consumption.	• Longer time to charge (heating/cooling). • During the peak summer, it takes a longer time to release heat over the night through natural ventilation in passive buildings.	[24–26]
Heat storage tanks (building level, district level, and system level)	• Peak hours energy demand reduction. • Reduced utility demand costs. • Efficiency improvement of renewable energy systems. • CO_2 emission reduction by reducing fuel consumption.	• Depending on the mechanical parts and water regulations. • Increased complexity due to piping and fittings. • The increased investment cost for smaller tanks.	[4]
Combined cooling, heating, and power (CCHP) (building level, district level, and system level)	• Peak hours energy demand reduction. • Overall efficiency is high. • High durability and reliability. • Work well with boilers. • Depending on heat sources, it can burn solids, liquids, or gases.	• Startup is slow. • The power-to-heat ratio is low. • Depending on the heat source, it may require a boiler for the steam source. • The efficiency of the other mechanical parts is linked with the efficiency of the CCHP system.	[4]

TABLE 4.3 Typical result of thermal mass potential.

Location	Thermal mass position	Energy saving	Cost saving	References
Montreal, Canada	Ventilated ceiling slab	28%	23%	[37]
Denver, USA	Thermo-active building systems	61%	56%–68%	[38]
Sacramento, Phoenix, San-Diego, Seattle, USA	Wall, ceiling, floor	–	6%–18%, ~60%	[39,40]
Eastman, Canada	Floor	–	0%–92%	[41]
Munich, Germany	Ventilated double-skin facade	–	21%–26% in summer and 41%–59% in winter	[42]
Puigverd de Lleida, Spain	Ventilated double skin facade	–	19%–26%	[43]

4.3.1 Building thermal mass

Thermal storage within building thermal mass contributes to reducing heating and cooling loads, and it also has the potential to contribute to managing DSF [27]. The efficiency of the building's thermal mass depends on its heat capacity, internal heat gain, and exterior wall insulation [28]. Building envelope insulation is the most significant factor in preventing heat loss to the exterior. Therefore, building envelope thermal mass has the potential to significantly reduce heating and cooling demands if properly designed [29]. Thermal mass can be boosted with the integration of phase change materials (PCMs) directly within the building structure and components (especially with the design of lightweight buildings) [30]. Microencapsulated PCMs are suitable to be integrated within building structures such as concrete [31], brick [32], plaster, façade [33], gypsum plasterboards, and glazing [34].

The excess heat from the interior is stored within the building's thermal mass during active hours of heating/cooling systems. During the peak hours, the heating/cooling system is off, and the stored heat is returned to the interior usually by natural convection [35,36]. Taking into consideration the duration of peak hours, building thermal mass works well with each building flexibility option introduced in the previous section. Table 4.3 presents the typical potential of energy savings during peak energy demand and cost-savings obtained from recent studies.

Different research results came to a similar conclusion that thermal mass has notable potential in energy savings and reducing building energy demand if combined with the other methods [44].

4.3.2 Heat storage tanks

Heat storage tanks are another technology used to manage peak energy demand and they are applicable for building/district heating and cooling. Tanks can be filled with

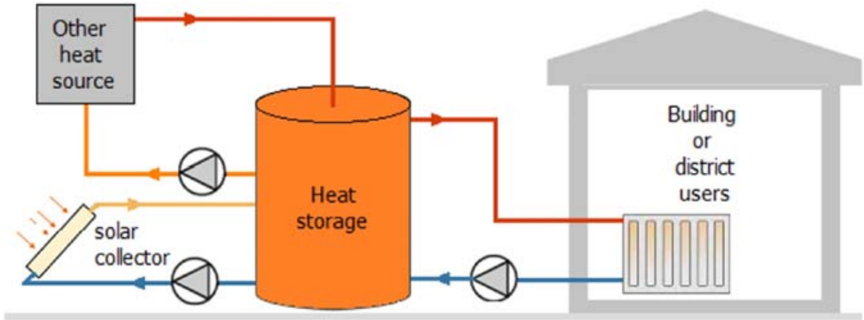

FIGURE 4.4 Working principle of heat storage in tanks.

water or PCMs as the heat storage medium. Depending on the cooling/heating season and climate zone, thermal comfort temperature ranges between 20°C and 27°C. Favorable energy storage temperatures in PCMs are between 0°C and 40°C, and in water between 50°C and 60°C. The heat from a heat source is transferred by a heat transfer fluid (HTF) to the heat storage tank. During the peak demand hours, stored heat from isolated tanks is distributed to building/district users through the other HTF circulating loop [13]. The working principle is shown in Fig. 4.4.

Most renewable energy heat sources need a heat storage tank. Solar thermal collectors, biomass boilers, and heat pump applications are just a few examples of heat sources. Recent trends are related to the application of more efficient heat storage tanks based on latent heat energy storage. The latent heat tank is impacted by a range of operating conditions and design characteristics. This type of heat tank is being researched intensively because it uses PCMs to store latent heat [45].

The results from the available research showed that heat storage tanks are critical components in building energy demand management through heating/cooling assistance. They notably improve the efficiency of RESs and offer a way to lower building energy demand during peak hours [46].

4.3.3 Combined cooling, heating, and power

CCHP systems are applicable for building/district heating, cooling, and electricity generation. Waste heat from the turbine (or district plant) is used to run an absorption chiller. Building cooling/heating is achieved through the distribution of the HTF from absorption chillers to end-users. CCHP works well with heat storage tanks. Heat demand is significantly low in summer, but the waste heat from the turbine can be transformed into cooling through the absorption chiller. Fig. 4.5 shows a conceptual working diagram of CCHP.

The most common CCHP operation strategies discussed in the literature are as follows: (1) the CCHP system is primarily designed to generate electricity to satisfy building electricity demand but the waste heat is used to meet all (or part) the thermal load of buildings; and (2) the CCHP system is primarily designed to satisfy building thermal load. In this case, electricity generation is secondary and it is used to partially satisfy the building electricity load. In each case, excessive generated electricity can be stored or dispatched to

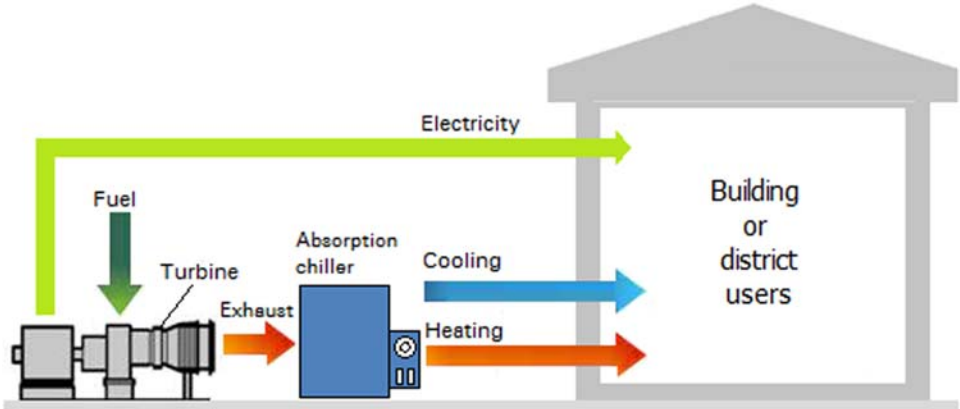

FIGURE 4.5 Schematic diagram of a CCHP system.

TABLE 4.4 Comparison of key performances of CCHP systems [49].

Technology	Reciprocating engines	Steam turbine	Gas turbine	Microturbine	Fuel cell
Efficiency	22%–40%	15%–38%	22%–36%	18%–27%	30%–63%
Overall efficiency	70%–80%	80%	66%–71%	63%–70%	55%–80%
Typical capacity (MWe)	0.005–10	0.5–250	0.5–300	0.03–1.0	200–2.8 commercial CHP
Typical power-to-heat ratio	0.5–1.2	0.07–0.1	0.6–1.1	0.5–0.7	2-Jan
Installed costs ($/kWe)	1500–2900	670–1100	1200–3300 (5–40 MW)	2500–4300	5000–6500
Operation and maintenance costs ($/kWe)	0.009–0.025	0.0060–00.01	0.009–0.013	0.009–0.014	0.032–0.038

the grid and the excess heat can be stored. In case of insufficient electricity generation, electricity is taken from the grid and the heat might be taken from the heat storage tanks [47]. The results from the available research showed that CCHP systems can improve power efficiency by 7.8% -14.83% [48]. Table 4.4 presents a comparison of typical results related to CCHP performances for different systems.

A CCHP system can be made up of a gas generator set, a wind turbine, a solar heater, an absorption heat pump unit, a ground source heat pump unit, a refrigeration unit, and other auxiliary equipment [50]. CCHP systems may all be combined in a variety of ways, and these combinations are routinely studied to meet thermodynamic and economic requirements. The sliding pressure operating system with the constant temperature gas storage tank has the maximum exergy efficiency and yearly profit [51]. As a result of their well-studied performance, CCHP systems are becoming increasingly popular. Natural gas usage

TABLE 4.5 Benefits and drawbacks of CCHP systems (building, system, and district level) [49].

CCHP system	Benefits	Drawbacks	Available sizes
Steam turbine	• Overall efficiency is high. • High durability and reliability. • Work well with boilers. • Can burn solids, liquids, or gases.	• Startup is slow. • Low power to heat ratio. • Requires a boiler for steam source.	50 kW to several hundred MWs
Gas turbine	• Reliability is high. • Emissions are low. • High-grade heat is provided. • Cooling is not required.	• High-pressure gas is required. • Efficiency is reduced as the ambient temperature is increased.	500 kW–300 MW
Microturbine	• Compact size. • A small number of moving parts. • Cooling is not required.	• High costs. • Efficiency is low. • Applicable for lower temperature systems.	30 kW–250 kW (multiple units up to 1000 kW)
Fuel cells	• Efficiency is high. • Emissions and noise are low.	• High costs. • Sensitive to fuel impurities so that they require fuel purification. • Power density is low.	5 kW–2 MW

can be slightly decreased, resulting in savings in energy and a reduction in emissions. The CCHP system can be researched from three perspectives including energy, economics, and environmental performance, due to its relatively high cost [52].

Table 4.5 presents the common benefits and drawbacks of the CCHP system.

4.4 Control systems for demand side management

The focus of this section will be the control systems from the demand side. DR includes all activities that affect the end user's energy use. It can be categorized into two categories: price-based and incentive-based [53]. Price-based DR includes dynamic pricing and tariffs, where end-users tend to change their consumption behavior according to the current prices to reduce their energy cost. In incentive-based DR, end-users are generally under contract with service providers or have other reasons, motivations, or sponsors to reduce their consumption at specific times. It includes voluntary load reduction, demand bidding, and emergency programs [54]. Each of these activities requires following a set of rules that aim to decrease the system load for a specific time period while considering demand-side restrictions, such as indoor environmental comfort for occupants. It has multidimensional nature and most of the time, with conflicting objectives, it makes this policy determination and control problems challenging. Currently available common control methods are:

- Heuristic or RBC.
- Optimal control method.

- Direct optimal control method.
- Model predictive control (MPC).

Developing optimal control models for DR is a challenging problem. There are different dimensions with different characteristics within the system such as time-varying price, limited storage capacity, and stochastic energy availability [55]. Optimal control methods can be classified as direct optimal methods and MPC methods. Direct optimal methods are generally open-loop systems and not iterative but the constructed model is solved once to obtain the optimal solution. Whereas, MPC methods are generally iteratively solved optimization problems where system dynamics or results from the previous iteration are used as the input for the next step.

4.4.1 Rule-based control methods

In general, RBC methods use a set of rules defined based on predetermined criteria, such as thresholds for specific parameters or the occurrence of some events (e.g., weather conditions, price changes). These set of rules are set by using knowledge about the environment and aim to react according to the changes in system parameters. For this purpose, the system should be monitored constantly or periodically to detect changes and act accordingly. Single or multiple criteria can be used, and multiple subsystems may communicate with each other and share information. Policies are defined using state vectors and action/decision vectors and the relationships between them.

Even though RBC methods are simple, nonpredictive, and relatively low-performing, they are still widely used today, due to their practicality. They are easy to apply as compared to more complex methods and less costly to track. Parameter selections are crucial since the change in parameters may highly affect the performance of the control method [56]. Since these methods have predefined criteria and target parameters, they might perform worse than other control methods without considering future states or perturbations in the system. Some of the latest studies on the application of RBC methods are given in Table 4.6.

TABLE 4.6 Recent studies on RBC.

Type of approach/ algorithm	Technology/system	Results	References
A rule-based algorithm in Building Energy Simulation	A heat generation system and a two-storage tank system in a residential building.	An overall increase in the heating system efficiency of up to 15%.	[57]
A rule-based algorithm was applied to three scenarios	A heating system with smart grid-enabled all-electric residential buildings.	A reduction in generation cost of 22.5%, electricity end-use expenditure of 4.9%, and carbon emission of 7.6%.	[58]
Cost-optimal and rule-based control	A heat pump, thermal storage, and electrical storage in a flexible residential energy system with photovoltaics.	Decreased cost by 13%–25% and grid feed-in by 8%–88%.	[59]

4.4.2 Direct optimal control methods

Direct optimal control methods mainly aim to construct the mathematical model of a real-life system and solve it with efficient optimization algorithms. Generally, the systems under consideration have nonlinear and continuous characteristics, which make them very challenging to reach the global optimum. Considering the complexity of energy systems, some assumptions are often required to obtain an optimally solvable model.

More than half of the studies in the literature simulated the system with a single objective [60]. However, in real life, energy systems have a multicriteria or multiobjective nature with generally two conflicting objectives: minimizing energy consumption and maximizing interior comfort [61,62].

Genetic algorithms, particle swarm optimization, and ant colony optimization are the most used algorithms to model energy management systems. In addition to these algorithms, dynamic programming is also one of the most used approaches to modeling the systems with decision-making to find optimal policies [63]. Some of the recently proposed direct optimal control models for different energy systems are presented in Table 4.7.

4.4.3 Model predictive control methods

MPC methods generally use a simplified model of the system that predicts the behavior in the future and optimizes an objective function (or multiobjectives) for the current states of the system, using computational control algorithms. It is a closed-loop system, namely, using the results of the repeatedly solved optimization models as the inputs for the next periods, by considering the future forecasts and sometimes other constraints and disturbances.

TABLE 4.7 Recent studies on direct optimal control methods.

Type of approach/ algorithm	Technology/system	Results	References
Mixed integer linear programming	A residential community grid with renewable generation and energy storage systems.	The time-of-use pricing program shifted around 96% of the load to off-peak hours.	[24]
Multiobjective mixed integer nonlinear programming	Optimal energy use in a smart house.	The mixed objective function value was improved up to 55% to the RBC method in hot weather and up to 63% in cold weather conditions.	[25]
Mixed integer nonlinear programming	A reward-penalty DR program for customers in smart distribution networks.	Can prevent peak rebound and increase the distribution company's profit by 106% compared with a conventional method.	[26]
Game theory	Basic and enhanced interaction strategies between a grid and buildings.	Net profit was increased by 8% and demand fluctuation was reduced by about 40% for the grid, with savings in electricity bills of 2.5%−8.3% for the buildings.	[4]

The forecasting methods for energy use in future periods can be classified into three categories: white-box, black-box, and gray-box models [64]. White-box methods include physics and mathematics-based straightforward analytical models. If there is a sufficient and accurate system information and knowledge, white-box models can predict energy use efficiently. However, for more complex systems, where the system is difficult to be modeled using physical equations, black-box models can be more appropriate. Black-box methods are data-driven models where the predictions are based on input-output relations via statistical analysis. If the system can be monitored and enough data can be collected, black-box methods can be a good alternative. Gray-box (hybrid) methods are the combined methods of white-box and black-box where the models with physical principles can be supported by some additional data-driven conclusions.

In addition to future energy use predictions, constraints and disturbances in the system can be introduced as boundaries, limitations of the variables, or manipulated values of the parameters during computational steps. MPC methods can handle different system characteristics and time-varying dynamics. As the economics of the energy market evolves, economic MPC models are becoming the most common models with cost optimization objectives [65]. Table 4.8 lists some of the selected studies on MPC methods.

By applying state-of-art and computationally strong algorithms, these methods are promising for further improvements. This is the reason why the research on MPC for different systems such as HVAC systems [70] has increased in recent years. A comprehensive review of MPC before 2015 is presented in [71]. In [56], some disadvantages and challenges of MPC models were reported and they are listed in Table 4.9. The high potential of developing a well-performing model is mentioned but also the theoretical and technical difficulties and necessity of high engineering efforts behind it, are highlighted.

TABLE 4.8 Recent studies on MPC.

Type of approach/algorithm	Technology/system	Results	References
Artificial neural network model	HVAC.	The cost savings in the heating and cooling season were 39.22% and 44.41%, respectively.	[66]
A gray-box dynamic thermal model using mixed integer linear programming	Floor heating system.	Reduced daily electricity costs by 1.82%–18.65% for residential end-users.	[67]
A multilevel demand charge, along with a real-time pricing program and incentivized signals	Thermal energy storage (TES) integrated commercial buildings.	The existence of TES in a commercial building led to more flexibility in Dr programs, and a reduction in energy costs while maintaining occupants' comfort level.	[68]
Gray-box control model	Condensing gas boiler and two identical air/water heat pumps in an office building.	An average cost saving of between 34% and 40% resulted as compared to the reference control.	[69]

TABLE 4.9 SWOT analysis for a control method.

Rule-based control methods	**Strengths**	**Weaknesses**
	• Simple and practical. • Low cost of development. • Does not require complex features. • Finding a feasible solution is always possible even if it is far from the optimal solution.	• Not as accurate as other methods. • Has limited energy-saving capabilities. • Performance is highly dependent on the parameter selection. • Lack of continuous adaptation cannot guarantee constraint satisfaction [72].
	Opportunities	**Threats**
	• Can be used as a starting point or submodel for more complex methods.	• As the energy systems are getting more complicated, the performance of this method tends to decrease.
Model predictive control methods	**Strengths**	**Weaknesses**
	• Involves time-varying system dynamics and predictions. • Can handle constraints and disturbances.	• Complexities associated with data collection and computation, causing high costs associated with modeling and operation. • Expert monitoring is required. • Technological limitations on implementation. • A disadvantage in terms of the modeling complexity.
	Opportunities	**Threats**
	• Better performing algorithms can directly affect the performance of the methods • Increasing the presence of distributed RES requires time-dependent models, where MPC is advantageous and promising.	• Computational complexity and cost of modeling will increase as systems get larger and more complex. • Simpler models are preferred to avoid computational costs. However, they result in errors in the solution.
Direct optimal control methods	**Strengths**	**Weaknesses**
	• Can guarantee optimal results. • Once the model is constructed, there is no need for continuous monitoring or data collection for the model to be run.	• High cost of modeling, especially for multiobjective. • Assumptions may result from the solutions to get away from real-life problem settings.
	Opportunities	**Threats**
	• More advances in technology for solving large models are promising for further improvement in model quality.	• Multidimensional real-world problems increase the cost of modeling.

Additionally, the cost of training the personnel (due to lack of qualifications) and their potential resistance to the implementation of MPC models are stated. MPC is the most used and analyzed method among the other alternatives in recent studies.

A SWOT analysis (i.e. strengths, weaknesses, opportunities, and threats) for different control methods is given in Table 4.9.

Each of the current common control methods has advantages and disadvantages as presented in Table 4.9. Among them, the MPC method is promising and attractive considering its capabilities to handle time-varying system dynamics, predictions, constraints, and disturbances. To support further improvements in model development, data management in energy systems will be an essential need and challenge in the immediate future.

4.5 Demand side pricing models

Demand-side pricing models stimulate customers to support load flexibility through various economic incentive programs or penalties. Incentive-based DR is targeting the reduction of electricity usage by offering permanent or time-dependent stimulus. Both models enhance the effectiveness of the grid system. Through DRs, investment in power systems can be reduced and energy savings can be achieved [73]. The pricing methods are seen as the main tool in achieving desirable outcomes such as reducing peak loads, enhancing grid reliability, and promoting higher usage of decentralized renewable energy with volatile power supplies [10]. The peak periods appear in less than 1% of the operating hours, but the costs caused by supporting these periods are more than 10% of the capacity investment. In addition, even a small reduction in electricity usage results in a large change on the production side [74]. Time-of-use pricing (TOU), real-time pricing (RTP), critical peak pricing (CPP), Peak-time rebate (PTR), and inclining block rate (IBR), are among the price-based DR pricing models that are illustrated in Fig. 4.6.

Static pricing strategies that include flat and step tariff pricing methods are traditionally used in most of the world owing to their simplicity and ease of implementation as the electricity price is fixed. It has long been recognized that flat tariff pricing suffers from several drawbacks, such as inadequate pricing mechanism, demotivation for the power sector reform, lack of efficiency, and unfairness as high-power consumers are treated in the same way as low-power consumers [75]. The flat tariff pricing results in the occurrence of grid overload during peak periods as consumers do not have incentives to change their power-consuming routines. Step tariff pricing, where the rate changes with the amount of use, addresses some of the issues related to the flat tariff practice but the main drawbacks, related to the static pricing method, remain unchanged.

The dynamic or time-varying pricing policy emerged as the main method of implementing DR programs. The time-varying pricing methods intend to shift consumers' electricity consumption from the peak periods to the off-peak periods, and in the long run, lead to customers' behaviors change [76]. The most dominant time-varying pricing methods are TOU, CPP, and RTP. The TOU program specifies the price of electricity for a time interval, most commonly for a few hours. CPP differs from TOU by charging significantly more during the selected peak periods. The common feature of both programs is that price schedules do not change frequently. This enables customers to easily mitigate their power usage from the period of high prices to a lower price period aiming to reduce electricity bills [77]. The RTP programs are continuously adjusting the electricity price as it is determined by the power grid condition in real time. So, RTP programs can

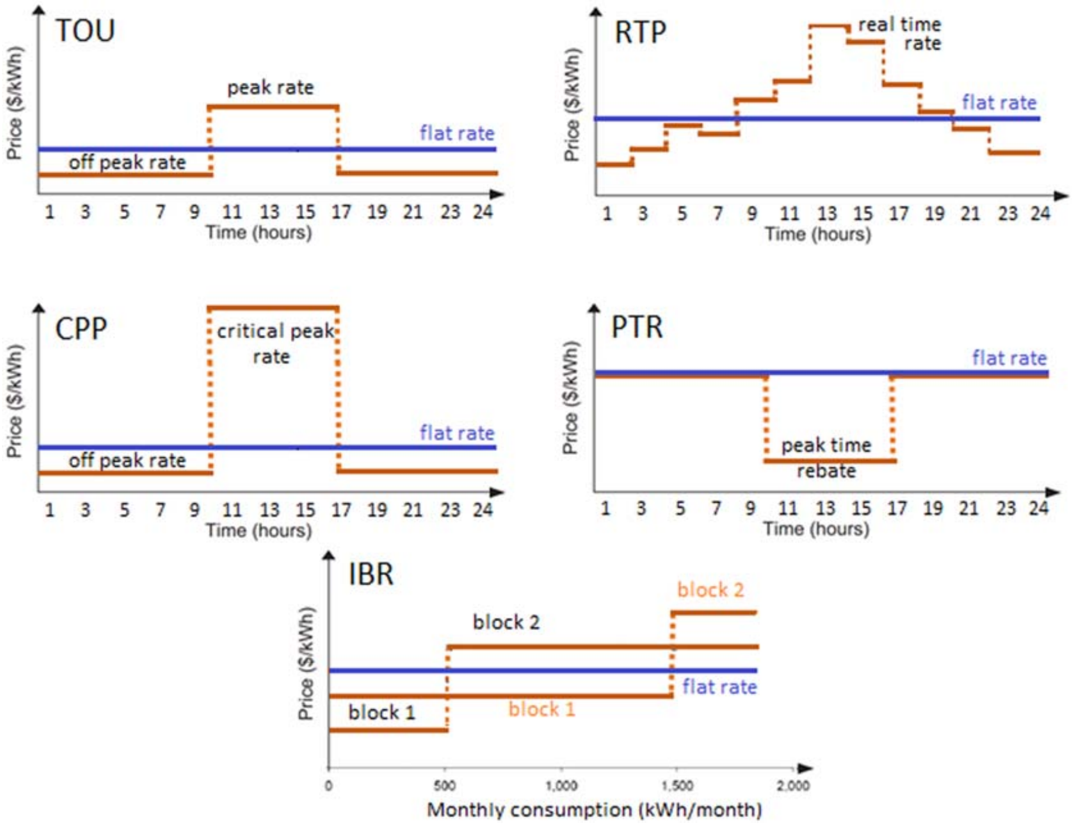

FIGURE 4.6 Illustration of different pricing model types.

be hour-based, and the electricity price can be set in advance for each hour or a few hours for one day, or "intra-hour RTP" programs, with a much shorter interval used for the electricity price (less than an hour) and announced for a shorter time in advance. The intra-hour RTP with high granularity such as 15- and 5-minutes intervals is presented in parts of North American markets, for example, Maryland, New Jersey, and Pennsylvania [78]. In this pricing program, customers have to be evolved in real-time, with high-intensity interaction with the power grid to track the instantaneous price information from the market. Not all RTP programs result in positive savings as reported in [76]. However, the majority of the tested RTP programs (29 out of 35) resulted in reduced electricity bills.

PTR and IBR are two programs that are gaining a lot of attention as they are designed to overcome some shortcomings of the existing time-varying pricing methods. In PTR customers are paid for load reductions on critical days. The rebate amount is estimated relative to a forecast of what the customer would have otherwise consumed (their "base-line"). IBR defines lower and higher blocks, such that users pay more per kWh when more electricity is consumed by a user. The electricity price increases when the consumer's (hourly/daily/monthly) energy consumption exceeds a certain threshold. In this way IBR incentivizes consumers to plan their loads over a 24 hours time to avoid higher rates, effectively reducing the grid's peak-to-average ratio [76]. Table 4.10 lists some of the key benefits and drawbacks of pricing models.

TABLE 4.10 Benefits and drawbacks of pricing models.

Pricing model	Benefits	Drawbacks	References
Time-of-use pricing (TOU)	• Easy to implement. • No need to notify members of events. • Lower yearly bills compared to the flat rate. • Good planning possibilities for customers. • Provides more savings to higher flexibility customers.	• Needs to react daily for maximum impact. • Lost revenue on every high-price block. • Predetermined price often causes deadweight losses.	[72,79,80]
Real-time pricing	• More savings compared to the flat rate yearly. • More efficient options with less flexibility. • Opportunities to use renewables.	• Price volatility causes the risk of paying higher bills. • Technological requirements cause higher costs. • Difficult for customers to plan their electricity usage.	[76,81,82]
Critical Peak Pricing (CPP)	• Maintains power system reliability. • More savings compared to the flat rate yearly. • More efficient options with less flexibility. • Opportunities to use renewables.	• Price volatility causes the risk of paying higher bills. • Technological requirements cause higher costs. • The number of hours to apply for the CPP is limited during a year. • Possible undercollecting revenue for utilities.	[83,84]
Peak-time rebate (PTR)	• Need to predict event days. • Need to notify members of the event. • Need to calculate an accurate baseline (what they would have consumed without the event).	• PTR is completely voluntary. • Relative to TOU revenue erosion is very low. • The rate structure does not need to change. • Participation rates in the programs are high. • High customer satisfaction. • No equipment (aside from advanced metering infrastructure) is required. • Small risk of "stranded assets" if wholesale rates change.	[85,86]
Inclining block rate	• Consumer savings can be increased by reducing the total amount of energy purchases. • Incentivize consumers to self-generate.	• Revenue instability for utilities whose profits are not decoupled from the amounts of electricity sold. • Consumers who fail to lower consumption in response to higher rates could pay higher costs. • Higher costs for larger, less utilization through lower capacity intensive consumers.	[87–89]

The time-varying pricing programs are becoming more present on the market and are here to stay. As the technology that supports the pricing programs would become readily available and reliable, the pace toward full implementation of the time-varying programs will speed up.

4.6 Summary

Under different DSM strategies, multiple flexibility technology options are available such as building thermal mass, HVAC system, CCHP, heat storage tanks, batteries, and photovoltaics. Grid-interactive buildings through smart technologies have significant potential in reducing stress on the electrical grid. Integration of smart supply side technologies (e.g., energy storage, on-site electricity generation) and smart demand side technologies (e.g., HVAC systems, electrical appliances, and lighting) for building energy demand management, can lead to energy demand reduction during peak load hours and consequently cut utility bills as well as CO_2 mitigation. The most used flexibility option is thermostatically controlled load with TES, followed by electric appliance scheduling.

The current development of smart control algorithms helps predict dynamic changes and the best timing for peak load shifting. The majority of the models relied on deterministic predictions of how to make investment and dispatch choices, and they ignored probabilistic and behavioral factors. Deterministic forecasting is useful for handling anticipated changes in supply or demand, but not so much for unanticipated changes. Among the control methods discussed above, the MPC method is promising in handling time-varying system dynamics, predictions, constraints, and disturbances.

A deeper insight into DSM through the use of energy flexibility options in buildings is provided. Traditionally, large industrial customers were targeted and the energy usage is controlled by the customer itself. Advances in new technologies such as metering and communication enable new commercial and residential customers to be involved. DR programs would likely become more common in the future and the customers will have an opportunity to choose a suitable one. These findings provided a general research trend in energy flexibility and DSM that can help readers to define their future research projects.

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SECTION II

Emerging technologies and case studies for enhanced energy flexibility

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CHAPTER

5

Thermal energy storage for enhanced building energy flexibility

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This chapter introduces the role of thermal energy storage (TES) systems in enhancing building energy flexibility and demand-side management. Different forms of TES and their related storage media and materials were reviewed and the link between TES systems and energy flexibility was discussed. The role of TES systems in building energy flexibility and demand-side management was then addressed in terms of long-term (seasonal) and short-term storage applications. Different TES materials or media, such as sensible heat storage by water tanks, aquifers, and latent heat storage by various phase change materials can be considered. Furthermore, different techniques that can be utilized to manage the demand with the aid of TES systems are discussed. Different approaches, such as model predictive control as one of the most prominent ones, can be considered to maximize the benefit of TES in demand-side management, and hence energy flexibility.

5.1 Introduction

Towards the new generation of energy production and utilization such as taking the benefits of renewable energy sources, the significance of thermal energy storage (TES) becomes more and more prominent as renewable energy sources such as solar and wind energy are intermittent [1]. Hence, a strong need for thermal storage arises when heating is related to these sources. Not only for effective use of renewable and/or intermittent energy sources but using TES is also a promising technique to improve the flexibility of energy by balancing the demand and supply in electricity as well as heating and cooling

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[2]. Thermal energy obtained from renewable energy sources (e.g., solar energy) or partly renewable energy sources (e.g., solar-assisted heat pumps) can be stored in an appropriate medium for later use. This later use can be arranged to manage the demand side and contribute to energy flexibility in buildings [3]. Grid stability can be improved by eliminating the mismatch between energy production and demand. A generic depiction of demand-side management of the energy flexibility with storage on the consumer side is illustrated in Fig. 5.1, in which a positive signal for the energy flexibility refers to the activation of storage, load shifting, or load reduction while a negative signal refers to charging of the grid power into the energy storage system.

TES can be handled in different forms, which are mainly sensible heat, latent heat, and thermochemical heat [4,5]. In the sensible heat thermal storage technique, the material where the heat is stored preserves its physical phase, and hence, energy storage or release is reflected by a significant variation in temperature. In latent heat thermal energy storage (LHTES), the material changes its phase (usually between solid and liquid) during the latent heat storage process, and hence, the temperature remains almost constant. In this technique, the mass, the latent heat storage capacity, and the thermal conductivity of the material are among the significant parameters [6]. Thermochemical energy storage techniques are driven by high-temperature endothermic chemical reactions in a thermochemical material along a physical or chemical reversible process [7,8].

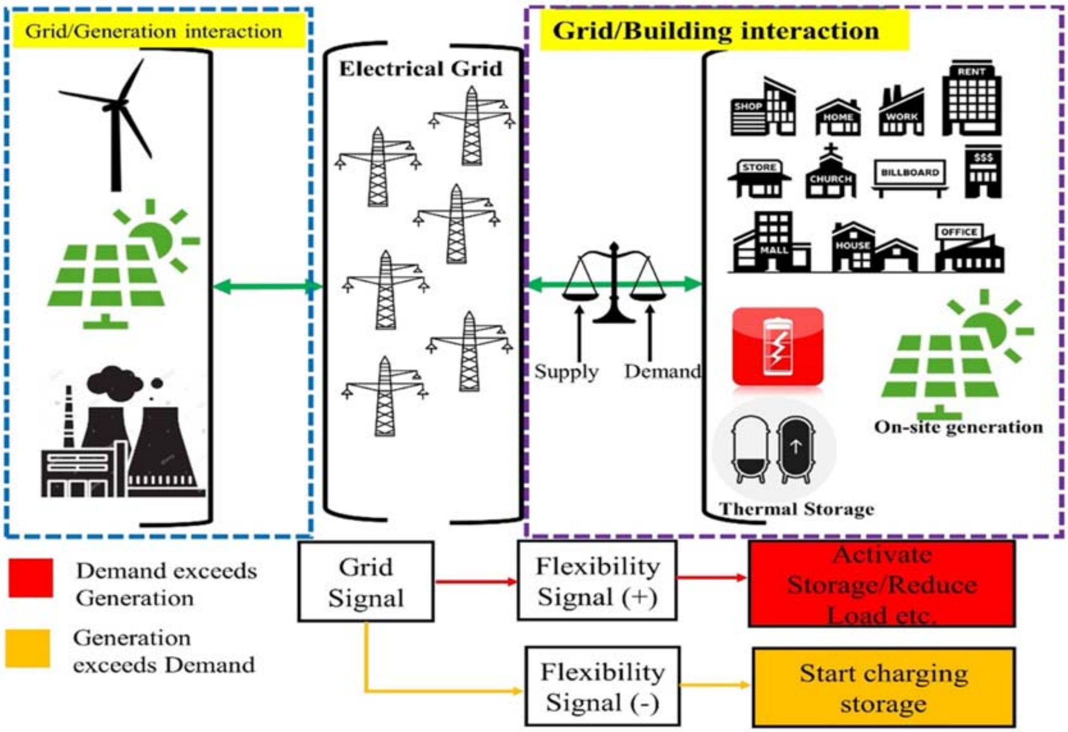

FIGURE 5.1 A generic representation of demand-side management with energy storage.

The media and materials for TES are highly dependent on the considered form of energy storage. For instance, water, ground, and aquifers are usually considered for sensible heat storage [9–11], while phase change materials (PCMs), which have different types such as organic, inorganic, and eutectic [12], are usually taken as latent heat storage materials due to their high latent heat capacities that can allow 5–14 times higher amount of energy storage at a nearly isothermal process, as compared to sensible heat storage at the same volume [13–15]. This high thermal storage capacity can also contribute to energy flexibility in buildings in various ways. TES for enhancement of building energy flexibility can be considered in two major groups, namely seasonal TES and short-term TES, which may be dependent on the application, energy source, storage medium, and demand scale of a building [16]. Moreover, different applications of TES in buildings based on the passive and active kinds can be depicted in Fig. 5.2.

5.2 Forms of thermal energy storage

Thermal energy can be stored in sensible, latent, or thermochemical forms as mentioned in the previous section. Sensible heat storage is a simple option, which often uses inexpensive materials or media such as water, ground, or existing building structure as the storage medium. The temperature range of the application is also important as the temperature of the utilized material noticeably varies during the energy charge and discharge processes [18].

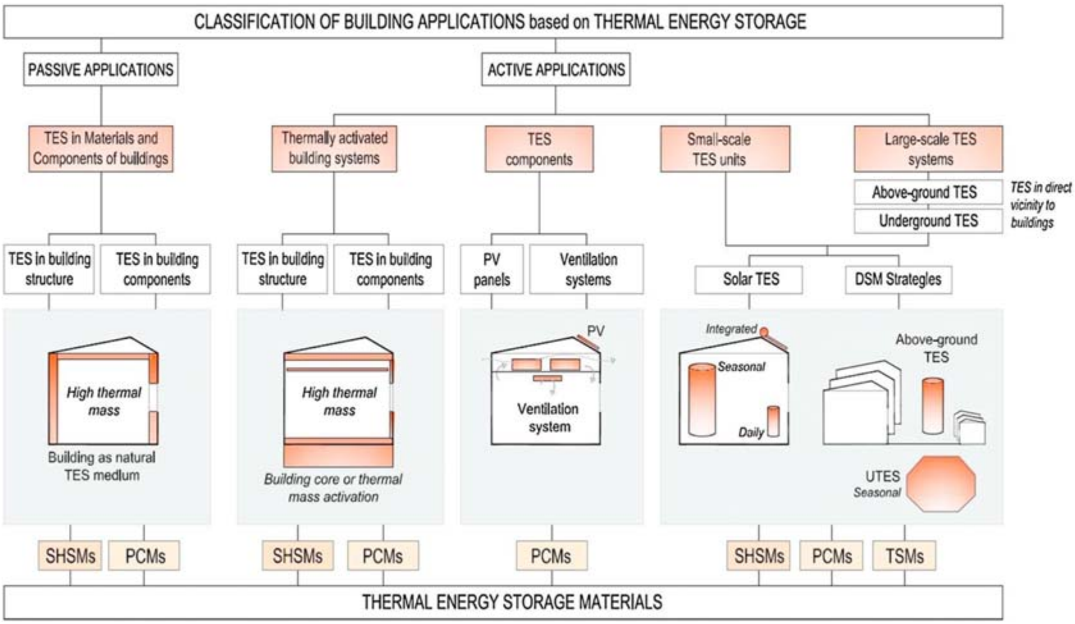

FIGURE 5.2 Different applications of TES in buildings (SHSMs: Sensible heat storage materials, TSMs: Thermochemical energy storage material) [17].

Latent heat storage, on the other hand, takes place via the phase change of the storage material, and hence, the material undergoes a nearly isothermal process [19]. During this process, the material absorbs (or releases) a significantly high amount of energy proportional to its latent heat capacity. Therefore, latent heat storage systems occupy a smaller volume or size, compared to sensible heat storage systems, due to the high energy density of the latent heat storage materials such as PCMs and the capability of nearly isothermal phase transition [20,21]. Thermochemical energy storage is a relatively more complex method compared to the previous two techniques. In this technique, thermochemical reactions are considered for TES where energy density is the highest among these three techniques [22].

5.2.1 Sensible heat storage

The mainly considered materials and media for sensible heat storage are water, which is usually considered in specifically designed tanks, aquifers, ground, and structural thermal mass in consideration of building energy applications, which are presented as follows.

5.2.1.1 Water tanks

Due to its relatively high specific heat and thermal conductivity compared to other fluids, water is a well-known and frequently used heat transfer fluid, as well as a sensible heat storage medium. In addition to that, its availability and ease of use make water one of the favorite materials in this field. Furthermore, water has a wide range of usages in the daily life of society, such as domestic hot water (DHW) and space heating purposes.

For thermal storage in sensible means, water tanks are frequently used. These tanks can be either constructed using different materials such as metal and plastics or can be formed by natural geological effects over a time period [23]. Water tanks can be utilized in various TES applications for different purposes. For example, in solar energy applications, water is a popular material for sensible heat storage, due to its large specific heat of 4.187 kJ/(kg K), and water tanks are frequently considered for thermal storage in the applications such as solar DHW utilization. In water storage tanks, the temperature range for the heating and DHW applications is usually between 25°C and 80°C [24]. Furthermore, a natural stratification phenomenon is occurred in water tanks due to density variation sourced by different local temperatures of water in the tank. Hence, the relatively higher temperature portion of water is accumulated at the top part of the tank, while the colder portion is sunk through the bottom due to higher density. The portion located between these two hot and cold portions, namely the moderate temperature one, is called thermocline [25]. The stratification depends on several factors such as tank geometry, the position of inlet and outlet ports as well as the natural or forced mixing effect in the tank. At this point, in a water tank dedicated to sensible heat storage, stratification is desired to be at a high order to improve system efficiency. Besides, one of the main issues in water storage tanks is the inevitable heat losses which degrade the thermal storage performance. Thus, this issue can significantly affect the flexible use of energy [24,26], and therefore the tanks should be well insulated.

5.2.1.2 *Aquifers*

Aquifers are natural geological structures occurred on the surface of the earth, and they include groundwater. These formations are significantly large, which makes them suitable for long-term storage, for example, seasonal thermal storage. The main advantage of aquifers for long-term storage is their low cost. Despite having a relatively low storage efficiency of about 70%, they usually do not require any costs once access to these structures is handled, and thus, they are still a popular way for low-cost sensible heat storage [27]. The operational principles of aquifers are also simple. They require a pump and a heat exchanger to transfer the thermal energy from its warmer side flowing through the residential place and then return to the well as the cold fluid, as shown in Fig. 5.3. In summer times, the same principle can be implemented for cooling [29]. Aquifers have large thermal masses, and hence, they can maintain heat or cold for a long period. Their heating is usually supplied by solar radiation implemented directly onto them. Hence, they do not require any other heat source. Low-grade heat such as industrial waste heat can also satisfy this purpose [27]. The contribution of aquifers to energy flexibility in buildings is discussed in Section 5.3.

5.2.1.3 *Ground*

Similar to aquifers to store thermal energy over a long time period, the ground can also absorb and release thermal energy for seasonal periods. The ground soil and rock beds

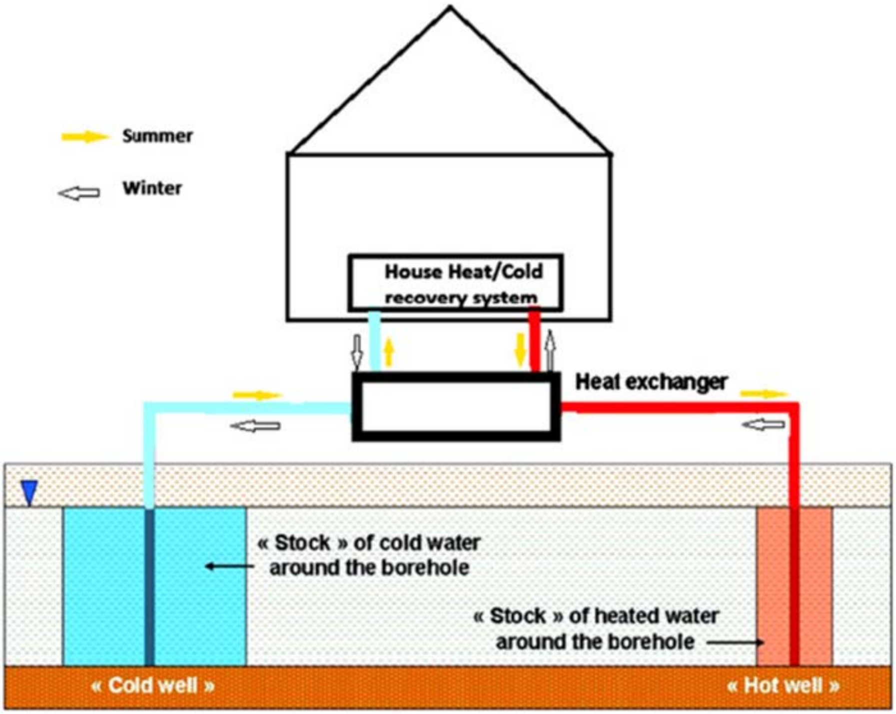

FIGURE 5.3 Basic operation principle of an aquifer TES in winter and summer conditions [28].

can be used as a long-term energy storage medium because solar irradiation can be naturally stored in such media. Having a high heat capacity, due to their large thermal mass and simple structure without requiring any separate site makes ground soil and rock beds a favorable medium for TES [30]. The high TES potential of ground can be quantitatively expressed by its large heat capacity, which is approximately 920 J/(kg K), and the high volumetric density which is around 1800 kg/m^3 [31]. Thus, these specifications, along with the high ability and simplicity, make ground thermal storage a promising technique for the applications of energy flexibility in buildings.

Charging and discharging thermal energy in the ground TES systems can be attained by simply using single or double borehole heat exchangers, which are usually installed at a depth of 30 to 100 m generally using polybutylene pipes [32]. Similarly, borehole heat exchangers with U-shaped piping are also used for bedrocks, and the significance of their design for effective heat exchange has been emphasized by researchers [33]. Using borehole heat exchangers, the stored heat can be extracted by using either heat pumps when the stored heat is at a low temperature such as 0°C−40°C, or by direct circulation via pumps when the heat storage is carried out at a high temperature such as 40°C−80°C. Nevertheless, due to the low thermal conductivity of some soil types and some inevitable heat losses, the storage efficiency is usually around 70% [34].

5.2.1.4 *Structural thermal mass*

TES can be directly considered via building components which have the ability of storing thermal energy depending on the properties of the utilized construction materials. Hence, with respect to the thermal mass of building construction materials, that is structural mass, the heating or cooling time of a building together with the time for preserving this thermal energy inside the building can significantly vary. For instance, lightweight construction materials such as construction steel or timber supported with fiber or other synthetic insulation materials usually have relatively low thermal mass, compared to structural materials such as masonry with heavy physical material content [35]. Structural mass used for TES in buildings does not require additional costs or technical setups apart from the building construction and also does not require maintenance or additional installation. Hence, it can be a promising alternative for energy flexibility in buildings [36]. However, technical issues due to the utilization of heat pumps and the lack of advanced control strategies can restrict the applications to which the solutions are addressed [36,37]. It should be also noted that the structural thermal mass can also contribute to energy savings in buildings [38]. In addition, structural thermal mass as a TES medium can reduce the temperature fluctuations in buildings, resulting in more efficient heating and cooling, and thereby, it can prevent excessive heating or cooling costs [39].

5.2.2 Latent heat storage

Latent heat TES is long under development and has a promising potential to eliminate the mismatch between energy production and demand by shifting the peak loads to the off-peak hours or storing the excess energy for later usage. Unlike sensible heat storage, latent heat storage has the ability to change its phase during heat storage and release as it is a high energy storage density within small volumes [40,41]. Both short-term and long-term TESs can be considered depending on the application type.

PCMs are utilized as the energy storage medium in LHTES systems due to their desirable and distinctive thermophysical characteristics such as high latent heat of fusion, isothermal or nearly-isothermal phase transition behavior, and proper melting temperature range [4,42,43]. Moreover, PCMs can provide other expected properties in LHTES systems including low subcooling, chemical stability, nontoxicity, and noncorrosiveness depending on the material type [44,45]. Although solid-liquid PCMs are commonly utilized, there are also other types of materials undergoing phase change between solid-solid, solid-gas, and liquid-gas for consideration in practical applications, and they are shown in Fig. 5.4 [46,47]. In fact, a remarkable amount of thermal energy can be stored during solid-to-gas and liquid-to-gas phase changes due to high enthalpy values; however, some technical problems including high variations in pressure and volume limit their practical applications [48,49]. Compared to solid/liquid-gas and solid-liquid phase change, solid-solid phase change has advantages such as low volume change and no leakage during phase transition, whereas it also has a significantly low latent heat storage capacity [50]. Therefore, the transition between solid and liquid phases is mostly considered in the latent heat TES applications since solid-liquid phase change is more stable, safe, and it has relatively small volume variations during phase transition [51].

Solid to liquid PCMs are further divided into three main groups (Fig. 5.4) according to their chemical compositions as organic, inorganic, and eutectic (mixture) substances [41,42,46]. Many of the organic and inorganic materials can be classified as PCMs considering their phase transition temperature ranges and latent heat capacities. Nonetheless, some of these materials cannot be treated as PCMs even though they have a proper melting temperature range and a high latent heat capacity since they lack significant thermophysical properties such as adequate thermal conductivity, chemical stability, and noncorrosiveness which are crucial for encapsulation. In the following sections, material

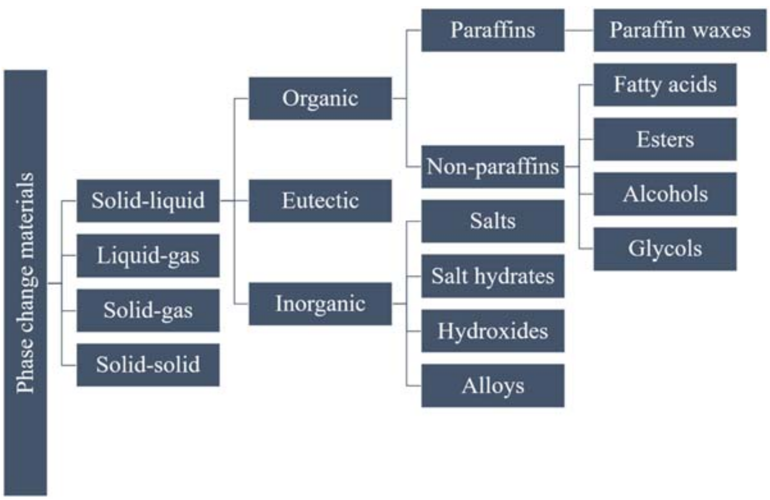

FIGURE 5.4 Classification of phase change materials.

properties are briefly reviewed for organic, inorganic, and eutectic types to reveal potential implementation areas for enhancing energy flexibility in buildings by using latent heat TES.

5.2.2.1 *Organic materials*

Organic materials are further divided into two subclasses including paraffin (paraffin waxes) and nonparaffin (e.g., fatty acids, esters, alcohols, and glycols). They show congruent phase transition with no or very low phase segregation during the heat storage-release process [42,52]. It is possible to achieve several melting/solidification cycles repeatedly without significant deterioration in the thermophysical properties including latent heat capacity and phase transition temperature range of organic materials due to their thermally stable nature [53,54]. This feature is especially important considering the operating conditions of PCMs implemented in buildings that undergo continual melting/solidification cycles. Besides, these substances are available for a wide range of phase change temperature ranges enabling diverse applications in different fields [55].

Paraffin is preferred as the TES material due to its commercial availability and reasonable cost [45,56]. Paraffin consists of hydrocarbon chains in the chemical form of C_nH_{2n+2}, and the number of carbon atoms determines the thermophysical properties such as phase transition temperature and latent heat of fusion [57]. Increasing the number of carbon atoms in the chain increases the melting temperature range as well as the latent heat storage capacity, and vice versa. Paraffin based PCMs are stable at temperature conditions under 500°C, safe, inexpensive, and chemically inert organic materials. Moreover, they show good compatibility with other materials [46]. The melting temperature range of some commercial paraffin materials varies between −9°C and 111°C, while the latent heat capacity varies in the range of 120−260 kJ/kg [58]. Despite these favorable properties, some negative thermophysical properties including low thermal conductivity (around 0.2 W/(mK)), high volume variation, and flammability are among the main limitations [59,60].

Among organic substances, nonparaffin materials including fatty acids, esters, alcohols, and glycols are also extensively utilized in TES systems due to their high accessibility [61]. Nevertheless, their high cost compared to paraffin materials limits their practical usage. High TES density, low supercooling, and no phase segregation are the main characteristic properties of these materials [46,61]. Fatty acids are the most used organic materials among the nonparaffin, and they exist in the chemical form of $CH_3(CH_2)_{2n} \cdot COOH$ while n is an even number that generally varies between 4 and 34. Their melting temperature range is around 5°C−76°C making them potential candidates for TES applications in buildings. Similar to paraffin substances, nonparaffin materials also suffer from low thermal conductivity drawbacks and substantial efforts have been devoted to overcoming this challenge [52,62].

5.2.2.2 *Inorganic materials*

Salts, salt hydrates, hydroxides, and alloys are solid-liquid inorganic substances often used for TES and they show incongruent phase transition with supercooling. The most noticeable positive thermophysical properties of inorganic materials are high latent heat capacity, high thermal conductivity, and low volume variation during the phase change process [42,46]. In general, their thermal conductivity is around 0.5 W/(mK) which is about two folds higher than that of organic materials [41]. The latent heat of fusion of these substances is significantly higher than that of organic materials and varies between 150 and 300 kJ/kg while they are available over a wide range of phase transition temperatures (from −52°C to 90°C) [58]. Besides, they are inexpensive and nonflammable compared to organic materials. However, despite their obvious advantages over organic materials, they are generally corrosive to metal containers and show phase segregation during the phase transition process [41,63].

Among inorganic materials, salt hydrates have been extensively studied for TES applications due to their high latent heat capacity, high thermal conductivity, and insignificant volume change during the phase transition process [64]. However, their phase segregation feature during phase transition is an important drawback since it decreases the TES capacity under continual melting and solidification cycles [65]. Besides, the corrosiveness of metal containers is also a negative side of using inorganic materials. Nevertheless, suitable containers can be used to overcome this problem [66].

5.2.2.3 Eutectic materials

A combination of organic−organic [67], organic−inorganic [68], or inorganic−inorganic [69] substances at different volumetric ratios can constitute eutectic materials. Unlike single compounds of organic and inorganic materials, eutectic materials may have desirable thermophysical properties for TES since different substances with diverse features can be combined at different proportions [1,4]. Besides, they have no phase segregation and supercooling during phase transition and have a sharp melting point along with a high latent heat capacity. The major drawback of eutectic mixtures is that they are significantly more expensive than organic and inorganic materials [52,70]. Moreover, there is a lack of thermophysical data for eutectic materials for many applications including buildings.

5.2.3 Thermochemical heat storage

Thermochemical energy storage is one of the methods utilized in TES systems. In sensible heat energy storage, the temperature of the medium is increased by delivering thermal energy to the material with a heat exchanger whereas in latent heat storage an extra phase change enthalpy is added to that energy [46,52]. Considering the nature of sensible and latent heat storage, it is obvious that both methods lack proper management of stored energy. Thermochemical energy storage, on the other hand, relies on a physically reversible procedure with two materials or reversible chemical reactions involving thermochemical materials (TCMs) [8]. Thereby, available thermal energy is absorbed by the endothermic process and used later when it is needed. The exothermic process is then invoked to release that energy for utilization in applications such as buildings [71]. There is no heat loss during energy storage and release processes since thermochemical energy storage is established on the composition and decomposition of molecular bonds [72]. Because of this feature, this method can be used for seasonal TES since it provides long storage periods, and theoretically, the stored energy can be maintained for an unlimited period. However, compared to sensible and latent heat storage methods, thermochemical energy storage is very complex to build and operate [8,73].

High energy storage density in relatively small containers can be achieved by the thermochemical storage method since it depends on the enthalpy of the reaction and the number of reactant moles [74]. Nevertheless, some major drawbacks such as the corrosiveness of TCM with metal containers and the necessity of additional energy to start discharging, that is exothermic reaction, also needs to be addressed [75].

Fig. 5.5 shows the required storage volume for a total thermal energy capacity of 10 GJ including 25% heat losses when different TES storage options are used [76]. It can be seen that energy density is significantly high for chemical storage, followed by latent heat and then sensible heat which is considered as water storage with a temperature difference of 70°C. Although thermochemical storage has a high density, the availability, applicability, and cost of operation should be considered. At this point, water comes up as the simple and practical solution for many TES applications, despite its relatively low energy density.

5.3 Using thermal energy storage to enhance building energy flexibility

TES is an effective contributor to improving building energy flexibility since it can help shift the load or shave the peak consumption due to its ability to store a significant amount of energy. The stored energy can be utilized during more appropriate periods depending on the operation strategy [77]. Thereby, energy saving can be achieved and the period for energy use can be effectively controlled to prevent the mismatch between energy supply and demand.

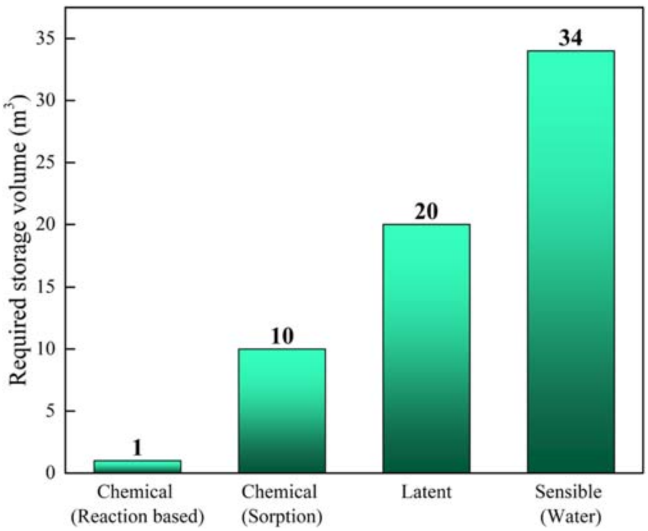

FIGURE 5.5 Energy density of different storage options.

To improve building energy flexibility, these TES techniques can be considered for long term, that is seasonally, or short term, for example, on a daily or weekly basis, depending on the strategies and the feasibility of the application.

5.3.1 Seasonal thermal energy storage

The intermittent nature, that is daily, weekly and seasonal fluctuations observed in energy availability, of most renewable energy sources is a major handicap leading to a mismatch between energy production and demand [78]. This mismatch can be eliminated by using appropriate TES. Both short-term and long-term energy storage systems are suitable to contribute to the energy flexibility of buildings and energy grid/network operation [23,79]. Seasonal TES is usually utilized when there is a long time difference between the energy availability and the demand for that energy. For instance, the most obvious seasonal energy storage necessity occurs for solar energy which is vastly available in the summer season whereas it is needed in the winter season for space heating purposes [79,80]. Seasonal energy storage falls into the category of long-term energy storage considering its high temporal difference between production and demand which can be up to several months. This concept enables storage of energy when energy is available and then discharges this energy when it is needed. Therefore, it increases the flexibility of buildings by seasonally balancing energy production and demand by eliminating the temporal mismatch [81,82].

It is noted in the literature that the roof of a typical house exposed to enough solar energy can easily meet the energy requirement of that house over a year period [23]. Considering the high share of the residential sector in total energy consumption (which is around 30%) also [83], it can be said that the utilization of solar energy is the most promising technology among all other renewable energy sources and fossil fuels to contribute to decarbonization and energy flexibility of buildings. Solar energy is an intermittent energy source on both a daily (during the day) and a seasonal (during summer) basis, and therefore, the offset between the available energy and demand should be compensated by energy storage. The daily mismatch in energy supply-demand is easy to eliminate by using short-term energy storage such as water tanks, structural thermal mass, and aquifers. On the other hand, the seasonal offset is more complicated and expensive to compensate for due to larger capacities requiring high volumes/spaces [78].

All three methods, namely sensible, latent and thermochemical heat storage systems, have been used in demonstration projects as well as in practical applications to provide seasonal energy flexibility [30,84]. For instance, an aquifer sensible heat storage plant was built for a multifamily apartment in Rostock, Germany, which consists of 108 separate houses [85,86]. Furthermore, the same researchers expanded the project to Hannover and Attenkirchen with hot-water heat storage and hot-water/duct heat storage methods, respectively. An aquifer TES system was designed to provide heating and cooling to a hospital located in Cukurova, Turkey [87]. The considered aquifer storage system is presented in Fig. 5.6. It was reported that this storage system was expected to reduce both the heating and cooling demand of the hospital by using seasonally stored energy. In another work, a ground TES consisting of 60,000 m^3 rock was used to meet the space heating of 50

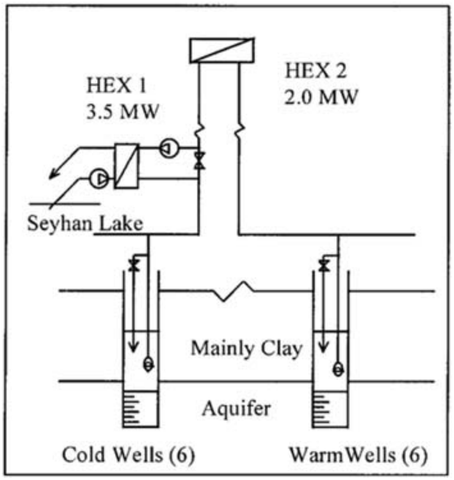

FIGURE 5.6 Considered aquifer energy storage systems [87].

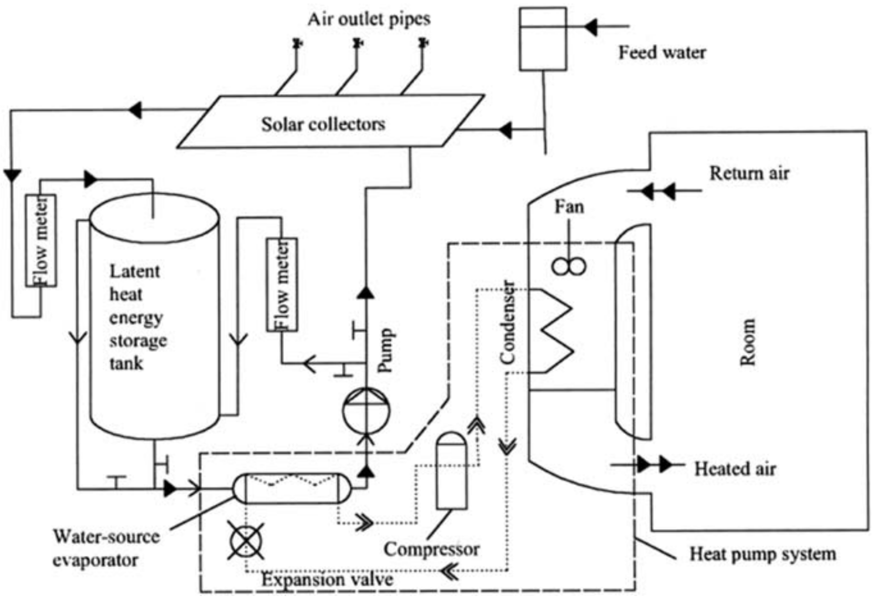

FIGURE 5.7 Latent heat TES integrated with solar energy [89].

residential units [88]. It was shown that this system performed as planned, and the energy requirement of each building was expected to decrease by about 30% after 3–5 years of operation.

A latent heat TES tank filled with 1090 kg $CaCl_26H_2O$ as a storage medium integrated with a solar-powered heat pump system was studied [89]. The system was designed to assist in heating a 75 m^2 laboratory environment (Fig. 5.7). It was concluded that the storage tank should be well insulated and the PCM in the tank should be changed after it loses its stability, after a certain number of cycles. Besides, the ratio of energy supplied by the PCM to the energy consumption of the conventional system was monitored and calculated. The heating of a 180 m^2 greenhouse by a seasonal latent heat TES was experimentally investigated [90]. The LHTES consisted of 6 tons of paraffin wax filled in a cylindrical tank. Consequently, the rates of energy and exergy efficiencies were reported to be around 40% and 4%, respectively, during the heating of the greenhouse.

Thermochemical heat storage was utilized by a closed sorption system with a working pair of (NaOH)-water for seasonal energy storage [91]. According to the findings from the single-stage prototype, solar heat input should be 150°C and the energy storage density was six times higher than that of traditional heat storage with water for space heating at 40°C. A project named *Watergy Thermo Chemical Storage* was conducted for solar seasonal TES and cooling purposes in Berlin, Germany [92], in which $MgCl_2$ was utilized as a thermochemical material with 267 kWh/m^3 energy density. Potential applications such as solar heating, solar cooling, and solar water generation along with the integration of solar desalination systems were reported. This system showed a great advantage in terms of cost reduction compared to the conventional ones. A thermochemical thermal energy accumulator, that is absorption process, was considered for space cooling applications, and up to 253 kWh/m^3 energy storage density (with LiCl) was reached in the laboratory test [93]. In another project, a closed thermochemical energy storage system was developed and utilized for space heating and industrial heat storage processes [94]. The system has a capacity of 750 L, and it was integrated with heat pipes. It was reported during the heat release process a desired thermal energy amount with temperatures higher than 60°C can be achieved for space heating and hot domestic water applications.

5.3.2 Short-term thermal energy storage

Due to the rapid increment of the utilization of renewable energy sources for electricity production, a large amount of uncertain load is often supplied to the grid which should be balanced with the demand, that is ensuring energy flexibility, especially for building energy applications since buildings consume a significant amount of energy for heating and cooling [95]. At this point, TES can help enhance energy flexibility in short time intervals. Short-term TES applications usually cover a period consisting of hours, or a couple of days [96]. During this period, thermal energy is stored using various ways as mentioned in previous sections. Furthermore, even larger heat storage media such as shallow aquifers can be used for short-term TES aiming to improve energy flexibility, and thermal energy stored during off-peak periods can be utilized at a rate of up to 90% during peak load periods [97]. In addition, the study indicated that, in such systems, low-temperature storage attained a larger rate of energy recovery (between 78% and 87%) while high-temperature thermal storages have lower rates of 53%−71%. Structural thermal mass can be also used for short-term TES which can improve building energy flexibility. For instance, the heating energy flexibility potential of building clusters was investigated by considering the effect of building thermal mass based on the economic penalty signal [98]. It was reported that the residual energy demand can be decreased up to 14% with the implementation of smart systems for both the light and heavy thermal mass clusters. However, in both configurations, that is light and heavy clusters, the energy flexibility index was found to be the same, and hence, it was revealed that the higher thermal mass of the cluster did not further increase the energy flexibility index. Foteinaki et al. [99] carried out a study focusing on the energy flexibility analysis of buildings for district heating by using thermal mass, and it was found that an energy decrease between 40% and 87% can be attained during the peak load hours.

In another similar study where thermal mass was utilized as the energy flexibility resource of a district heating system, a significant amount of load shifting was achieved, ranging from 41% to 51% [100]. The comparison of the effects of the structural thermal mass of a poorly insulated building and a well-insulated building on energy flexibility showed that the heat modulation characteristics are noticeably different. The poorly insulated building can regulate a relatively larger amount of heat for a shorter period of time. However, on the other hand, the well-insulated passive house regulated a smaller amount of heat for a longer period [101]. Similar conclusions have been reported in other modeling studies [36]. The influence of building thermal mass on energy flexibility was evaluated by Hall and Geissler [102], and it was found that the operation schedule of the heat pump was greatly impacted by the construction type of the building. A higher thermal mass was more beneficial to energy flexibility than low thermal inertia.

The short-term demand response potential of a ventilated floor system that was heated by electricity was investigated by comparing a traditional power system with the one using demand response signals. It was reported that the ventilated floor has the advantages of enhancing the thermal load flexibility, and reducing power consumption (e.g., 62.7%) [103]. In another study, the energy flexibility of a heat pump hot water storage system for a residential building was evaluated by considering various factors including environmental climate conditions, control algorithm, tank storage capacity, and efficiency [104]. It was reported that the control algorithm, occupant behavior, and climate conditions are the most effective parameters for the energy flexibility potential. According to the results, the energy flexibility of the house can be altered by 2−4 factors depending on these parameters and the energy flexibility potential can increase up to 25% by using smart controllers. By ensuring building heating energy flexibility, it is of great importance not to have the risk to violate thermal comfort and technical constraints. At this point, apart from the fact that the TES capacity of a building is determined by its total thermal inertia, the insulation level of the envelopes was found to be the most important parameter for heating load shifting [105].

Integration of TES to heat pumps can significantly contribute to improving building energy flexibility in the short term. Thermal energy produced by heat pumps can be stored in TES and used later to achieve load shifting operations [106,107], as will be discussed in Chapter 7 in detail. The integration of TES devices to heat pumps for ensuring energy flexibility can be considered in different ways such as the connection of TES units to the heat sink (condenser side) for buffering purposes or to the heat source (evaporator side) of the heat pump for storing renewable energy (usually solar) to control its usage with respect to the demand side [108]. In the experimental study carried out by Kuboth et al. [109], the model predictive control approach was applied to two identical residential heat pump systems with TES units to compare the impact of the model predictive control on flexible operation within a test period of 120 h. It was shown that the mean value of the coefficient of performance of the heat pump was increased by 22.2% while average operational costs were decreased by 34%. The same control approach with different strategies was implemented on a heat pump test rig in laboratory conditions, and these strategies were evaluated with respect to various parameters such as cost, carbon emissions, thermal comfort, and flexibility of energy [110]. The results indicated that the reductions of up to 7% in operational costs and 17% in CO_2 emissions were achieved by using the flexible control strategy. However, it is emphasized that the energy savings were not sufficient during the 24 h operation time considered. The system with model predictive control had a larger overshooting effect compared to the reference case, which resulted in larger energy consumption than expected. It is worth noting that the authors pointed out that a larger energy saving was predicted in numerous modeling studies in the literature. A recent work [111] revealed that TES systems have a high potential to shave the electric load peaks and contribute to demand-side management. The quantitative results in this study showed that up to 14% reduction in the peaks can be achieved by using either a 5 m^3 hot water storage tank or a 0.25 m^3 adsorption TES unit, in a dwelling located in a small residential neighborhood.

Hirmiz et al. [112] considered a TES tank connected to the condenser side of a heat pump (see Fig. 5.8) aiming to achieve demand-side management. The influences of both sensible heat by considering only water in the TES tank and latent heat by considering PCM modules inside the tank with different percentages were tested. It was concluded that the implementation of TES can reduce CO_2 emissions due to its capability of shifting electric loads to off-peak periods, which ensured bringing a lower load to the electricity grid. Furthermore, this technique can ensure more effective utilization of renewable sources and provide energy flexibility. Nonetheless, it is emphasized that the COP of the heat pump was decreased as the storage temperature increased. Hence, TES was not found to be an energy efficient solution. In addition to that, it was pointed out that storage volumes can be significantly reduced by using latent heat storage materials such as PCMs.

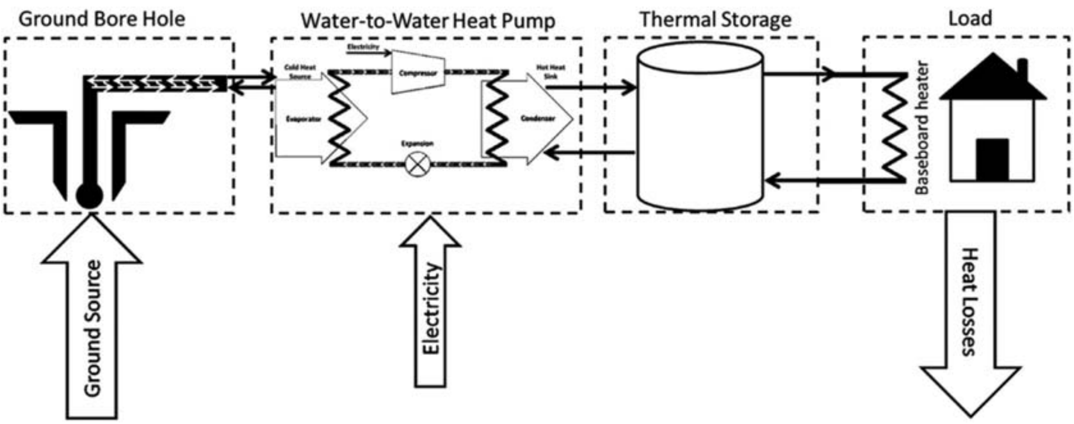

FIGURE 5.8 Integration of a TES tank to the condenser side of a heat pump for demand-side management [112].

Relatedly, in another study [113], it was found that larger TES tanks can shift a larger amount of energy during off-peak periods. However, using them as space heating tanks inevitably increases the cost for the end-users, as compared to the case without using a demand response strategy.

Comparing the structural thermal mass and TES tanks integrated into the condenser side of heat pumps as short-term thermal storage options, a recent study [114] showed that using thermal mass, which was considered passive storage, required significantly less investment than the installation of water tanks for TES. Besides, in the case of only using water as the storage medium, the required volume can be notably large which brings the challenge for space requirements. Therefore, PCMs can be an alternative. On the other hand, it was reported that water tanks for thermal storage were remarkably successful in enhancing building energy flexibility, whereas structural thermal mass showed limitations due to thermal comfort constraints. In addition to that, heat pump and TES combinations can be also used to improve building energy flexibility during space cooling applications along with renewable energy utilization, and the trade-off between thermal comfort, energy consumption, and energy flexibility should be well analyzed from the short-term perspective, by considering various strategies [115]. Using appropriate demand-side management strategies for a solar-powered air-source heat pump and TES with water tanks can result in a 76% reduction in annual electricity demand from the grid by using a 5 kW photovoltaic system [116]. No further improvement in yearly consumption was noticed once the storage tank volume was beyond 5 m^3 in this case. This clearly showed that effective utilization of the TES unit should be analyzed and optimized. By doing this, a multi-aspect analysis should be carried out which involves the system performance, and necessity of design, as well as electrical and technical constraints including required space for the volume of TES units. To achieve load shifting and energy efficiency as much as possible, different layouts for the integration of TES units into the heating system are considered. An experimental and simulation study considering different novel layouts for the TES integration was performed [117], and the relevant TES unit is shown in Fig. 5.9. It was revealed that a more efficient load shifting is possible with three different considered layouts proposed with an improvement ranging between 22% and 26% (see Fig. 5.10 for the example of load shifting considered). It was shown that, although the opposite was reported in some studies, the reduction in heating expenses can be possible while achieving load shifting, and this clearly indicated the importance of future work in this direction.

Alternatively, energy flexibility can be attained by using both sensible and latent heat storage units in combination with different smart strategies to further augment the flexibility in the short term, namely on a daily basis. A simulation study conducted by Lizana et al. [118], considering two different demand-side management strategies, revealed that a cost-saving of 4% to 20% for end-users and 12% to 25% for retailers were achieved. Even though the two strategies resulted in higher energy consumption, shifting the loads to the off-peak period offered the aforementioned savings as well as lower carbon emissions. Aside from strategies, integration of the layouts for TES units into the heating systems via different layouts can have a remarkable influence on the management of the demand side and energy flexibility.

Quantification of energy flexibility achieved by TES is of great importance for both seasonal and short-term storage options. The main findings of the previous work on using

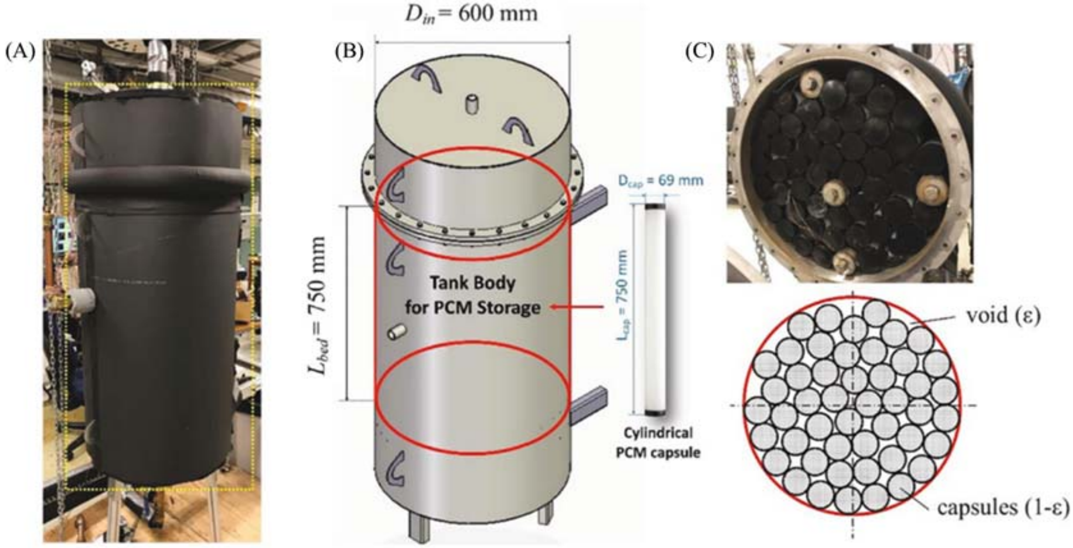

FIGURE 5.9 (A) TES tank utilized for tests, (B) its 3D model with dimensions, and (C) cross-sectional view illustrating the PCM modules [117].

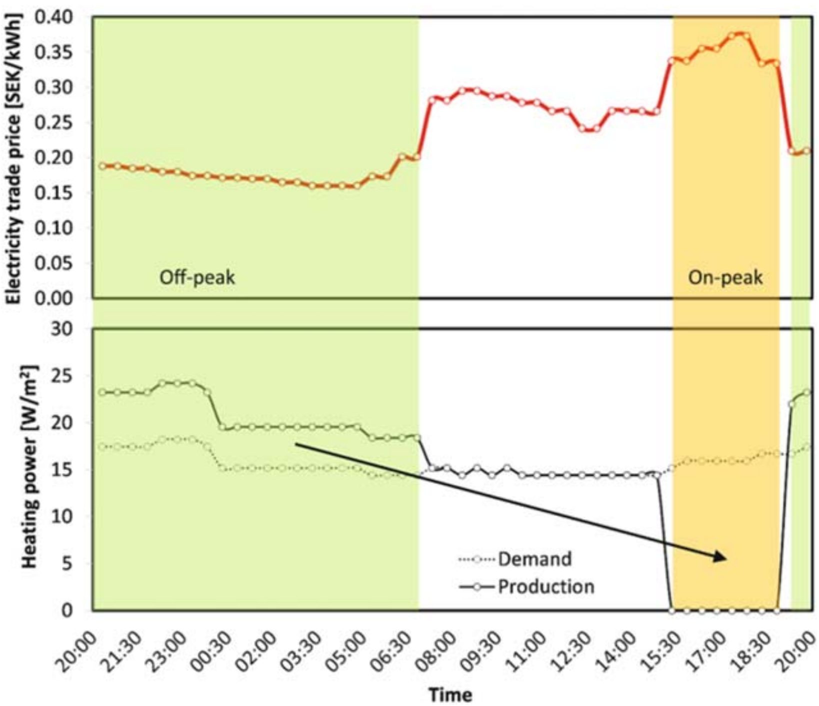

FIGURE 5.10 An example of load shifting operation in a residential building [117].

TES to increase building energy flexibility and demand-side management are summarized in Table 5.1. It can be seen that consideration of TES systems for the purpose of energy flexibility in terms of load shifting and demand reduction as well as the reduction in carbon emissions has a remarkable enhancement effect, depending on the considered storage type and application.

5.4 Limitations

Although using TES systems is a remarkably beneficial way to enhance building energy flexibility, their utilization has some restrictions from several perspectives. These perspectives can include the availability of the storage material or medium, heat transfer capability of the materials, and chemical stability, as well as a common challenge of cost.

5.4.1 Availability of required thermal energy storage materials

Water is one of the most commonly used TES media in energy flexibility applications. The major properties making it so favorable for TES are the abundance, low-cost, high sensible heat storage capability in a large temperature range, and easiness in implementation [121]. However, the main drawback of water storage tanks is their high volume requirement, which can be challenging for some applications [122]. The issue of high storage volume requirement can be overcome by using PCMs, which have a significantly high energy density per unit volume as compared to sensible heat storage units [123]. For latent heat storage systems, various PCMs can be utilized, and they generally have lower availability compared to other sensible heat media such as water (tanks) and aquifers since PCMs are usually commercially available for utilization of TES systems rather than natural ways. In addition to that, the stability of PCMs can be questionable, especially for short-term storage when the PCM undergoes numerous phase change cycles that can negatively affect its chemical structure, which is explained in the following subsection.

5.4.2 Low thermal conductivity of thermal energy storage materials

Even though some sensible heat storage materials have relatively larger thermal conductivity values [e.g., water having a value of approximately 0.6 W/(mK)] [124] at room temperature and some soil types have thermal conductivity values ranging from 0.37 to 1.42 W/(mK) [125], PCMs usually have a low thermal conductivity which comes up as a major restriction for their wide utilization in TES systems [126]. Although numerous techniques, such as fin attachment to latent heat storage units [127,128], the addition of nanoparticles [129], embedding metal foams [130], and hybrid methods including more than one of them [131], have been proposed and continuously studied to cope with this challenge, the low thermal conductivity has still not dropped down from the top of the list regarding the drawbacks. From the perspective of energy flexibility, this issue becomes significant as the charging and discharging of thermal energy should be precise to ensure

TABLE 5.1 Energy flexibility with TES studies and significant findings.

	Energy storage type			Application		Energy storage duration		Evaluation		
Refs.	Sensible heat storage	Latent heat storage	Thermochemical heat storage	Heating/ domestic hot water	Cooling	Long-term thermal energy storage (seasonal)	Short-term thermal energy storage	Theoretical analysis or Simulation	Experimental	Energy flexibility potential/significant findings
[87]	✓			✓	✓	✓		✓		■ 3000 MW electricity saving ■ 2100 tons/year reduction in CO_2 emissions
[88]	✓			✓		✓		✓		■ 3000 kWh electricity demand reduction per unit
[89]		✓		✓			✓	✓	✓	■ PCM should be changed after a predetermined stable number of thermal cycles
[90]		✓		✓		✓		✓	✓	■ 40% net energy savings ■ 4% exergy efficiency
[92]			✓	✓	✓	✓	✓		✓	■ Cost reductions achieved
[97]	✓			✓	✓		✓	✓	✓	■ Recovery of thermal energy up to 90%
[98]	✓			✓			✓	✓		■ 14% energy demand reduction ■ Higher thermal mass does not necessarily increase the energy flexibility index
[99]	✓			✓			✓	✓		■ Cost reduction up to 15% during the heating season ■ 40%–87% energy demand reduction during morning peak hours
[100]	✓			✓			✓	✓		■ Achieved load shifting between 41% and 51%
[101]	✓			✓			✓	✓		■ 25 kWh/m^2year heat can be modulated for poorly insulated buildings during the peak price period ■ Well insulated buildings enable modulation of a smaller amount of heat for long time periods
[102]	✓			✓			✓	✓		■ Construction type greatly influences the flexibility potential of the building

(*Continued*)

TABLE 5.1 (Continued)

Refs.	Energy storage type: Sensible heat storage	Energy storage type: Latent heat storage	Energy storage type: Thermochemical heat storage	Application: Heating/ domestic hot water	Application: Cooling	Energy storage duration: Long-term thermal energy storage (seasonal)	Energy storage duration: Short-term thermal energy storage	Evaluation: Theoretical analysis or Simulation	Evaluation: Experimental	Energy flexibility potential/significant findings
[103]	✓			✓			✓	✓		■ Nearly 62% reduction in energy consumption
[104]	✓			✓			✓	✓		■ 25% variation (in both positive and negative directions) in energy flexibility depending on smart controllers and occupant behavior
[105]	✓	✓		✓			✓	✓		■ Energy flexibility index was increased by 111% and 35% with PCM wallboards for low insulation and high insulation light-structure houses, respectively ■ 42% increase in building time constant because of indoor items and furniture in the built environment
[107]		✓		✓			✓	✓		■ Solar energy covered 78% of the heat required
[119]		✓		✓			✓	✓		■ Latent heat storage provided great flexibility ■ The operating performance of the heat pump increased by 12.3% by using the latent heat storage
[120]	✓	✓		✓			✓	✓		■ Load shifting increased heat pump electricity consumption ■ Load shifting by heat pump utilization should be carefully synchronized
[109]	✓			✓			✓	✓	✓	■ Average heat pump COP increased by 22% ■ 34% average reduction in heat pump operational costs
[110]	✓			✓	✓		✓	✓	✓	■ Cost reduction up to 1%–7% ■ Decrease in CO_2 emissions by 3%–17%
[111]	✓		✓	✓			✓	✓		■ Adsorption was too costly for load peak shaving alone ■ 14% reduction in peaks with either water storage or adsorption

[112]	✓	✓	✓		✓	✓		■ A low-temperature heat exchanger can be combined with thermal energy storage to increase the COP of the heat pump ■ Peaks were sustained between 2 and 6 h with a proper storage capacity
[113]	✓		✓		✓	✓		■ Up to 11% energy production reduction can be reached ■ Larger amount of energy can be shifted by larger storage tanks; however, applying demand response inevitably increases consumer costs
[115]		✓	✓	✓	✓	✓		■ Heat pump solar contribution (i.e. energy consumption provided by PV/heat pump total energy consumption) up to 100% can be achieved ■ Energy consumption for heat pumps can also increase by approximately 5-folds because of using thermal energy storage under the demand-side management strategy
[116]	✓		✓	✓	✓	✓		■ 76% decrease in grid electricity demand for heat pump ■ Peak load shaving by 45%
[117]		✓	✓		✓	✓	✓	■ The system with LHTES provided 22%−26% better performance ■ Up to 5% reduction in operational costs ■ 14% reduction in CO2 emissions
[118]	✓	✓	✓		✓	✓		■ Costs reduction up to 20% and 25% for end-user and retailer, respectively ■ CO2 emissions remained almost constant ■ High payback period, roughly 10 years

sufficient flexibility in building energy systems. Therefore, the thermal conductivity of TES materials is desired to be sufficiently high [70,132,133].

5.4.3 Chemical stability of thermal energy storage materials

When PCMs are used for TES, continuous phase transition, for example, from solid to liquid and vice versa, may significantly affect the chemical structure of the materials [134]. Deterioration of chemical properties may lead to considerable changes in the phase change temperature or latent heat capacity [135], and hence, testing of these materials is of great importance for applications such as enhancement of building energy flexibility.

As mentioned previously, some techniques can improve the thermal conductivity of PCMs. It is noted that some additives such as nanoparticles that are added to PCMs can deteriorate their chemical stability [136]. Thus, the trade-off between heat transfer augmentation and the chemical stability of PCMs should be analyzed in such situations. Chemically unstable storage materials are ineffective for TES applications. Hence, although it is usually neglected in numerical simulations, this issue becomes a remarkable restriction for practical applications that should not be overlooked.

5.4.4 Cost of thermal energy storage materials

Cost is one of the major limitations of many practical engineering applications. The implementation of TES also requires a significant cost [137], especially when organic PCMs are considered since these materials are relatively more expensive as compared to inorganic salt-based materials [138]. In addition, the life-cycle cost analysis should be carried out to evaluate the feasibility of latent heat TES implementations including energy flexibility as TES systems can be used for long-term operations to ensure flexibility once they are integrated into the system. For instance, the integration of PCM into the brick wall was not found to be cost-effective as a result of a 30-year life-cycle cost analysis [139]. On the other hand, as a sensible heat storage unit, water tanks are usually considered simpler systems as compared to TES systems with PCMs. However, for demand-side management applications, they are regarded as less cost-effective when compared to latent heat storage or structural thermal mass, due to the high possibility of heat loss from large-volume water tanks [111,114,140]. Therefore, the cost-effectiveness of TES options for building demand-side management and energy flexibility should be evaluated along with other constraints that are aforementioned.

5.5 Summary

This chapter introduced the role of TES systems in enhancing building energy flexibility and demand-side management. Different forms of TES and their related storage media and materials were reviewed and the link between TES systems and energy flexibility was discussed. The role of TES systems in building energy flexibility and demand-side management was then addressed in terms of seasonal and short-term storage applications.

Different TES materials or media, such as sensible heat storage by water tanks, aquifers, and latent heat storage by using various PCMs can be considered. Furthermore, different techniques that can be utilized to manage the demand with the aid of TES systems are discussed. For instance, in seasonal energy storage, that is long-term, latent heat TES tanks can be integrated with heat pumps, and additional sensible heat storage tanks can be also used in these systems to enhance their TES capability, depending on the application. On the other hand, short-term TES can be considered together with the structural thermal mass and/or heat pumps. Here, the TES unit can be charged by renewable energy sources or by heat pumps and stored within the short term in order to be discharged later with an appropriate strategy to enhance building energy flexibility during heating or even cooling operations. At this point, different approaches, such as model predictive control as one of the most prominent ones, can be considered to maximize the benefit of TES in demand-side management, hence, energy flexibility.

Nevertheless, some studies revealed that heat loss is large from TES units, such as large water tanks at relatively high temperatures. Therefore, it is reported in some studies that the demand-side management application with TES tanks resulted in a decrement in the energy efficiency of the system even though the TES utilization was found to be successful in shifting the load to the off-peak periods and shaving the peaks in the electricity load, and thus, reduced CO_2 emissions and excessive load in the grid. Nonetheless, some other studies concluded the opposite and reported that energy savings can also be achieved together with energy flexibility. This indicates a significant research gap in the field and the need for further studies on this topic. Besides, it is worth noting that there are numerous modeling studies with different strategies that have been developed. However, there is a lack of experimental studies. Furthermore, more research studies are needed to sufficiently reveal the relations between demand-side management, reduction of CO_2 emissions, energy efficiency, and utilization of renewable energy sources. In addition, the strategies of integration and operation of TES systems are of great importance. Thus, different strategies for coupling and operating TES systems with building energy systems should be further investigated to enhance energy flexibility in various applications dealing with seasonal or short-term TES.

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CHAPTER

6

Renewable energy for enhanced building energy flexibility

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There is strong scientific evidence that the Earth's average surface temperature is increasing. This is a result of the increased concentration of CO_2 and other greenhouse gas emissions in the atmosphere, due to burning fossil fuels. This will eventually lead to major changes in the climate of the atmosphere, which in turn will have a major impact on human life and the built environment. Therefore, efforts should be made to reduce the use of fossil energy and promote renewable energy, especially in the building and construction sectors. This chapter is dedicated to examining the importance of renewable energy resources and how to use them in buildings to improve their energy flexibility characteristics. The renewable energies considered in this chapter include wind energy, solar energy, geothermal energy, and biomass energy.

6.1 Introduction

With the increase in world population and limited energy resources, many countries are facing a shortage of energy supply. The crises that threaten countries and human societies are the limited resources of nonrenewable energy and the increase in environmental

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pollution caused by excessive consumption of fossil fuels, which are among the factors that make it necessary and important to pay more attention to the use of renewable energy sources (RESs) such as solar, bioenergy, wind, small hydro, geothermal, and tidal. Reducing carbon emissions, lowering maintenance costs, and removing moving or rotating components are among the key benefits of integrating renewable energies into energy networks [1,2]. Therefore, reducing the consumption of nonrenewable energy sources is necessary and renewable energy will play a vital role in the future of world energy.

Traditional fossil fuel power plants can ensure the stability of the power grids. Due to their environmental pollution, most communities decide to phase out and replace them with RESs, which are very diverse and have a wide impact on the sustainability of energy networks. Therefore, there is a need to move from "production on-demand" to "consumption on-demand" to adapt energy consumption to energy production and increase energy flexibility. Hence, flexibility is vital and inevitable for the operation and usage of energy systems [3]. Buildings can significantly contribute to energy flexibility. To this end, the pattern of building energy utilization can be changed by using load shifting, peak shaving, and valley filling to better fit the production of renewable energy sources, as well as reducing costs associated with strengthening the network weaknesses and operation of peak power production units [4]. This chapter mainly discusses wind power systems, solar energy systems, geothermal energy systems, and biomass systems for increased building energy flexibility.

6.2 Wind power systems and building energy flexibility

Usually, the electricity produced by medium and large wind turbines is used to supply electricity to the grid's local substations and these turbines are called grid-connected or On-Grid. Thus, this type of wind turbine does not contribute to the energy flexibility of buildings directly. However, they can supply a share of the energy demand of the building via a grid system. The low-capacity wind turbines called small-scale wind turbines are used independently from the grid and are called Off-Grid. This type of wind turbine in windy areas can participate in improving building energy flexibility.

In the case of utilization of wind energy in buildings, a sufficient wind speed and consequently, enough power is essential. The stability of wind direction in complex terrains could be another challenge. A tail vane as a simple and passive direction control system is very common in small-scale wind turbines. However, it causes high gyroscopic loads in instant changes of wind direction and decreases the blade's life. It is noted that due to building dimensional restrictions, the swept area of the wind turbine must remain limited. Increasing the swept area increases the wind turbine power output at the expense of significant loadings in the base of the tower which should be bared by the building structure. Therefore, in most cases, only small-scale wind turbines can be used in buildings.

Wind turbines can be mainly divided into two general categories based on the orientation of the rotation axis, as shown in Fig. 6.1 [5]:

- Horizontal axis wind turbines (HAWTs).
- Vertical axis wind turbines (VAWTs).

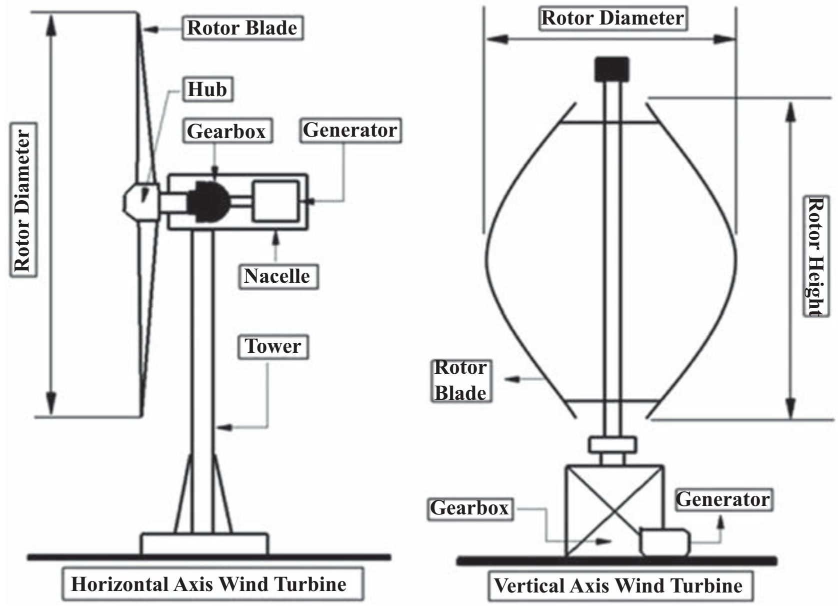

FIGURE 6.1 Horizontal and vertical axis wind turbines [5].

The characteristics of the horizontal axis turbine rotors are very similar to airplane propellers. The airflow moves on the aerodynamic cross-section of the blades and creates the lift force that causes the rotor to rotate. The nacelle of the horizontal axis turbines which is placed on the top of a tower accommodates the gearbox, generator, and other subsystems of the turbine. The area that each blade sweeps is called swept area and is the main factor defining the wind turbine power capacity. The tower provides the required height to achieve higher wind speeds and prevents blades from falling while the rotor is rotating. The HAWTs should directly face the wind to generate the maximum electricity. Therefore, a system is needed to adjust HAWTs to be aligned with the wind, which is called the yaw system. Therefore, the whole nacelle can turn towards the wind while the wind direction can change continuously [6]. On the other hand, in addition to the wind direction, the wind speed and the rotation speed of the HAWT rotor are also changing. Therefore, to adapt the turbine to these changes and produce maximum electrical energy, another system called the pitch system is used in the turbine, which adjusts the angle of attack of each blade concerning these conditions instantaneously.

In the VAWT turbines, the axis of rotation is vertical. The equipment like gearbox and generator can be located on the ground which is a significant advantage for maintenance purposes. Another advantage is that these turbines can work in all wind directions. This also makes the control system simpler. On the other hand, since these turbines are placed very close to the ground, they occupy a larger area for their rotor. Meanwhile, the wind intensity on the ground is lower than that at higher heights, and as a result, less electricity can be produced by these turbines.

Although the most attention in recent years has been grabbed to large-scale wind turbines, small-scale wind turbines have their particular situation in providing energy for local consumers, especially for buildings, sailing boats, and remote communication posts. A classification of wind turbines based on their scale is presented in Table 6.1. In this classification, small-scale wind turbines which highly contribute to building energy flexibility, are divided into micro, mini, and household classes, where the last class lies in power ratings of 1.4–16 kW [7]. Small commercial wind turbines with a rating of 25–100 kW, are rarely used to supply energy for buildings directly. Larger wind turbines with ratings of multihundred kilowatts to multimegawatts are mostly used for utility-scale wind farms and supplying power to grids. Table 6.2 summarizes the common types of wind turbines based on their technologies, axis orientation, and power rating regarding their role in building energy flexibility.

Additionally, there is a willingness in modern communities to utilize wind turbines in buildings due to architectural elements for energy generation and demonstrating the importance of green energy to the public. One example is the World Trade Centre in

TABLE 6.1 Classification of HAWT based on rotor diameter and power rating [7].

		Rotor diameter (m)		Swept area (m^2)		Standard power rating (kW)		Building energy flexibility
Small scale	Micro	0.5	1.25	0.2	1.2	0.004	0.25	High
	Mini	1.25	3	1.2	7.1	0.25	1.4	High
	Household	3	10	7	79	1.4	16	High
Small commercial		10	20	79	314	25	100	Low to moderate
Medium commercial		20	50	314	1963	100	1000	N/A
Large commercial		50	100	1963	7854	1000	3000	N/A

TABLE 6.2 Summary of the characteristics of common wind turbine types.

Rating	Turbine type	Blades	Axis orientation	Force type	Grid	Rotor speed	Noise level	Contribution to building energy flexibility
Small	Classic	3/2	HAWT	Lift	Off/On	High	High	**Direct**
	Darrieus	3/2	VAWT HAWT	Lift	Off/On	Medium	Low/ Medium	Rooftop or close to building for local consumption
	Savinius	2	VAWT HAWT	Drag	Off/On	Low	Low	
Large	Classic	3/2	HAWT	Lift	On	Low	High	**Indirect**
								Onshore and offshore utility-scale wind farms

FIGURE 6.2 Bahrain world trade center; left schematic front view and right: real photo from behind [8].

Bahrain, which is equipped with three wind turbines installed on the connecting bridges between two nozzle-shaped buildings (Fig. 6.2).

Wind generation cannot always offer a reliable capacity to an independent electrical power system due to the stochastic nature of the wind. Additionally, the indicated variations may occasionally result in issues with stability, harmonics, or flicker. A common way in household-scale energy systems is to use batteries to store energy in times of excess production and consume it in times of demand and shortage of production. When properly sized, an energy storage system can match the extremely variable wind power production with typically variable system demand, dramatically lowering the cost of energy production (e.g., by generating capacity savings). The lifetime expectancy, energy efficiency, depth of discharge, and initial and ongoing costs of the storage devices that could be utilized in a wind hybrid installation are crucial factors that should be considered in this context [8]. The other solution to overcome variations in wind energy is to use photovoltaic (PV)/wind hybrid systems [9].

6.3 Solar energy systems and building energy flexibility

The use of solar energy is usually achieved in two ways, that is, active or passive methods. Passive systems are structures whose design, placement, or materials optimize the use of heat or light directly from the sun [10]. Active systems have devices to convert solar energy into a more usable form, such as hot water or electricity [10]. Solar energy systems used in buildings can be classified into active and passive systems. In passive solar systems, buildings are designed in such a way that the needs of heating/cooling and lighting are provided naturally and compatible with the climate. For this reason, they are called passive systems and can minimize the operation of heating and cooling system. Active solar systems are systems that collect and convert solar energy into electricity and useful

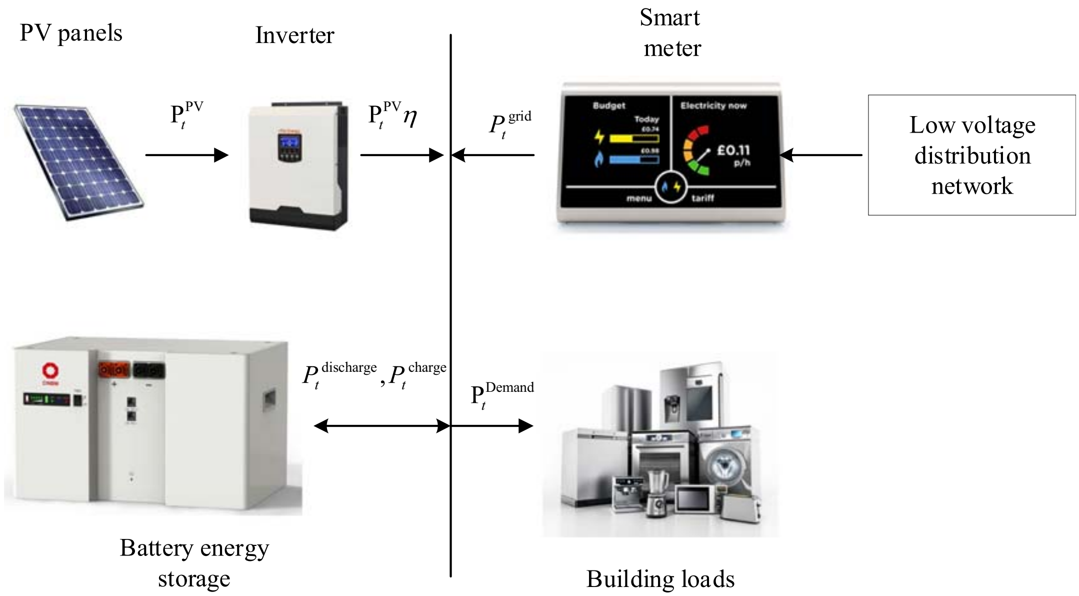

FIGURE 6.3 The schematic of the building equipped with the PV systems.

heat with the help of mechanical equipment so that it can be transferred to the interior of the building at the right time [11]. Greenhouses and Trombe walls are examples of passive systems and solar water collectors, photovoltaic systems, and solar air heaters are examples of active systems.

Using solar energy to generate power and heat can increase building energy flexibility and thus support building demand-side management. Solar energy can be produced for on-site use or dispatched to the grid during off-peak demand hours [1].

6.3.1 Photovoltaic systems

Installing PV panels in the distribution networks, especially in buildings, is increasing [12]. To indicate the advantages of the PV panels in supplying building demand, this resource can be integrated with battery energy storage (BES)[1] as shown in Fig. 6.3. It can be seen that the building demand can be supplied through the power generation of the PV, discharging power of the BES, and the purchased power from the grid. For this purpose, the optimal decision to meet the building demand should be determined based on the electricity price of the grid. In the low energy price hours, the building demand can be supplied by purchasing power from the grid. In these hours, the power generation of the PV can be saved in the BES. The remaining capacity of the BES can be charged by purchasing power from the grid. Then, in the high energy price hours, the purchased power from the grid decreases, and instead, the building demand can be met through either the PV generation,

[1] The combination of the PV panels, inverter, and the BESs is called the PV system in this subsection.

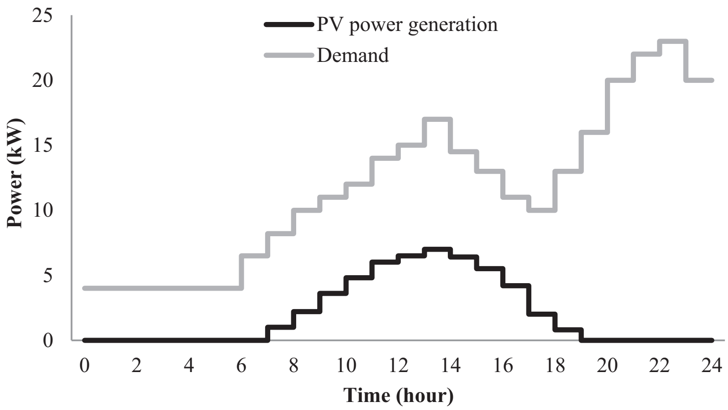

FIGURE 6.4 The power demand of the building and the PV power generation.

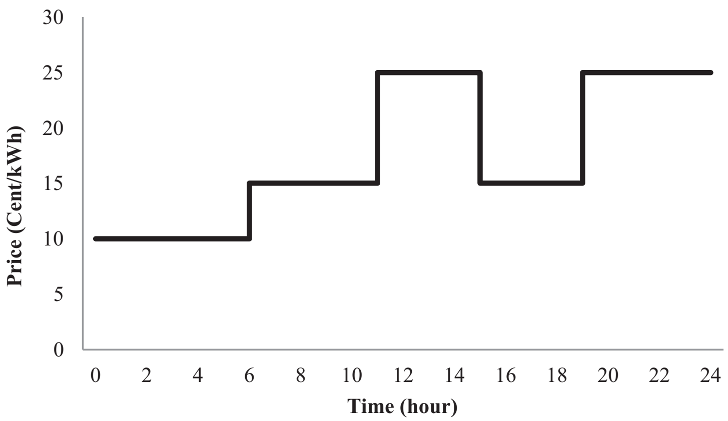

FIGURE 6.5 The TOU tariff.

discharging power of the BES, or both. These decisions can decrease the building energy cost. The schematic presented in Fig. 6.3 is generic so that BESs can be charged through either the PV panels and the purchased power from the grid or only through the PV panels.

To show the effectiveness of the PV system to increase building energy flexibility, a building with power demand and PV power generation, as shown in Fig. 6.4, is considered. The time of use (TOU) tariff is shown in Fig. 6.5. The electricity prices in the off-peak period (i.e., hours 1–6), shoulder period (i.e., hours 6–11 and 15–19), and peak demand period (i.e., hours 11–15 and 19–24) are 10, 15, and 25 cent/kWh, respectively. The efficiency of both the inverter and the BES is 0.98 and the maximum limitation of the purchased power from the grid is 25 kW. Two cases are defined as follows:

Case I: The building does not use the PV panels and the BES.
Case II: The building is equipped with both PV panels and the BES.

The purchased power from the grid in the two cases is shown in Fig. 6.6. The power charging/discharging of the BES in Case II is shown in Fig. 6.7. It can be seen that the purchased power from the grid in Case II decreased at hours 7–19 regarding the power

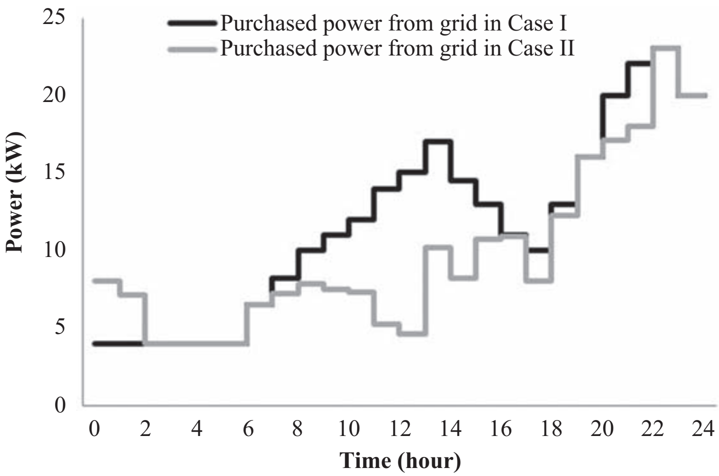

FIGURE 6.6 Power purchased from the grid in two cases.

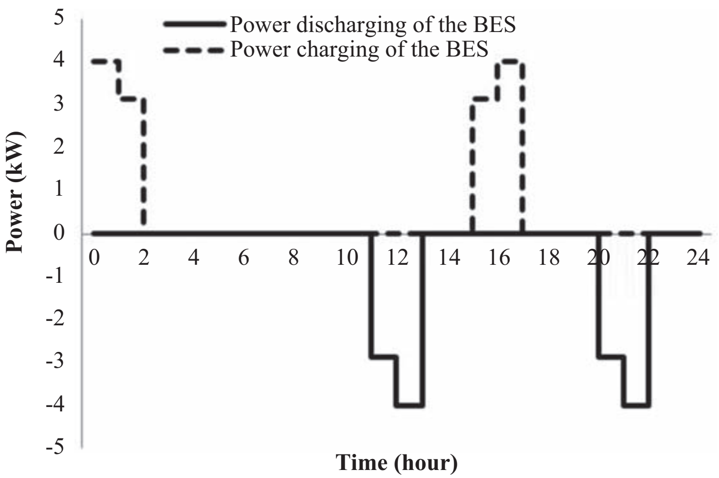

FIGURE 6.7 The power charging/discharging of the BES in Case II.

generation of the PV panels. The purchased power from the grid also decreased at hours 20 and 22 regarding the discharging power of the BES. The BES was charged at hours 1-2 and 16-17 using low-price grid power. Then, the BES was discharged at hours 11-13 and 20-22 when the energy price was high. These decisions to supply building demand decreased the sum of the purchased power from the grid in the 24 hours operation from 280 kW in Case I to 231.77 kW in Case II as shown in Table 6.3. In addition, the total cost of supplying the building's demand decreased from $56.98 to $45.45. Therefore, in the presence of the PV system in Case II, the purchased power from the grid and the total energy cost decreased by 17.22% and 20.23%, respectively, in comparison with Case I (see Table 6.3). The main conclusion of these results is that PV systems can increase building

TABLE 6.3 Comparison of the results obtained for two proposed cases.

	Total cost ($)	Sum of the power purchased from the grid (kW)	Percentage of decreasing the total cost (%)	Percentage of decreasing the purchasing power from the grid (%)
Case I	56.98	280	–	–
Case II	45.45	231.8	20.2	17.2

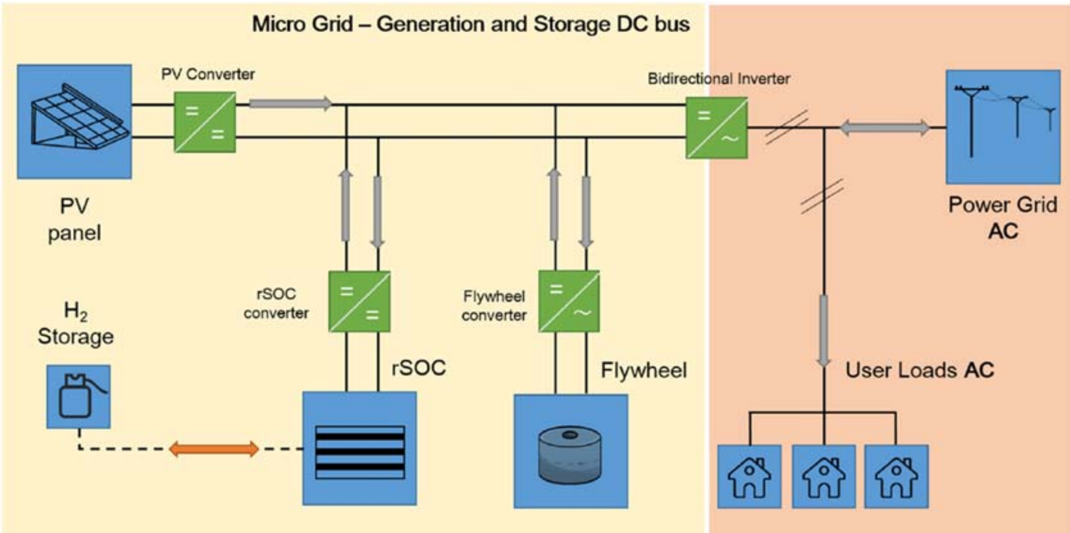

FIGURE 6.8 Schematic view of the hybrid energy storage system suggested by Baldinelli et al. [14].

energy flexibility to meet building electricity demand by both making optimal decisions on charging/discharging the BES and purchasing energy from the grid.

In demand-responsive buildings, in addition to batteries, other storage systems such as ice storage [13], hybrid reversible Solid Oxide Cells (rSOCs), and flywheels [14] can also be used to improve the capability for demand side management. The rSOCs, which are a device for simultaneous electrolysis and hydrogen reelectrification, enable the integration of hydrogen in microgrids. The load-following capability of rSOCs is weak, and for this reason, they must be combined with other equipment such as flywheels to provide regulation in short time intervals. Flywheels ensure a fast response to load changes and can be used at high capacity factors, providing a continuous charge/discharge service without exhibiting severe hysteretic behavior, or performance degradation due to cycling [14]. In the hybrid rSOCs-flywheel system, energy storage (through hydrogen production) and its conversion into electricity are achieved inside the rSOCs, while control of rapid changes, absorption of high-frequency contributions, and modulation of power flows are achieved by the flywheel. The layout of a hybrid rSOCs and flywheels system is demonstrated in Fig. 6.8.

Smart building clusters integrated with PV arrays are another preferable option to diminish peak load and improve building energy flexibility [15]. These clusters usually consist of several buildings that supply their electricity to a microgrid, and therefore, the excess electricity produced by the PV panels in one building can be sold to another building or the smart grid [16]. In these clusters, the energy cost could be significantly diminished under various electricity pricing plans and thermal comfort requirements [17].

Photovoltaic systems combined with inverters in some buildings are used directly to power various equipment such as air conditioners. However, energy generation by PV panels cannot always match the energy demand of the building. To improve these conditions, a temperature range can be considered for indoor thermal comfort [18]. This technique (i.e., variable indoor air temperature) provides a significant improvement in the energy flexibility features of the building [18].

Photovoltaic panels, in addition to participating in meeting the electrical load of the building, can also participate in meeting the thermal load of the building in different ways. For example, PV-assisted heat pumps can be used in buildings, and the electricity produced by the panels can be used to produce heat or cold by using heat pumps [19,20]. The heat produced by this method can be stored and used when needed. Another technique is based on the low electrical efficiency of the panels. Photovoltaic panels convert sunlight into electricity with an efficiency of 12%−22% [21]. Therefore, most of the solar light received by the panels is converted into thermal energy and the efficiency of the panels decreases with the increase in the panel temperature [22]. To solve this problem, the excess heat of the panels can be transferred to a fluid and/or a phase change material (PCM) and used for space heating/cooling or domestic hot water purposes.

The results from the above discussions demonstrate that PV systems, especially when used in conjunction with energy storage systems, can play a significant role in improving building energy flexibility.

6.3.2 Solar water collectors

By definition, a solar thermal collector is a device that can collect different wavelengths of solar radiation and convert it into useful energy. The two main categories of collectors based on the area absorbing solar radiation include concentric and nonconcentric types. Paraboloid and parabolic solar collectors are in the concentric category, meaning that the collector surface is larger than the absorber area. However, flat plate collectors are in the nonconcentric category, with the same interceptor area and absorber area [23].

In residential and commercial buildings, electric heaters, boilers, or heat pumps are often used to supply hot water, which requires electricity or fuel to function. All or part of hot water consumption in buildings can be supplied using solar collectors equipped with water storage tanks. With this method, the water heating bill, the amount of fuel consumption, and the emission of carbon dioxide can be significantly reduced [24,25]. Thermal energy in the hot water coming out of solar collectors can also be stored in building thermal mass or PCMs and used for space heating/cooling during peak hours and hours when sunlight is not available. This method also leads to a significant improvement in building energy flexibility. Solar thermal collectors can also contribute to building energy flexibility by providing a fraction of building heating/cooling demand. Two examples of the methods proposed by the researchers to use solar collectors in building heating are combined biomass gasifier-solar thermal collector systems [26] and solar floor heating systems [27]. Moreover, solar collectors can be used to generate the heat needed to produce the fuel used by the micro gas turbines to generate electricity [28]. Finally, the thermal energy produced in solar collectors can be used as a heat source for absorption chillers and liquid desiccant systems and contribute to space cooling [29].

As an example, a Net Zero Energy Building (NZEB) designed and constructed in the Materials and Energy Research Center located in Tehran, Iran is introduced in this section (as shown in Fig. 6.9). This is the first net zero energy building in Iran, which was designed and implemented in 2012 to reduce primary energy consumption and compensate for energy consumed through the production of energy from renewable and clean energy sources. Solar water heaters with embedded flat-type collectors are used for space heating duty and domestic hot water applications. An attempt was made to reduce building energy demand as much as possible through advanced architectural design and factors

FIGURE 6.9 Solutions for reducing energy consumption in the NZEB in the Materials and Energy Research Center located in Tehran, Iran.

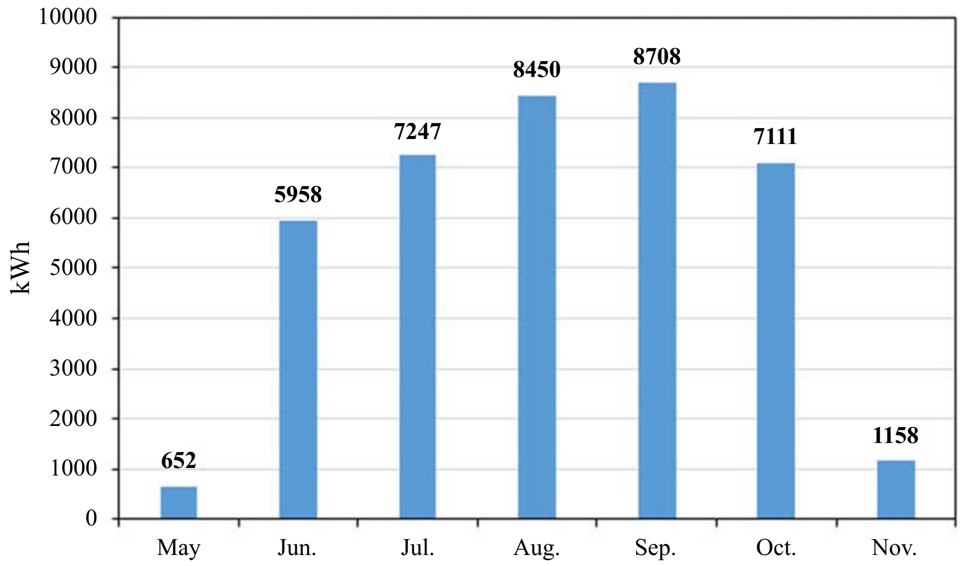

FIGURE 6.10 Thermal capacity of hot water sold to the other buildings (Operation during 2021).

such as windcatchers and a greenery glasshouse. On the other hand, most of the energy demand of the building can be met by using solar energy. Passive solar design, building orientation, placement of spaces, and insulation in the architectural design are among the main elements that were considered and the application of new design standards has helped reduce building energy consumption by 85% as compared to conventional buildings.

Fig. 6.10 shows the monthly thermal energy production by 60 flat plate solar thermal collectors with an area of 2 m^2 each in the building. It should be noted that two 2000-L double wall tanks were used for storing the hot water from the collectors. This leads to an improvement in building energy flexibility.

6.3.3 Solar air heaters

Solar air heaters, which convert incoming radiant energy into a useful form of thermal energy, are nonconcentric and flat plate types of solar collectors. These types of collectors are inexpensive and easy to manufacture and are mainly employed in medium and low-temperature applications.

In a general classification, all solar air heaters can be divided into the following two categories:

- Air heaters with nonporous absorber plates.
- Air heaters with porous absorber plates.

However, a comprehensive categorization of solar air heaters is presented in Fig. 6.11 [30].

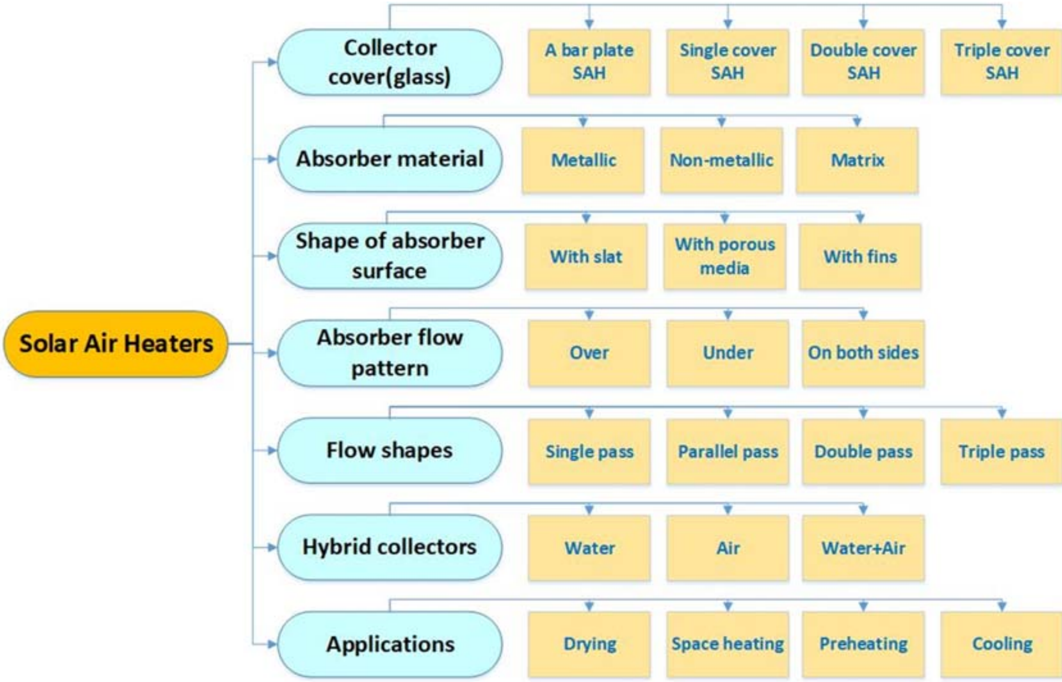

FIGURE 6.11 Comprehensive categorization of solar air heaters. *Modified from Saxena A, Varun, El-Sebaii AA. A thermodynamic review of solar air heaters. Renew Sustain Energy Rev 43 (2015) 863–890.*

Solar air heaters can be used for space heating, and timber seasoning to avoid the use of moist wood in construction projects and drying in agriculture [30]. They can play a role in improving building energy flexibility by meeting building heating and cooling demands (if hot air is used to power desiccant wheels, for instance). The hot air coming out of the solar heaters can be used to charge the PCM placed in the walls, ceiling, or floor of the building. In this case, the PCM can be used to assist in managing the room temperature and reduce building energy consumption for heating and cooling [31]. In addition, in the areas where electric heaters are used for space heating, the heaters can be equipped with PCM and hot air from the solar air heaters can be used to charge the PCM. In this case, grid electricity will not be required to heat the building during peak hours. Moreover, solar air heaters can be used as an auxiliary system for heat pumps [32], geothermal systems [33], and boilers [34].

6.4 Geothermal energy systems and building energy flexibility

Geothermal energy has been utilized as a renewable energy resource for district heating, power generation, and industrial process heat supply. The large-capacity application of this energy resource usually depends on the establishment of very deep wells in the location of geothermal reservoirs. However, there is an increasing use of small-scale shallow ground-source energy due to the characteristic of nearly constant temperature of the underground at the depths below a certain level, depending on the local climate and geological attribution of a particular area.

The application of geothermal energy is not only possible for a single building but also in the modular forms for a group of buildings or even on a larger scale through district heating. Recent studies implied the suitability and importance of multiple-source district heating as an integration of various thermal energy suppliers to empower the flexibility of the system. Solar collectors, biomass-fired boilers, biogas-fueled poly-generation systems, and geothermal energy are all practical examples that can be integrated to configure a flexible energy architecture [35].

Utilization of geothermal energy for space heating/cooling and domestic hot water is feasible for the buildings through shallow exploitation of ground-source thermal energy. Moreover, district heating and industrial direct use of geothermal energy are possible by middle-deep or deep exploitation. Furthermore, power generation, as well as poly-generation, is commercially feasible through deep geothermal utilization as shown in Fig. 6.12.

The deep geothermal system usually includes wells with 400 m or greater depths along with borehole heat exchangers that can be integrated with a steam-turbine generating cycle for power generation as well with a district heating scheme that in turn might work by direct utilization of geothermal heat or by waste heat recovery from the power generation cycle [35]. The heating system might easily be transformed into cooling mode by

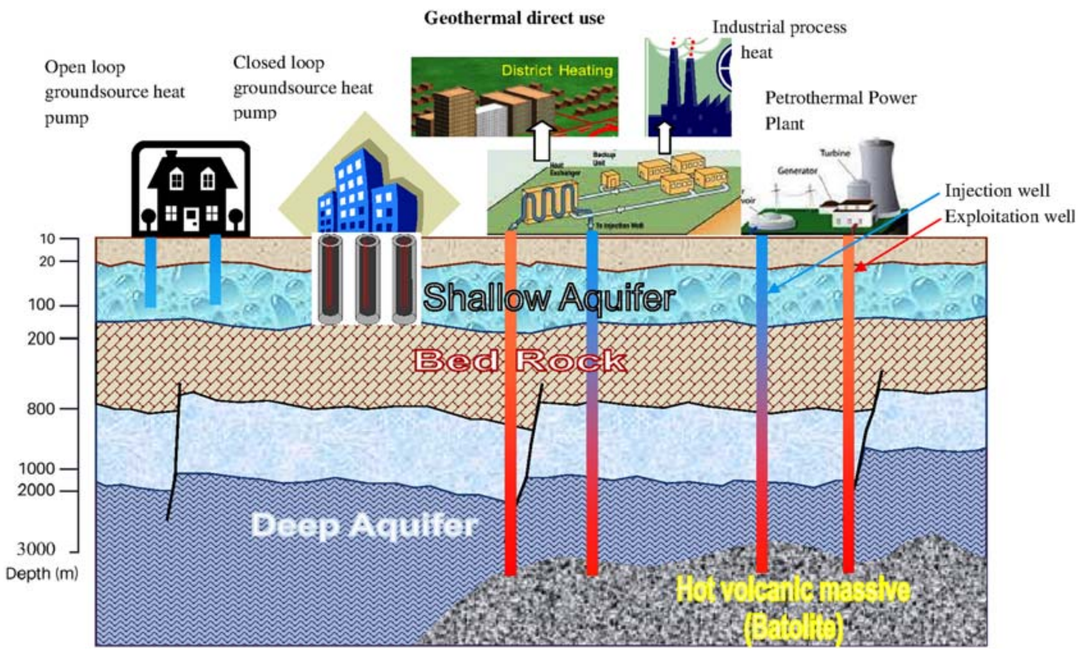

FIGURE 6.12 Schematic illustration of geothermal energy applications in terms of depth of operation.

employing an absorption chiller. Deep geothermal energy exploitation has so far been well developed in many countries for example China, Iceland, Philippines, Türkiye, Germany, Japan, and the United States. In nearly all the target countries, space heating and district heating account for a major share of the applications of middle-deep and deep geothermal energy.

Shallow geothermal heating/cooling systems consist of ground-source heat pumps and underground heat exchanger networks. This system may cover part or the whole demand of a building for heating and cooling. The heat exchange procedure might be performed by an open loop or a closed loop integrated ground source heat pump. In the open loop system, the heat is discharged or withdrawn through water flow to or from a natural pond or a shallow aquifer. The ground source heat pump absorbs the heat from the indoor space and rejects it to the open source during the cooling mode and vice versa, and the thermal energy is extracted from the low-enthalpy open source and supplied to the indoor space during the heating mode.

The geothermal energy storage concept is another method of using geothermal energy to improve building energy flexibility. Thermal energy can be stored whenever it is available and used whenever it is needed. For example, the heat of the solar collectors or the waste heat of the ventilation system can be stored in the warm months for space heating and used when necessary, such as in the winter months. The working principles of this system are shown in Fig. 6.13. During the hot seasons, the excess heat energy from solar collectors or other sources is transferred to the ground using borehole heat exchangers, and in the cold seasons of the year, it is extracted from the ground through these heat exchangers. Industrial process waste heat can be similarly stored and used later. Seasonal thermal energy storage reservoirs can act as discrete heating systems. The annual peak design temperatures of the seasonal reserves for heating are usually in the range of 27°C−80°C [36]. Some systems use a heat pump to help charge and discharge the storage throughout the cycle.

There are several types of seasonal thermal energy storage technologies that are used in different applications from small-sized buildings to discrete thermal networks. Generally, as the system size increases, its efficiency increases, and the specific manufacturing cost decreases.

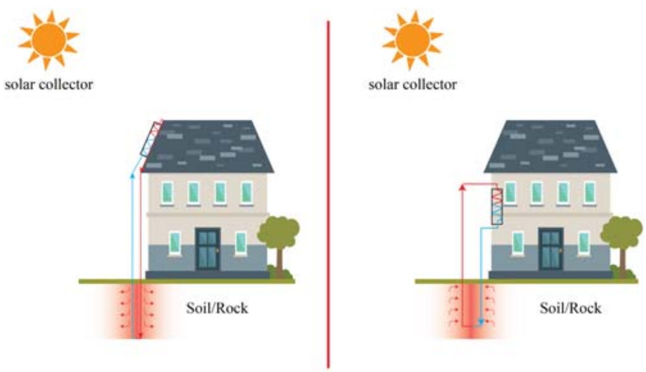

FIGURE 6.13 Working principles of borehole thermal energy storage [36].

Geothermal energy can cover a significant share of building thermal energy demand, especially in the district heating scale. Utilization of geothermal energy would be more economical through combined cooling-heating and power (CCHP) generation systems on a large scale. Even the application of narrow geothermal heat pump systems is feasible for a single or a group of buildings but the expensive costs of excavation, heat exchanger pipes and equipment are among the main limitations to overcome.

6.5 Biomass systems

The energy carriers derived from biomass resources are generally applied among two main approaches, that is, direct and indirect, in buildings. The direct applications of biomass energy are often in the form of distributed and independent units, while the indirect applications usually rely on centralized facilities that deliver the bioenergy carriers to a large or small group of consumers.

Bioenergy provided 4.6% of total global heating energy for buildings, 9.0% of global heat for industries, 4.0% of total fuel energy for transportation, and 1.7% of the world's electricity in 2019 [37].

Wood-fired or pellet-fired stoves or small biogas units are examples of direct applications of biomass energy in buildings. On the other hand, a biomass-fueled centralized district heating facility and a biorefinery that provides biofuels for consumption in buildings are examples of indirect bioenergy applications.

Bioenergy can be applied to buildings and many other final consumers such as urban infrastructures, agro-industries, transportation fleets, agricultural farms and greenhouses, and industrial complexes, via diverse energy carriers. One unique characteristic of bioenergy is that, in many cases, useful byproducts are also achieved in parallel to energy production. Another desirable attribute of bioenergy is the capability of the diversification of energy supply. Bioenergy technologies can often be easily combined with other renewable or fossil energy systems and consequently raise the reliability and flexibility of the energy supply. Another highlighted advantage of bioenergy is the ability to combine with carbon capture and storage schemes [38]. Bioenergy can provide flexibility on several levels, that is, feedstock-side flexibility by storing dry biomass; intermediate energy-carrier flexibility by long-term storing solid or liquid or gaseous biofuels; operational flexibility by thermal energy storage or grid-oriented biomass-to-power management; and product flexibility by switching between heat and power or bio-based products generation [38].

As shown in Fig. 6.14, biomass energy may provide a convincible outlook of flexibility for energy planners according to the wide-range diversity in the forms of energy carriers and their applications.

Bioenergy systems can start in operation and be connected to the energy grid within a couple of minutes regardless of daytime (despite direct solar systems) or seasonal time according to the storage ability in the various points of a biomass-to-energy chain. These characteristics enable bioenergy plants to be highly effective in contributing to energy flexibility either on the smallest scale (e.g., a single building) or a large scale (e.g., a positive energy district) [39].

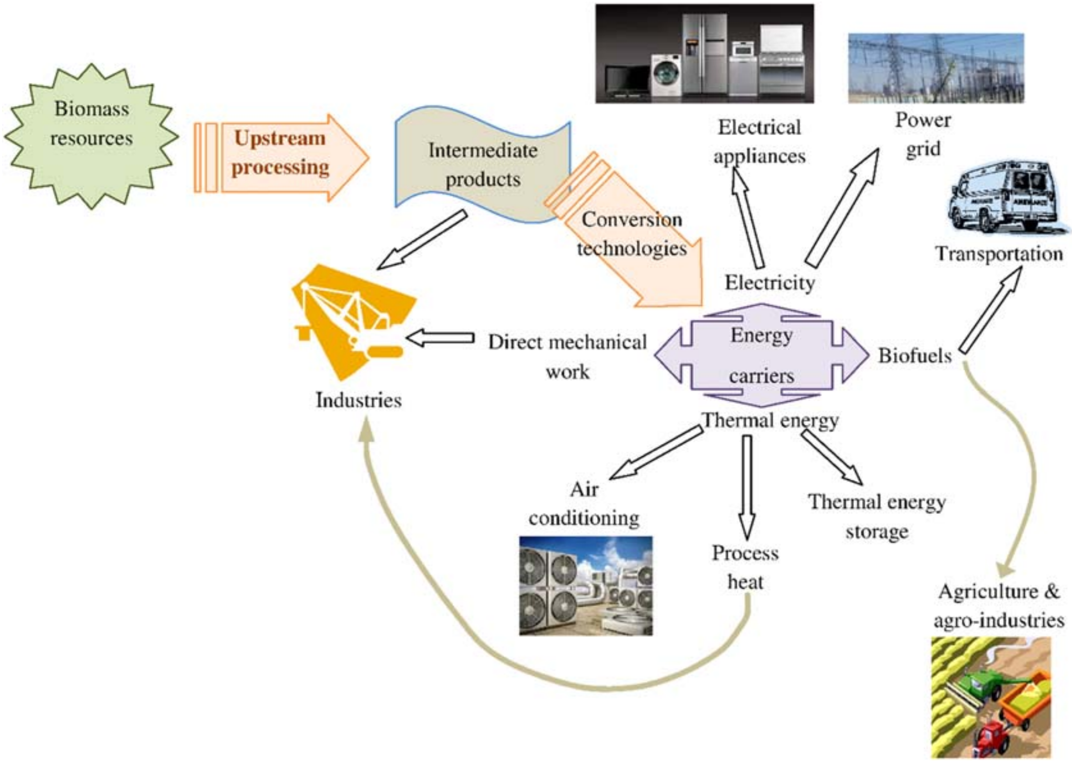

FIGURE 6.14 The chain of biomass resources into energy conversion and applications.

6.5.1 Employing thermochemical conversion of biomass for building energy supply

Thermochemical processes for the conversion of biomass into energy carriers include direct combustion, pyrolysis, gasification, and torrefaction. However, for building applications, direct combustion and torrefaction are the most applied and commercialized options. The stoves and boilers that can be designed to utilize solid biofuels such as hog wood, wood chips, wood pellets, and biomass briquettes, are well-developed and commercialized direct thermal appliances for heat supply in buildings. Some types of solid biofuels that are utilized by biomass-fueled heating systems are in turn a manufactured output of the torrefaction process such as biochar and char briquette.

Modern biomass-fueled heating systems for building applications mainly include log-wood stoves, pellet-fired stoves, wood-chips boilers, and automatic pellet-fired boilers. All of these appliances can be activated into operation within a couple of minutes or even as fast as several seconds by employing a smart energy management system to increase building energy flexibility and support demand response [38].

Beyond the biomass-fired heating systems, solid biomass-fueled power plants play an influential role in increasing the flexibility in energy supply for large groups of buildings in particular within the framework of district energy supply systems. These bio-electricity generating plants may be connected to the power grid as fast as necessary [40]. The incentives for biomass energy generation have been recommended by energy planning experts to empower building energy flexibility via using renewable energy resources [40].

6.5.2 Employing biological conversion of biomass for building energy supply

Biogas technology as a biochemical-based approach may be used to provide partial or full energy demand. This technology with more than one century of background was once planned and used to meet the rural households' demand for cooking and lighting. With technical advances through the decades, larger and more sophisticated biogas plants were developed to respond to the diverse energy needs of the communities. The early generations of anaerobic digesters were constructed by masonry techniques to receive animal manure and produce biogas to be utilized in rural community buildings. Nowadays, more advanced anaerobic digesters that are fabricated by modern construction materials within a compacted fashion can serve various buildings, particularly the villas that have access to diverse varieties of organic feedstock such as animal manure, biodegradable agro-residues, and food leftovers. The buildings in both rural and urban communities may be indirectly benefited from biogas energy by utilizing the electricity and/or heating/cooling/biomethane produced by a nearby centralized anaerobic digestion facility.

Diverse technologies might be integrated with an anaerobic digestion facility to supply and deliver energy carriers to buildings. Many biogas-to-electricity conversion products are commercially available in the market. Biogas-fired spark-ignition engine-generating sets and fuel cells are capable to be employed on a wide-range scale from a few kWs to 250 kW. Large gen-sets are available from 100 kW to around 2000 kW for utilizing biogas and delivering electricity to medium or large groups of buildings within a dedicated or public power grid. Large power capacities usually up to 10 MWe might be achieved by gas turbines or Rankine cycles comprising biogas-fired boilers and steam turbines in the vicinity of huge bioenergy resources such as large landfill sites, large wastewater treatment plants, and large facilities for processing of biodegradable waste resources. The biogas-to-electricity equipment can in turn be integrated with the heat recovery devices to generate useful thermal flows for space heating, domestic hot water supply, or even space cooling. These purposes also known as combined heat and power or combined cooling, heating, and power generation might be fulfilled for a single or a small group of buildings or a large number of buildings as well through the district heating/cooling. The phenomenon of cold supply using waste heat stream is possible by employing many processes among which, the absorptive cooling process using lithium-bromide (LiBr) absorbent or water/ammonia cycle is frequently applied [38].

Another great advantage of the integrated biogas-power-heating-cooling system is the capability of working within the framework of a circular economy. This concept enables bio-waste resources to be utilized optimally inside a closed cycle to provide energy and new recycled materials that can reduce the demand for over-harvesting of natural resources and nonrenewable reservoirs. Fig. 6.15 demonstrates the capabilities of anaerobic digestion (AD) technology in contributing to energy flexibility and circular economy. It can be seen that various bio-resources might be processed by the AD facility, in which

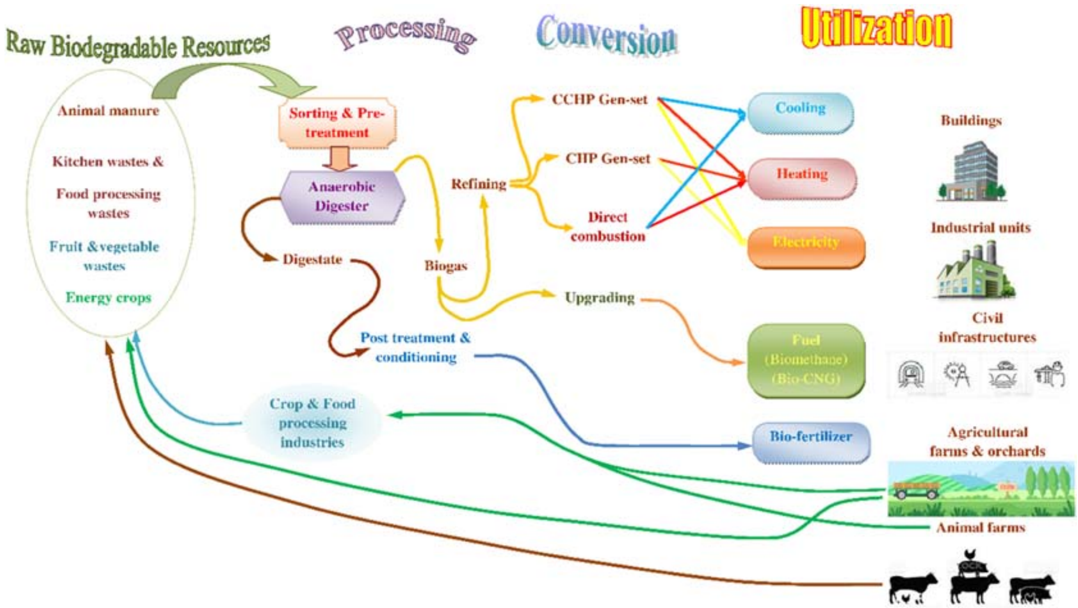

FIGURE 6.15 Graphical description of energy carriers' diversity and circular economy by anaerobic digestion technology.

biogas and digestate are the two main primary products. Biogas might be refined to be further converted into electricity, heat, and/or cold or be upgraded into biomethane as an alternative renewable fuel that can either be pressurized into Bio-CNG to be delivered at vehicle fuel stations or injected into the local gas network. Digestate can in turn be processed into biofertilizer to apply in farms or orchards and replace chemical fertilizers. All aforementioned energy carriers and products are utilized by the final consumers among which, buildings in the rural or urban areas as well as agro-industries and livestock farms will directly or indirectly be benefited from the outputs of those systems and the biodegradable parts of their waste streams might be returned into the AD facility. Therefore, the chain of circular economy will be established. The electrical power and heat supplied by the biogas-fired power generation/cogeneration facility will effectively contribute to the energy flexibility of the targeted buildings located in the service zone of the power grid and/or district heating in favor of peak demand compensation during the cold season. Similarly, the power and cooling application supported by a biogas-fired CCHP facility can play an influential role in peak shaving during summertime in hot climate countries such as Iran, Oman, and Saudi Arabia.

The capability of biogas and its upgraded product for compression and storage, and its compatibility with different energy conversion technologies as mentioned before, make it an attractive option to allow building energy systems more flexible.

The biogas digester may even be utilized in modern small-size units for individual buildings or rural houses to partly cover building energy demand. These small systems are easy to install and are flexible to accept various low-solids content substrates such as

FIGURE 6.16 A sample of a prefabricated easily installable anaerobic digester for microscale biogas generation [[42]]. *Photo courtesy of PUXIN® Technology.*

animal manure slurries, and food waste slurries. A sample of a portable microsize biogas digester is shown in Fig. 6.16.

The anaerobic digesters on different scales from small units to large centralized plants are capable to be integrated with various power and heat generation systems, especially with solar energy equipment. An off-grid hybrid renewable energy power plant for a hypothetical commercial building was conceptually designed by taking into account different climatic conditions in eight cities in the United States [41]. The considered power plant consists of a biogas digester, photovoltaic panels, a battery bank with a charger, a unitized regenerative solid oxide fuel cell, a biogas-fired internal combustion engine generator, and a DC/AC inverter. The assumed building was found to feasibly and completely benefit from this power plant if the biodegradable resources and the operational situation of the AD plant can produce 6000∼9500 standard cubic meters of biogas annually and the battery bank is fully charged at the beginning of the operational year [41].

6.6 Summary

In this chapter, first, an introduction was presented regarding the importance of renewable energy resources and the importance of using them to improve the energy flexibility aspects of buildings. Then, in the next sections, materials were presented about the contribution of wind, solar, geothermal, and biomass energies in building energy flexibility.

In the wind energy section, it was found that while on-grid wind turbines cannot directly play a role in the energy flexibility of buildings, the opposite is true for off-grid wind turbines. The solar energy section was dedicated to explaining how PV systems, solar water collectors, and solar air heaters contribute to the energy flexibility of buildings. It was seen that the PV panels integrated with the storage systems can supply the electrical and thermal power requirements of buildings. In addition, it was revealed that the participation of solar water collectors in building energy flexibility is through the supply of hot water and provide heating/cooling through the storage of thermal energy in the hot water coming out of solar collectors in building thermal mass or PCMs. Furthermore, it was found that solar air heaters can play a role in improving building energy flexibility by meeting building heating and cooling demands. In the geothermal energy section, it was illustrated that the involvement of geothermal energy in building energy flexibility is done through the participation of the shallow geothermal systems in the heating/cooling load and the supply of hot water needed by the building, district heating and industrial direct use of geothermal energy by middle-deep systems, and power generation through deep geothermal utilization. The geothermal energy storage concept is another method of using geothermal energy to enhance the energy flexibility features of buildings. Finally, in the biomass energy section, it was found that biomass-fired heating systems and solid biomass-fueled power plants can play a noticeable role in boosting the energy flexibility aspects of buildings in particular within the framework of district energy supply systems.

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CHAPTER

7

Heat pumps for building energy flexibility

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The global heat pump (HP) market size has been successively growing over the last years and this technology is expected to further expend in the energy sector in the near future. The popularity of HPs can be directly linked to the role they play in the decarbonization of the heating and cooling sector. Due to the substantial technological progress in HP technology together with the increasing generation of electricity from renewable energy sources (RESs) they are now recognized as one of the most energy-efficient technologies used for heating and cooling applications. The potential to further reduce emissions is its ability to be integrated with intermittent RESs such as electricity generated from photovoltaics and wind turbines. Electricity is converted into heat which can be subsequently stored in thermal energy storage systems. Such a feature provides a high level of flexibility in the heating, cooling, and energy systems, enabling effective use of RESs and resulting in smoothing and shifting the peak demand. This chapter focuses on HP systems and their ability to improve building and system operating flexibility. The first part provides a systematic review of HPs, and their parameters and operation ranges. Different integration configurations of HPs with heat sources or heat storage at the building level are discussed in the following part. As HPs show capabilities to integrate thermal and power systems, the last part of the chapter provides information on the improvement of building and network operating flexibility.

7.1 Introduction

The flexibility of HPs can be regarded from multiple angles. On an individual level, it could be regarded in terms of flexibility in its operation as a wide range of HPs allow them to be applied to various operating conditions and different types of heat sources.

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As the cooling cycle can be reversed, HPs can be used in heating systems, cooling systems, and for hot water production including harvesting waste heat to provide flexibility. On the system level, HPs can be integrated with different energy sources. Combining HPs with RES and thermal energy storage (TES) solutions greatly increases the flexibility of the use of renewables. This solution adjusts to fluctuations in energy generation from intermittent sources and fluctuations in the energy demand profile. Moreover, HPs are flexible in terms of energy demand and energy capacity. Irrespective of the scale, whether on a building level or on the grid level, they can improve stability in energy supply, increase the use of currently available RES, and provide flexibility in building system/grid operation.

7.2 Overview of heat pump technologies

7.2.1 Types of heat pumps

A HP is a device that, with the supply of electrical or mechanical energy, allows to transfer heat from a source with a lower temperature to a source with a higher temperature, and vice versa. HPs are applied when there is a heat source with a relatively high temperature but still too low for direct use. If there is a need for heating and cooling, thermal energy could be transported over a long distance and then the use of a HP reduces investment costs. HPs are used to generate heat and cool for the needs of technical systems in buildings and also in various industrial applications. The classification of HPs can be achieved in different ways, for example in terms of application, thermal efficiency (size), or the type of heat sources and heat distribution systems, and some of them will be discussed below.

HPs can be divided into those supplied with electricity (compressor HPs, Fig. 7.1), gas (absorption HPs, Fig. 7.2), and thermochemical energy (adsorption HPs). Compressor HPs implement the thermodynamic cycle (the Linde cycle), which is the reverse cycle of the heat

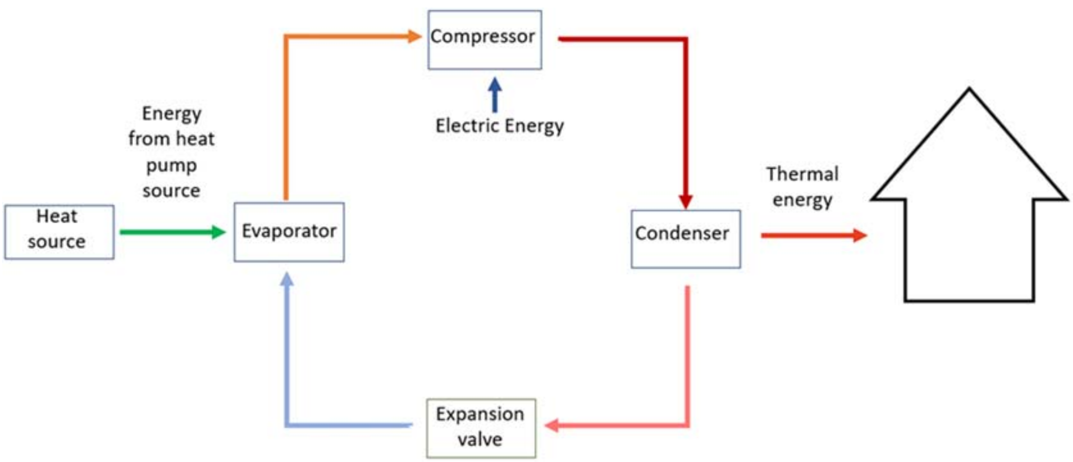

FIGURE 7.1 Scheme of a compressor heat pump.

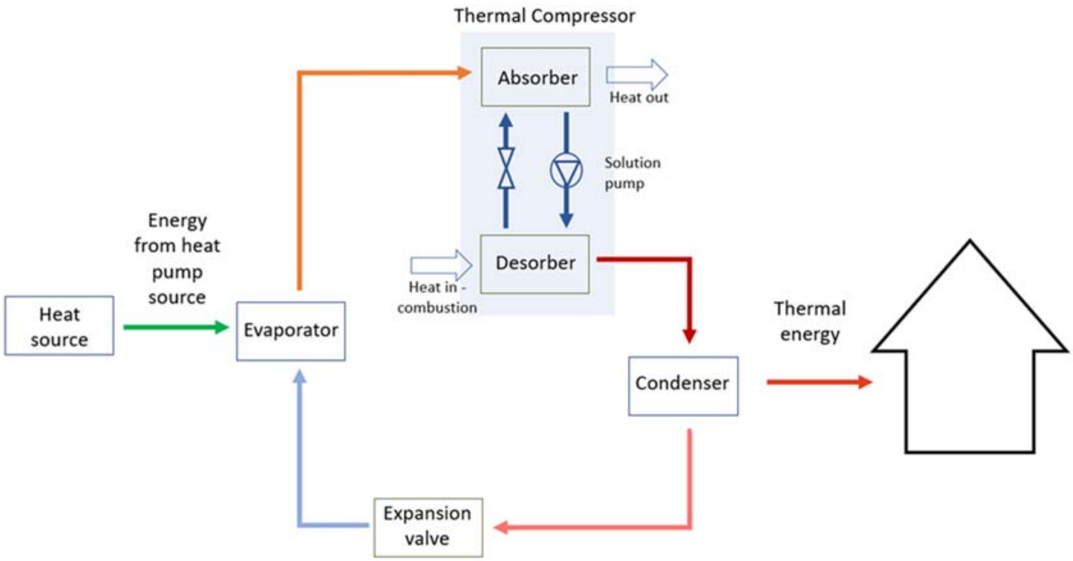

FIGURE 7.2 Scheme of an absorption heat pump.

engine. The heat is absorbed by the evaporating liquid working medium (evaporator—low HP source) and as the steam goes to a compressor powered by electricity, its pressure is raised. The steam then gives off its heat in a second heat exchanger (condenser) as a result it condenses. Then, the medium in the form of a liquid flows through the expansion valve where the pressure drops, and the liquid goes back to the evaporator.

Absorption HPs operate in the same way as traditional compressor HPs, but they differ in their construction, that is, instead of using a compressor in the absorption device, a generator-absorber (thermal compressor) system is used. Absorption HPs typically run-on natural gas. These HPs are characterized by low failure rate and quiet operation due to the limited number of mechanical elements. Absorption HPs are used where both heating and cooling are required. The operating principle of the adsorption HP is the same as that of the absorption HP, and the only difference is that the adsorption HP uses solids instead of liquid sorption.

Thermoelectric HPs use the Peltier effect, which means that at a constant voltage applied to a circuit composed of two semiconductors, one weld will be heated and the other will be cooled. These devices can be used for both heating and cooling, although the main practical application is for cooling. Their main disadvantage is their limited efficiency compared to compressor HPs.

The common way to split HPs is the type of heat source. During its selection, the availability of the heat source and its ability to regenerate is very important because at the time of operation the amount of energy drawn from the source should not be too low. The ideal HP source should have a stable and sufficiently high temperature throughout the whole year. The basic types of HPs include air-source HP, geothermal (ground-source) HP, exhaust air HP, solar-assisted HP, water source HP, hybrid HP (twin source), and waste heat driven

HP (including adsorption and absorption HPs). The heat for the HP's evaporator can be obtained from one heat source (monovalent systems) or many sources, for example, two (bivalent systems). Bivalent systems are used when the power of one source is too low. The temperature of natural heating sources depends not only on the type of source but also on the season of the year, and the temperature of the waste heat depends on the course and specifics of the technological process. Air is the most readily available source of heat source and is therefore often used especially in the case of single-family houses. The problem, in this case, is that with decreasing outside air temperature, the building heating demand increases. However, when the temperature of the heat sink, i.e. outdoor temperature decreases, HP's efficiency drops also resulting in lower heating power. Another disadvantage that increases the surface of the heat exchanger of the heat source is the low air heat transfer coefficient. The popularity of this solution is high due to the low investment costs. Water as a heat source has favorable properties due to large values of heat transfer coefficient, which allows reducing the heat exchanger surface. Surface water can be a heat source for medium HPs, but due to a more stable temperature, groundwater is a better source, but the cost of such a solution is higher. In the case of ground heat exchangers, two basic types, horizontal and vertical, are frequently used. The horizontal exchanger mostly uses the energy of the sun and rainwater, as pipes run close to the ground surface. Therefore, it is important to provide a large space for it. Vertical heat exchangers operate at a relatively stable ground temperature throughout the year, so the efficiency of such HPs is higher than using a horizontal heat exchanger. Vertical heat exchangers require less space but are more expensive. The use of waste heat is possible not only in industry but also in buildings, for example, from exhaust air or sewage, but it requires appropriate design and cooperation of HVAC systems and water and sewage systems. The choice of technology and heat source must take into consideration local climatic conditions, the efficiency of the device, investment and operating costs.

Components of compressor HPs are compressors, expansion valves, condensers, and evaporators as well as regulation and control devices. The following compressors are used in HPs: displacement (reciprocating, rotary, scroll, screw) and centrifugal (flow)

7.2.2 Heat pump market

In 2018, the size of the global HP market was valued at 55.2 billion USD, and in 2026 it is expected to reach 99.6 billion USD [1]. The European HP market has recorded an annual sales increase of 10%−13% in the last 5 years. In 2019, according to European Heat Pump Association (EHPA) estimations, 1.45 million devices were sold, and the HP industry had an impact on the employment of about 101,000 people. There are currently around 41.9 million HPs in operation in the 21 European Union countries [2]. In 2030 in Europe, 40% of all residential buildings and 65% of all commercial buildings are expected to be heated by electricity [3]. Due to decarbonization in the European Union by 2050, the HP market has great development potential not only in housing construction but also in the industry especially through reusing waste heat and the use of RES instead of fossil fuels. When determining the market potential, both the aspects related to the size and number of units and the determination of the potential use of a given solution are important.

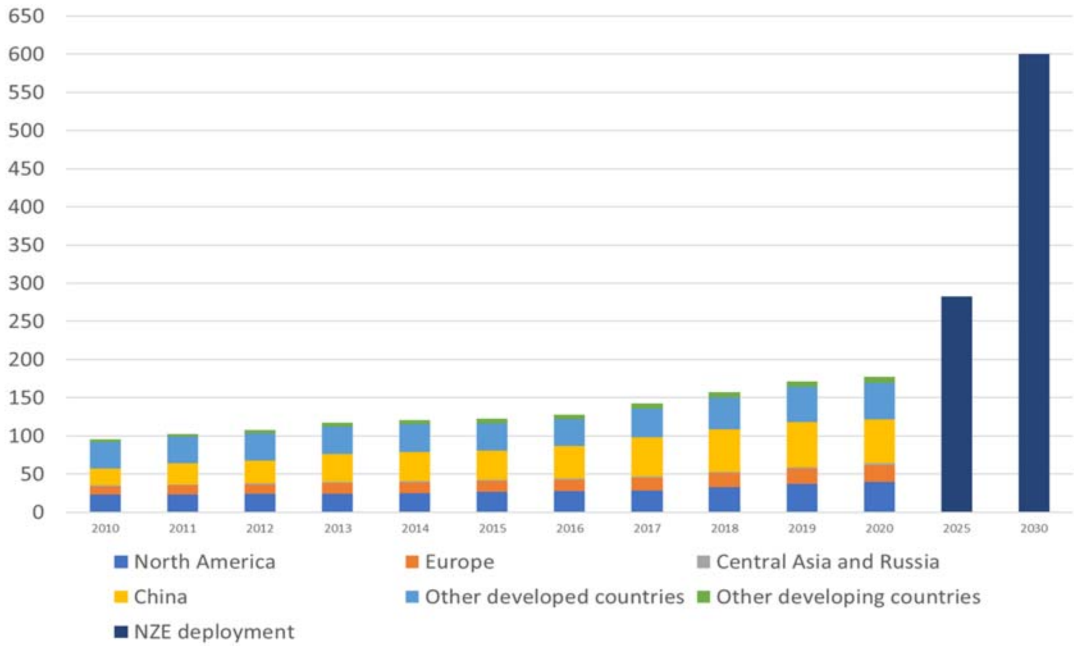

FIGURE 7.3 Installed heat pump stock by region and global net zero scenario deployment 2010–30 [6].

Such an approach was presented in [4] where the potential in various industries (paper, chemical, food, and refinery) was defined, taking into account the division into the sink temperature.

According to IEA data, approximately 178 million HPs were used for heating in 2020 (North America 40.1 million, Europe 21.8 million, Central Asia and Russia 2.4 million, China 57.7 million, other developed countries 47.6 million, and other developing countries 7.7 million) [5]. However, according to the Net Zero Emissions by 2050 Scenario [6], the number will increase to 600 million by 2030 (Fig. 7.3).

The analyses showed that in order to achieve the goals related to the decarbonization of the entire economy of the EU countries by 2050 at the level of 95%, electrification of the construction industry should be implemented at the level of 63%. In the case of energy demand for heating, this will only be possible through the extensive use of HPs [7]. The market for HPs around the world is developing very well and due to the features of HPs, more and more HPs are expected to be deployed not only in buildings but also in the industry sector.

7.2.3 Technology performance—flexibility parameters of heat pumps

HPs have many advantages, including consistent efficiency (efficiency does not decrease significantly with time of use), long service life, low operating costs, low energy production costs, low maintenance costs, simple construction, quiet operation, and no chimneys (no combustion process). The disadvantages are their relatively high price and installation costs, the dependence of their operation on electricity, and large dimensions (both devices and exchangers).

The performance of HPs is mainly characterized by the following parameters:

- COP (Coefficient of Performance): It determines the efficiency of the HP, and it is the ratio of the amount of the produced energy to the energy consumed at a given moment by the HP.
- EER (Energy Efficiency Ratio): The definition of EER is analogous to the COP. It describes the cooling capacity of the HP, and it is the ratio of the cooling capacity of the HP to the consumed electrical power at a given temperature. The EER is closely related to the description of the cooling capacity.
- SCOP (Seasonal Coefficient of Performance): It takes into account the variability of the heat demand of the building and the variability of the efficiency of the HP throughout the heating season.
- SEER (Seasonal Energy Efficiency Ratio): It takes into account the variability of the cooling demand of the building and the variability of the efficiency of the HP throughout the cooling season.

The use of appropriate control and software enables the cooperation of HPs and their communication with energy management systems in the building or external networks. Proper cooperation with an external power grid reduces electricity consumption and enables optimization of the time of energy consumption from the grid. Integrated power supply systems ensure that energy is obtained from the network at times of its lower load and that energy is stored in building systems. The parameters that affect the flexibility of such solutions include heat demand, HP size, storage type and size, and dynamic system properties. Heat demand determines not only the amount of energy that can be shifted in a given period but also the time in which storage is fully charged and discharged. The size of the HP affects the possibility of the load shifting within a certain time and power that can be ramped up or down. When, how much, and how long energy can be stored depends on the storage type and its size. Other important factors for flexibility are the dynamic operating parameters of the HP. For example, the time needed to change the speed of the compressor, that is, the power consumption of the device over time. Frequent switching of the operating mode of the device reduces the service life, which negatively affects flexibility. All these elements must be taken into account when designing systems with HPs cooperating with other network elements and installation.

7.2.4 Level of development

Currently, most HPs on the market can operate with flow temperatures (the temperature at the input of the installation from the HP) as high as 65°C. In the case of standard applications, that is, central heating in buildings, the supply temperatures should not be higher than 55°C on the supply side and 45°C on the return side. However, such parameters are not sufficient for industrial installations and processes. The maximum supply temperature of the available systems, including cascade systems, is up to 100°C with a difference between the source and receiver temperatures of approximately 50°C per compression stage. The use of HPs above this temperature is challenging but not impossible. In 2021, the world's first HP which can increase temperature up to 180°C was developed. Such high temperature guarantees the possibility of using HPs in many branches of industry and will allow one-fifth of European industry to reduce energy consumption by up to 70 percent [8].

A very wide range of HPs with heat power ranging from around a few kilowatts for a single device to even 50 megawatts of a vast HP is available on the market.

The development of the HP market depends on many factors such as efficiency, size, and prices of the available devices. The efficiency of the unit depends primarily on the type of HP. For example, the average seasonal efficiency ratio SCOP of air-to-air HPs is currently approximately 2.5, an air-to-water HP is 3.5, and a ground-source HP is 4.0. The theoretical maximum COP of the HP is described by Eq. (7.1).

$$\mathrm{COP}_{\max} = \frac{T_{\text{condenser}}}{T_{\text{condenser}} - T_{\text{evaporator}}} \tag{7.1}$$

where $T_{\text{condenser}}$ is the temperature of the heat sink (K), and $T_{\text{evaporator}}$ is the temperature of the heat source (K).

From Eq. (7.1), it can be concluded that the greater the temperature difference between the condenser and the evaporator, the smaller the maximum achievable value. The figure below shows the change in $\mathrm{COP}_{\max}$ as a function of the condenser and evaporator temperatures in accordance with the Carnot efficiency equation (Fig. 7.4).

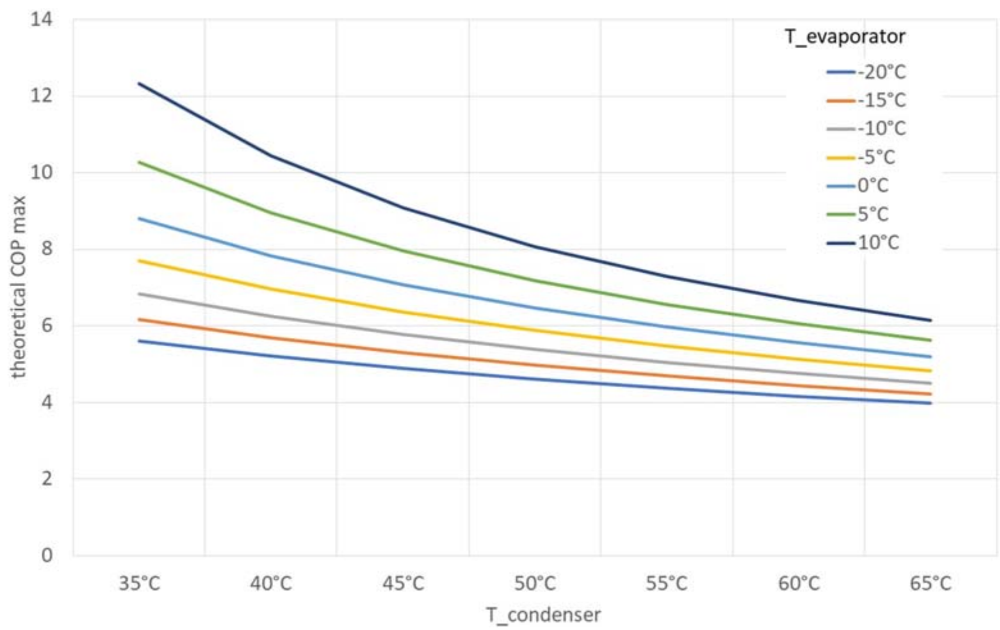

FIGURE 7.4 Maximal theoretical COP of heat pumps.

TABLE 7.1 Compressors types used in different heat pump applications.

Applications	Compressor type
Car air conditioning	Rotary
Household refrigerators	Reciprocating compressor Rotary
Window air conditioner	Reciprocating compressor Rotary (to 10 kW) Scroll (from 5 kW)
Air conditioner	Reciprocating compressor
Heat pumps	Scroll
Commercial devices	Reciprocating compressor Scroll (to 70 kW) Screw (from 150 kW)
Big commercial devices and heat pumps	Reciprocating compressor (to 200 kW) Screw (to 1600 kW) Centrifugal (from 350 kW)

The diagram shows that the lower the temperature of the HP source the lower the efficiency however, currently, there are available devices that even can operate at a temperature of −25°C.

One of the main factors affecting the efficiency of a HP is the compressor. Table 7.1 shows the compressors that have been used for different applications. The different designs of compressors and the principle of their operation affect the possibilities of their application.

7.3 Flexibility to integrate heat pumps with different energy sources

HPs can be designed to provide heating or cooling. They can cover the entire energy load or can be supported by an additional energy source. The flexibility in using a HP is associated with many variables, that is, type and parameters of heat source (air, ground, water), type and parameters of the heat sink (heating installation, domestic hot water installation, technology, i.e., ventilation), and availability of fuels or energy carriers. A schematic of an example of a simple system with a ground-source HP working for the building heating circuit is presented in Fig. 7.5.

In this simple system, the HP obtains heat directly from the heat source (i.e., the ground) and directly supplies the heat sink (the heating circuit in the example case). There are no other devices in-between the HP and source or sink. However, the HP must cover the entire heating load, even on the coldest days. Also, the regulation of its operation is not so effective, especially in the case of convective radiators in the heating circuit.

These types of radiators heat up and cool down very quickly, which result in the continuous on/off operation of the HP. Therefore, in order to increase the efficiency of the system, additional devices like heat sources or thermal storage are being used.

Four main groups of the system have been identified:

- Combination of the HP with an additional heating/cooling energy source on the sink side of the HP.

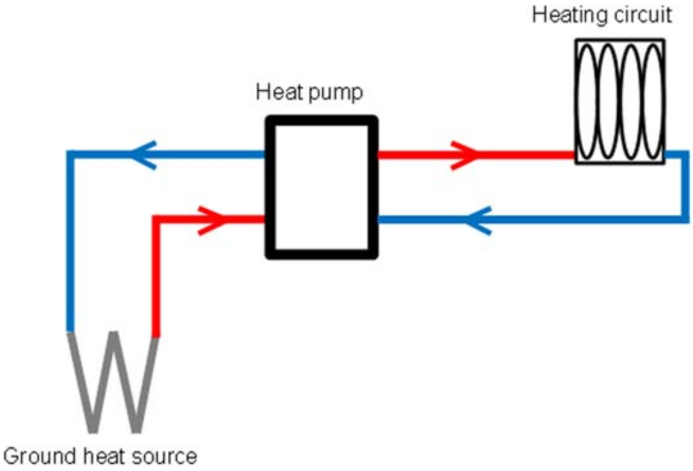

FIGURE 7.5 Schematic of a ground-source heat pump.

- Combination of the HP with additional heating/cooling energy source on the heat source side of the HP.
- Combination of the HP with thermal storage on the sink side of the HP.
- Combination of the HP with thermal storage on the heat source side of the HP.

7.3.1 Operational modes of heat pump systems

In many cases, the use of a single HP to cover the whole heating or cooling load of a building can not be technically possible or economically effective. This is particularly true for air-source HPs as they have a minimum outdoor operating temperature. At very low external temperature the efficiency and thermal capacity of the air-source HP decrease. Therefore, such installations should be supplemented with additional heating sources in order to provide the required energy needs during the coldest days. The supplementary heating source can also be useful in order to defrost the HP.

As indicated in Fig. 7.6, there are three following basic operating modes of the HP:

- Monovalent.
- Mono-energetic.
- Bivalent.

The monovalent mode of the HP means that the HP covers 100% of the heating needed for the building, without cooperation with another heat source. It is mainly used for ground/water HPs in new buildings with an energy efficiency standard. When selecting an air-to-water HP, reducing the heating capacity at low outdoor temperatures should be considered.

The mono-energetic mode of the HP introduces an additional electric heat source (built-in electric heater or electric boiler). The HP covers about 90% of the annual heating demand. Mono-energetic mode allows only the electrical connection to be used for the building (e.g., in the absence of access to the gas network).

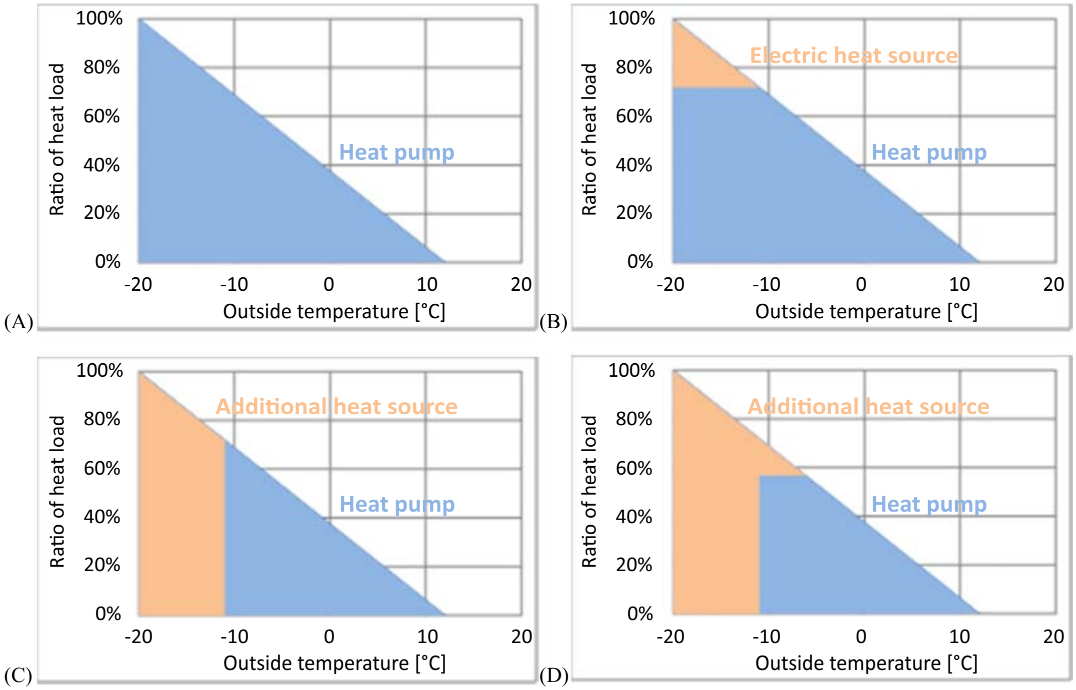

FIGURE 7.6 Operating modes of the heat pump— (A) monovalent, (B) mono-energetic, (C) bivalent alternative, (D) bivalent parallel.

In the bivalent mode of the HP, an additional heat source is required. When the outside temperature is low, the additional heat generator completely takes over the role of the HP to meet the heat demand (bivalent alternative mode) or works in parallel with the HP (bivalent parallel mode). The bivalent alternative mode can be used with any energy source, even with solid fuel boilers. The bivalent parallel mode can be used with devices with good flexibility of operation, such as gas boilers with modulated power adapted to the current heat demand.

The monovalent mode is the simplest and cheapest technique, as there is no need to install additional equipment and controls. The choice of the operating mode of the HP is affected by:

- The temperature of the heat source: the higher and constant it is during operation, more often the monovalent mode is chosen.
- The temperature of the sink: the lower the temperature, more often the monovalent mode is chosen;
- The heat load: the more constant value during the operational time, more often the monovalent mode is chosen.

All the operating modes can be supplemented by thermal storage on the sink or heat source side of the HP.

7.3.2 Integration with a heat source—sink side of the heat pump

The capacity of the HP is dependent on the heat source and the sink temperature. With the constant sink temperature and lower heat source temperature, the capacity of the HP decreases, and the entire heating load may not be covered.

To maintain designed installation parameters on the sink side, an additional energy source must be used. It can be a simple electric heater, a conventional boiler (i.e., gas or biomass), or a renewable energy source (i.e., solar collectors). The range of the solutions is wide and the specificity of the HP allows for flexible selection of the appropriate energy source.

The supplementary heat source can be connected with the HP in parallel. In Fig. 7.7, a schematic of a ground-source HP in parallel connection with a gas boiler is presented.

The HP is the primary energy source. When the outside temperature decreases and the heat load increases the supplementary heat source starts to work to support the HP. With the further increase in the heating needs, the auxiliary energy source can overtake entire heat production. This is a common situation in the case of air-source HPs that cannot operate at low outdoor temperatures. The system with a direct parallel connection of the HP and the auxiliary heat source can be applied if the heat capacity of the supplementary energy source is easily modulated. The heat load of the building can change quickly over time, and the heat source must be able to easily adapt to the current demand. Therefore, for the parallel system, usually a gas boiler, an oil boiler, or an electric heater (or boiler) is used as an auxiliary heat source.

The heat sources like solid fuel boilers, solar collectors, or even fireplaces can also be combined with the HP. However, a buffer tank must be used in the system, as shown in Fig. 7.8.

The role of the buffer tank is to increase the hydraulic regulation of the installation on the side of the heating circuit. The heat capacity of the solid fuel boilers cannot be precisely modulated so a direct parallel connection with the HP is not recommended. In addition, the buffer tank can be used as thermal storage or a domestic hot water tank if the dual installation is designed. The HP works as a primary energy source and a heating coil connected to the HP is placed at the lower part of the buffer tank. The coil from the

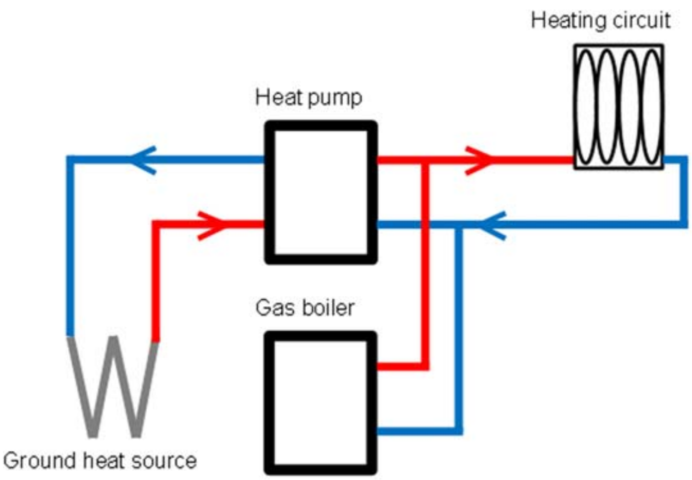

FIGURE 7.7 Schematic of a ground-source heat pump in parallel connection with a gas boiler.

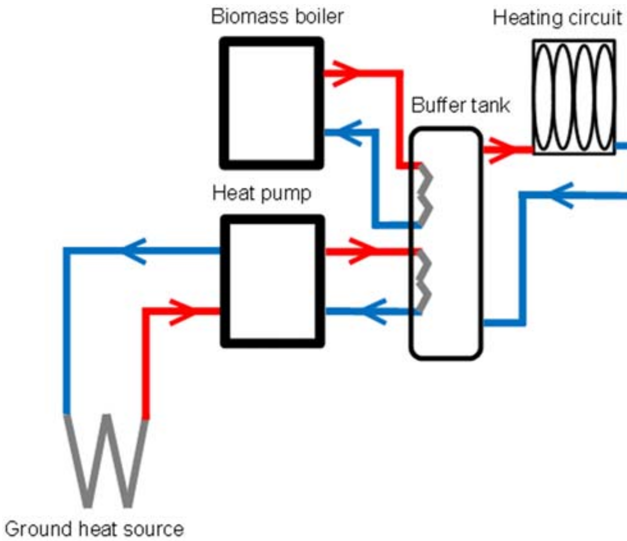

FIGURE 7.8 Schematic of a ground-source heat pump in parallel connection with a biomass boiler with the buffer tank.

auxiliary heat source is installed in the upper part when the supplied temperature is higher than from the HP. When a higher temperature in the heating circuit or for domestic hot water is needed, the auxiliary heat source starts to operate.

In the system where solar collectors are combined with the HP, the situation is inverse. The solar collectors are the primary energy source, and the coil is placed in the lower part of the buffer tank. The coil of the HP is placed in the upper part and the HP operates when the entire heat load is not covered by solar collectors. Although the arrangement of coils in the heat accumulator is flexible, those fed from a high-temperature heat source should be placed in the upper part.

7.3.3 Integration with a heat source—heat source side of the heat pump

The efficiency and capacity of the HP increase with the increase of the heat source (air, ground, water) temperature. Several types of improvements with additional energy sources have been used to increase the efficiency. If the additional heat source can reach the sink temperature, there is no rational sense for using it on the heat source side. In most cases, waste heat or low-temperature sources supplement the heat source. Thus, conventional boilers or electric heaters are not used for this purpose.

In one of the most common systems, exhaust ventilation air is used to increase the temperature of the heat source for the air-source HP. For example, in residential buildings without heat recovery in the ventilation system, the exhaust air temperature is above 20°C over the whole year. The use of this airflow as supplementary for the air-source HP increases the temperature of the heat source, especially in cold periods. Due to a constant exhaust air temperature during the whole year, such a solution is very often used for the preparation of domestic hot water.

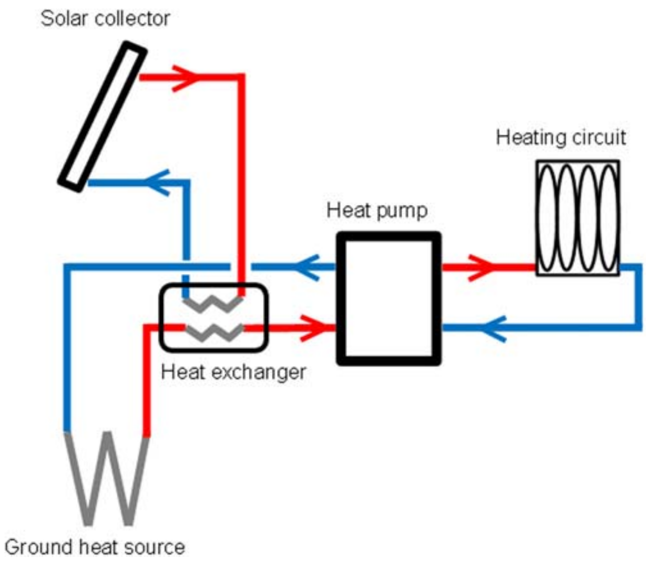

FIGURE 7.9 Schematic of a ground-source heat pump with the liquid solar collector connected to the heat source side.

Other systems use solar collectors to increase the heat source temperature for the HP. There are several examples of the use of solar collectors for this purpose. In the first one, the liquid solar collector is used to increase directly (or with the use of a heat exchanger) the heat transfer fluid temperature from the ground-coupled loop. A schematic of a system with the heat exchanger is presented in Fig. 7.9.

In the cooling-dominated regions, the ground-source HP used for cooling loads can be supplemented on the heat source side by the cooling tower. The heat transfer fluid is cooled down in a direct circuit or with the use of a heat exchanger in a passive way in the cooling tower. This system will allow to decrease the size of the ground heat exchanger loop and increase the energy efficiency of the HP.

In addition, the solar collector can be used as a heat source for the HP (Fig. 7.10). The transfer fluid is heated directly in the liquid solar collector. The use of a collector allows using solar heat to increase the temperature of the heat source and therefore increase the capacity and efficiency of the HP.

7.3.4 Integration with thermal storage—sink side of the heat pump

The use of thermal storage on the sink side of the HP can be related to two main cases: to combine inputs from several technologies or to decrease peak loads. The heat pump system can work with additional energy sources such as conventional boilers, electric heaters, or solar collectors. The best solution to combine the inputs from several different technologies is to use a buffer tank (see Fig. 7.8). The tank is supplied with the heat of different temperatures by the heat exchanger, usually in the form of heating coils. The heat inputs may be higher than the actual heating needs, and the medium in the tank is heated up to store extra heat. The integration of the storage tank also allows it to supply different

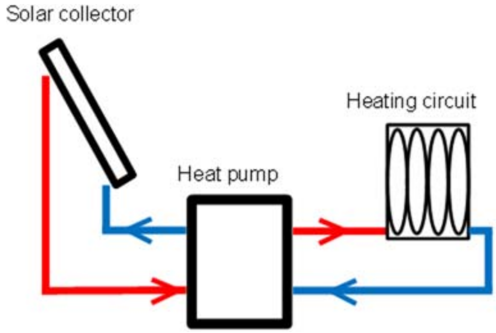

FIGURE 7.10 Schematic of a heat pump with the liquid solar collector as a heat source.

heating needs in the system, like heating, domestic hot water preparation, or technological needs such as ventilation.

The heating needs are not constant over time, especially for heating purposes. To not oversize energy sources, thermal storage might be used. The tank is loaded at the time when production of the heat exceeds actual needs. In the period when a higher heating load occurs the energy sources operate with constant power and the additional energy is taken from the thermal storage.

The thermal storage on the sink side of the HP is short-time storage, and mostly daily periods are considered. The use of long-time storage (like seasonal) is not economically feasible, as the heat losses from the tank would be high due to the high temperature of the medium in the buffer. The level of temperature also determines the medium used in such thermal storage. In most cases, it is water, however, phase change materials can also be used. For the system where the HP works for the cooling needs the ice or phase change material is more frequently used as a thermal storage medium. The choice of appropriate medium is flexible and depends on the temperature level, space limitation, and economic viability.

7.3.5 Integration with thermal storage—heat source side of the heat pump

The temperature of the heat source for the HP is lower than the heat sink, and therefore there is higher flexibility to use thermal storage starting from the short, medium, or long-time storage, and ending with water, ice, or ground type storage.

The first example with the short-time storage is the system with solar collectors but with an additional water buffer tank on the heat source side. A schematic of such a system is presented in Fig. 7.11.

The thermal storage system is loaded with heat supplied by a solar collector. The HP uses the heat from the buffer tank. During the daytime when the heat load from the solar collector exceeds the HP needs, the temperature of the water in the tank increases. During the nighttime when there are no solar gains, the HP can still work with high energy efficiency, as the heat source (water in the buffer tank) has a higher temperature than the external environment. Due to stationary heat losses from the tank, the accumulation of the heat, in this case, is considered in the daily periods.

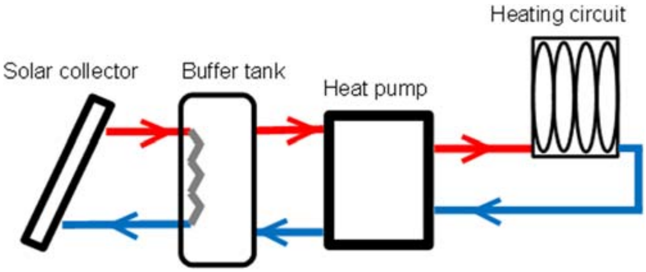

FIGURE 7.11 Schematic of a heat pump with the liquid solar collector and water thermal storage.

In order to increase the thermal capacity, or to decrease the size of the buffer tank, ice-water storage can be used. In this system, the temperature in the tank is equal to 0°C and the solar collectors are used for the regeneration of heat in the buffer. Due to the low temperature of the thermal storage, waste heat (i.e., from cooling installation) can also be used for regeneration.

In most cases, the heating needs of the building and the possibility of using solar heat are not occurring at the same time. The higher needs occur during the winter period when the solar irradiation is lower, and on the contrary during the summer period heating needs are low and energy delivered by the sun is higher. To use summer heat during winter, seasonal thermal storage must be used. Due to a long time between the loading and the unloading of the storage, such a system should be characterized by high thermal capacity, low temperature of the storage, and relatively good thermal insulation from external climatic conditions. The most common system is to use ground for this purpose. The heating coils are placed directly in the ground during summertime, and they deliver the heat from RESs (i.e., solar collectors) or low-temperature waste heat (i.e., exhaust ventilation). The same heating coils can be later used by a HP to take away the heat from the ground. The temperature of the ground is increased only by a few degrees, as the heat capacity of the soil is high. If the heating coils are not installed deep below the ground surface, a layer of thermal insulation is applied above and on the sides of the ground heat storage. This measure decreases the heat losses and, in the end, increases the efficiency of the HP. A schematic of a HP system with a ground thermal storage supplied by a solar collector is presented in Fig. 7.12.

This system is similar to the system with the water thermal buffer on the heat source side of the HP presented in Fig. 7.11. The solar collector is used to load the thermal storage but not to directly cover the heating loads. The difference between both presented systems is that the first system with water buffer is short-time storage and the second with ground buffer is long-lime storage.

7.3.6 Multiintegrated systems

The HP systems include usually an additional energy source or thermal storage or cover several needs such as heating, domestic hot water preparation, and even cooling. It is related to the desire to maximize the potential of each technology. The combinations presented in the previous chapters can be supplemented with a photovoltaic system that covers the electricity needs of the HP compressor.

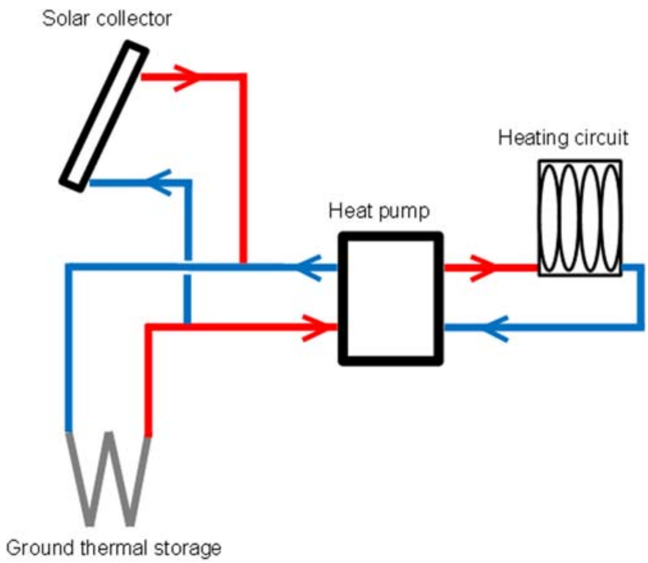

FIGURE 7.12 Schematic of a heat pump with the ground thermal storage supplied by a solar collector.

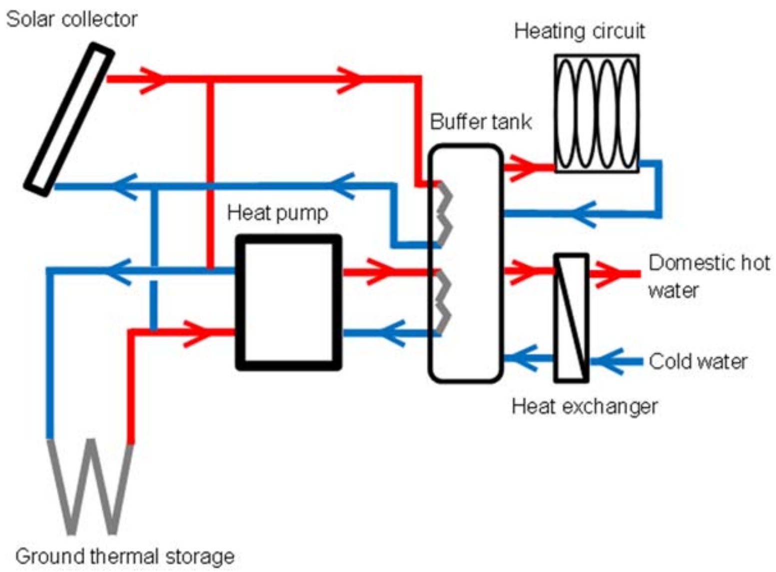

FIGURE 7.13 Schematic of multiintegrated systems with a heat pump, a ground thermal storage, a solar collector, and a buffer tank.

In most of the buildings, not only heating but also domestic hot water needs are present. The use of the HP system, especially with additional heat sources or thermal storage only for one of those needs would be inefficient. The solar collectors could cover the direct heat load of the domestic hot water and in the time when heat production exceeds current needs, it might be used by the HP to cover the space heating load. A schematic of a multi-integrated system with a HP system, ground thermal storage, a solar collector, and a buffer tank for a heating circuit and domestic hot water is presented in Fig. 7.13.

The use of the reversible HP can decrease the investment cost in comparison to separate heating and cooling energy sources. In the case of the ground-source HP, it will also increase the energy efficiency of the whole system, as the ground heat source can be regenerated with heat from the cooling of the building. In such a system, heating needs should be equal to the cooling needs of a building. Otherwise, the temperature of the ground will constantly increase (or decrease) from season to season, and finally, the system will not be able to operate efficiently.

There is a wide range of flexible solutions using the HP systems however, the integration of any element with the HP needs a technical and economic feasibility study, taking into consideration the type and value of energy loads, the temperature of the sink, heat source, investment cost and operational cost.

7.4 Heat pumps for improved operating flexibility

7.4.1 Role of heat pumps in the operating flexibility of future energy systems

Future smart energy systems integrate and coordinate district heating and cooling, energy grid, gas grid, and transportation. The integration of those sectors aims at providing more flexible and sustainable systems, increased energy production from RESs, lower use of fossil fuels, and overpassing challenges and imbalances that are now encountered in each network. The future transformation of energy grids, shown in Fig. 7.14, shifts towards so-called the 4th Generation District Heating (4DH). Defined by Lund et al. [9], it diversifies the energy sources and moves towards the integration of thermal systems (heat and cold production) with power systems. More information can be found in Chapter 9 Smart grids and building energy flexibility.

In this transformation, HPs play an important role due to their capabilities to integrate all energy systems. HPs can provide flexibility in terms of available energy sources for heat and cold production resulting in boosting the use of RESs and waste heat. Secondly, if integrated with TES, they can transform excess energy produced from RESs to TES for heat storage. Shaving the peak demand contributes consequently to increased flexibility and security of the power system.

7.4.2 Large heat pumps in centralized energy production

HPs that have a capacity exceeding 100 kW are considered as large HPs (LHPs). Although they have been mostly applied in the industry sector, they have great potential to be integrated into energy systems, especially into district heating network (DHN) for heat production. Along with the increased energy production from intermittent sources such as wind or solar energy, they can use the excess energy produced from RES to produce heat or cold, and when integrated with other energy sources and seasonal thermal heat storage, altogether can improve the stability and performance of centralized energy production. The integration of LHPs in DH networks can furthermore contribute to higher resistance to the future fluctuation of energy prices. HPs can produce heat during periods when there is an overproduction of electricity, especially from RES,

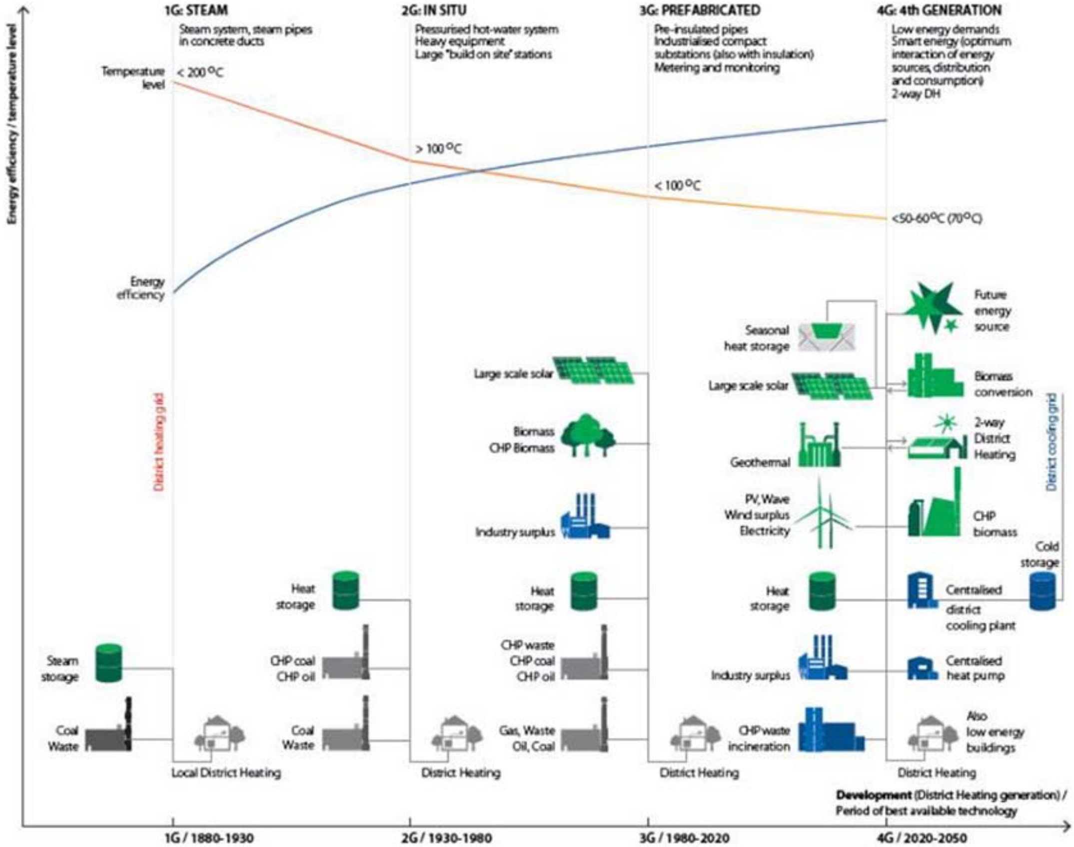

FIGURE 7.14 The concept of transformation of the district heating systems [9].

and therefore at a lower electricity price. Moreover, as the future heating networks are supposed to operate at lower temperatures compared to existing ones, HPs will achieve higher efficiencies which consequently will also improve their economic feasibility. However, the is no one unified and recommended solution. The type of HP and its integration with the system depends on the local conditions, that is, available renewable sources, type of heat and power source, electricity mix, demand profile, local market, etc. One of the possible solutions is the integration of LHPs with Combined Heat and Power (CHP) systems, regardless of the fuel type (waste, biomass, or fossil fuels). In such a solution, HP can be used to preheat the water, while the CHP can be used to boost the supply temperature if necessary. LHP operating together with a waste-to-energy plant can recover condensation heat from flue gas. The other option is to use the LHP as a supplementary heat source, operating under favorable conditions. Finally, LHPs can operate as the main and only heat/cold source to supply the DHN.

Analyzing the type of available RESs, one of the common solutions for centralized heat production is to use geothermal energy, where HPs are used to elevate the temperature entering the supply pipe of the district heating network (DHN). The proximity of the wastewater treatment plant (WWTP) allows for the harvest of the heat from sewage and the transfer of this energy into the heating network. Aside from the use of waste heat, the effect of lowering the temperature of the sewage water is also beneficial for aquatic wildlife. When the CHP is located close to the sea, seawater can be used as a heat sink for the LHP. However, the fluctuations of the water temperature would to some extent influence the HP's efficiency. An example of such a system can be found in Copenhagen in Denmark where an 800 kW capacity groundwater HP supplies a local DHN, with a water temperature of 68°C–74°C [10]. In Drammen, Norway, HPs deliver heat even at such high temperatures as 90°C covering 85% of the district heating demand using deep seawater from the fjord as a heat source [3]. The system efficiency depends on the type of HP, temperatures of the heat source, and the operating temperatures in the district heating loop. The typical temperatures for different heat sources are shown in Table 7.2, while the output temperature on the heat sink side usually stays in the range between 60 and 90°C.

To increase the flexibility of such systems, it is important to incorporate some types of heat storage solution for example, short-term storages versus long-term storage such as boreholes, tanks, and pits, which would work as a buffer between heat demand/supply and available energy from intermittent sources. More information can be found in Chapter 5 Thermal energy storage for enhanced building energy flexibility. Moreover, the economical benefits of the operation of the LHPs depend strongly on the energy prices. In certain periods, when the COP represents low values, heat can be produced only from the primary heat source or is discharged from the TES.

HPs can also be used to integrate district heating and cooling network. DHN can be used as a heat sink for a HP which is supplying a cooling network. It will result in a simultaneous operation of both grids and therefore higher system performance. Depending on the location and purpose, HP can be designed to act as the main source for cold production or as a decentralized source to harvest waste heat from urban infrastructure. The heat storage unit can be used to maximize the potential of system integration and to balance the heat/cold demand and production.

7.4.3 Urban heat pumps integrated with the district heating network

One of the concepts of the future generation of energy grids is that heat and power are not only generated from centralized power plants but can also be produced from different and varied sources. Moreover, with the use of HPs, the energy can be exchanged between

TABLE 7.2 Temperature range typical for different types of heat sources.

Temperature range (°C)	0.5–9	10–20	10–40	14–46	10–50	15–75
Type of heat source	See water, river, lake water	Wastewater	Flue gas	Industrial waste heat	Urban waste heat	Geothermal heat source

energy grids minimizing the level of energy waste. The concept of prosumers in the power grid has been already implemented in many countries, however along with lowering the supply temperature in the DHNs, it will also be possible to supply heat to the DHN from individual users. This includes buildings that generate great amount of waste heat such as the industry sector but also local urban infrastructure and a wide range of building stock that produces excess heat, including domestic stock and commercial buildings such as offices and shopping malls. This concept can open new opportunities for different users who can feed heat into the network and therefore transform into active participants in the heating grids. Consequently, it can improve the building energy efficiency and provide more flexibility in the building operation as the excess heat can be sold to the grid. If a proper control strategy and heat storage are applied, the excess heat could be traded during periods with favorable energy prices.

The industrial sector is regarded as one of the most promising heat prosumers. Generated waste heat is often substantial in terms of power and temperature. Moreover, as the industrial process is conducted in stable and controlled conditions, the waste heat production profiles are therefore more predictable and constant. For this reason, in many countries, this potential has been recognized and industrial waste heat is already supplying the local DHN. High-grade waste industrial heat can feed into the DHN through heat exchangers but for those with lower temperatures, even nowadays HPs can elevate the temperature up to 150°C, which is enough to supply most of the existing high-temperature DHNs. Such examples can be found in Sweden, where waste heat from industry accounts for around 10 percent of district heat, or in Slovenia, the DH is partially supplied from the excess heat from a Pharmaceutical company. In Bergheim, Germany, HPs are used as a heat source to sump water from a lignite mine to supply a local district heating system with a water temperature of 55°C−60°C achieving the COP at the level of 4.4 [3]. Still, the potential of industrial waste heat is not fully exploited. For high-grade waste heat, the energy can be recovered in several ways, and then redirected back into the production process, for example, to preheat the air or be used to produce electricity. However, in the case when the waste heat cannot be further used within the industrial plant, it could be used to feed thermal networks. HPs have the highest potential in the sectors with low-grade waste heat such as petrochemical, chemical (e.g., pharmaceutical), paper and pulp production, food-processing, and beverage production. The main drawback of this solution is the proximity of the industrial site to the heating network and end-users. Considering the type of applicable HPs, electric HPs, and thermally-driven HPs were found to be most suitable for industrial waste heat.

The transformation of the current district heating into a new generation system also includes lowering network water supply temperatures to 55°C. Apart from the multiple benefits resulting from this change such as a decrease in grid losses, improved use of low-temperature RESs, and increased efficiency of CHP [9,11], it will open new possibilities for using low-grade waste heat from local urban infrastructure. This includes rejected heat from the building cooling and refrigeration installations like supermarkets using a cascade HP [12,13], wastewater (WW) [14], data centers [15−17], and even unconventional systems like underground ventilation [18]. Currently, only small quantities of urban waste heat from cooling systems are used for building space heating and DHW. Substantial quantities are simply rejected by the atmosphere and lost to the environment mostly because the volume of produced waste heat exceeds demand for space heating or DHW, or no heat recovery is implemented. Connecting those heat sources to the municipal energy systems through HPs could boost the use of waste heat that would be acting as supplementary decentralized sustainable heat sources in the network. Since the waste urban heat represents temperatures that are below the supply temperature in the DH network, it is the role of the HP to efficiently harvest this low-temperature heat source and transform it to obtain higher operating temperatures.

Considering the increasing demand for cloud-based services and the volumes of generated waste heat, data centers could in the future represent a relevant source of urban waste heat. Depending on the operating temperatures, generated streams, point of the heat capture, and the type of data centers (air-cooled, water-cooled, and two-phase cooling systems), there are different solutions for integrating HPs with the cooling system. Nevertheless, the most suitable location for HPs to capture waste heat is either from return air from the hot aisle or the chiller condenser. In water-cooled and two-phase cooling systems, the operating temperature of waste heat can reach 60°C−80°C and 70°C−90°C, respectively [15,19], allowing the application of different solutions for harvesting this high-grade heat including only heat exchanger or absorption HP for cooling. In air-cooled systems, which are applied in the majority of currently operating data centers, the temperature of the waste heat represents lower values and therefore a HP is necessary to elevate the temperature. Heat can be recovered directly from exhaust air from the rack (typically 30°C−45°C), at the air inlet to computer room air handler (CRAH) or computer room air conditioning (CRAC) unit (30°C−40°C), from water return to chiller condenser in CRAC systems (15°C−20°C) and from condensate waterside in CRAH systems (40°C−50°C) (see Fig. 7.15).

The economical benefits depend, however, on many factors such as climate conditions, the proximity of data centers, demand profile of end-users, supply temperatures in the

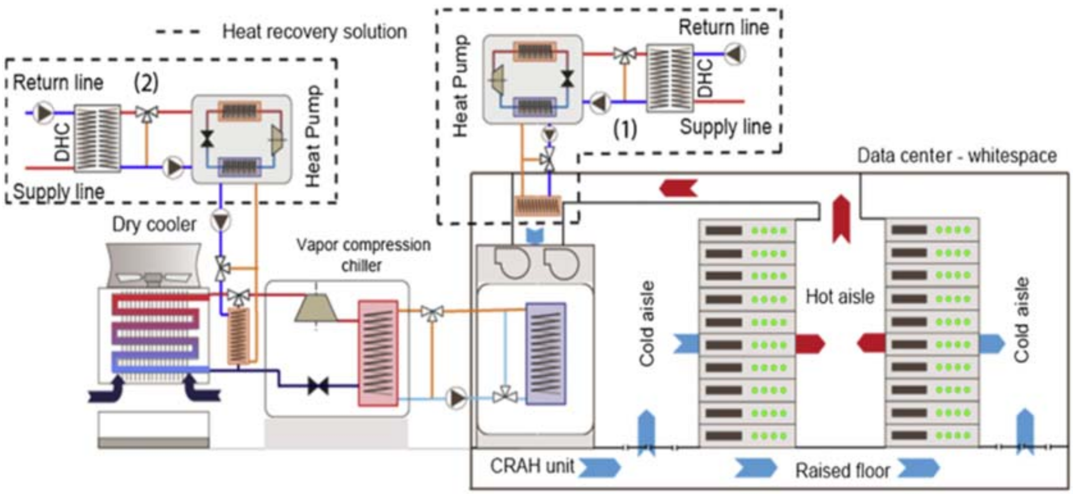

FIGURE 7.15 Scheme of the heat recovery for CRAH cooling technology [17].

DH network, and costs of heat. For high temperatures in the heating network, this application cannot be economically beneficial. Moreover, even though from the technical point of view, this solution appears to be feasible, the temperatures of the waste heat allow the use of heat recovery, and the aspects of the data center's operation security might hinder the potential benefits. Adding HPs to the system might create a single point of failure, not acceptable in this type of buildings. Nevertheless, this solution has been already applied in Finland in the city of Mäntsälä. Excess heat from a data center is first recovered through heat exchangers and then HPs are used to raise the water temperature from 40°C to 85°C at a COP of 4.0.

Heat recovery from WW can be harvested using HPs on a building level at a drain point, in a building cluster in a sewer system, and at the WW treatment plant (Fig. 7.16).

A wastewater source heat pump (WWSHP) represents a solution to capture the waste heat from WW and sewage systems. Considering urban heat, it can be applied in municipal WWTPs and the urban sewage network. The temperature of the WW ranges from 10°C to 15°C throughout the year with a possible rise up to 20°C, or in some cases even to 25°C during the summer period. Those operating conditions allow both heat and cold production as in winter the temperature of WW is higher than the external air temperature, while in summer, it is a few degrees lower. Moreover, the quantity of the generated WW is substantial, especially in big cities, and, in most cases, constant throughout the year.

The efficiency of this system varies between 1.77 and 10.63 for heating and between 2.23 and 5.35 for cooling [14]. For this reason, WWSHP has been widely implemented in recent years all around the world. Although the heat is mostly used within the facility, in the future, it might provide heat to the DHN. The critical aspect is the proximity of the WWTP to the city center or the end-users and the operating temperature of the DH network. Too high distance might result in too high heat losses which might question the potential economical benefits. An example of such a system can be found in Stockholm, Sweden, which represents a multienergy system. The main heat source is a CHP (waste

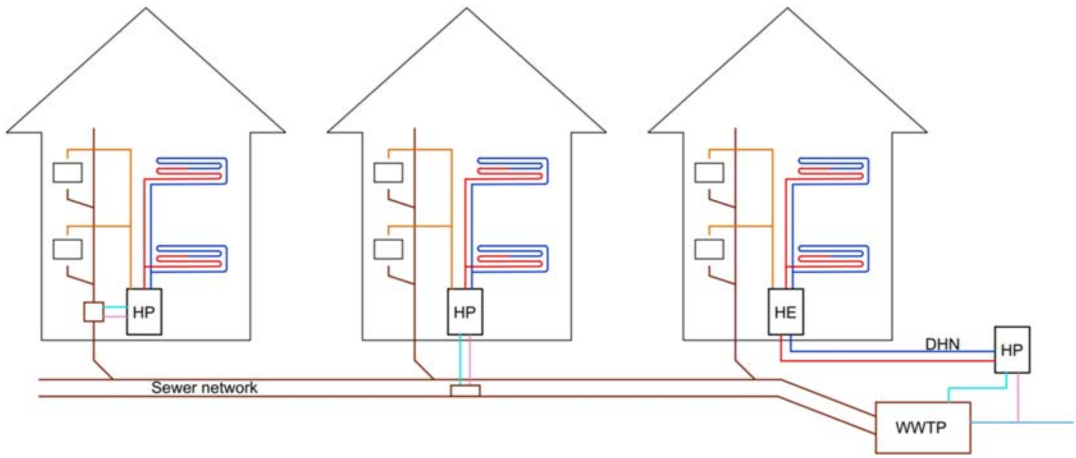

FIGURE 7.16 Wastewater source heat pump applications.

and biomass incineration plant), while centralized HPs are used to supply the DHN using heat from WWTP, seawater, and even from a district cooling network [20].

The current research outcomes showed that harvesting urban heat with LHPs can to some extent replace individual heat sources. However, due to potentially limited volumes of waste urban heat, it could only be regarded as a supplementary heat source. The use of HPs in data centers is considered one of the most promising solutions as they can supply with heat the DH network during the winter season which corresponds well with the seasonal demand profile. Analyzing the current state of development, HPs demonstrate a high potential to harvest energy from urban waste heat. However, there are still several limitations before they could be successfully implemented. The technical solutions still need to be further investigated to provide viable and scalable results. Moreover, an appropriate regulatory framework and standardized contracts are needed to encourage and attract potential investors [21]. Finally, advanced control strategies are crucial for the proper coordination of all systems [15].

7.4.4 Residential heat pumps—supply and demand side management for energy flexibility

The level of building energy flexibility can be divided into operation flexibility, meaning the flexibility in the building operation which can be enhanced through the integration of multiple technologies; building demand flexibility, meaning the ability to respond to variable building loads, at the same time providing desirable internal conditions and finally, energy generation flexibility which is linked to on-site and off-site energy and heat generation. HPs can improve the building's overall energy flexibility as they can be easily adapted to different heat sources and operate under various conditions, can be integrated into multiple systems (described in Section 7.3), and can shift energy between systems.

In future energy systems, individual HPs can be integrated into the heating and power network which, in consequence, could increase the flexibility in the power grid and contribute to system stability. Along with increased power production from prosumers, the current and future energy grids can encounter imbalance issues. Energy production from renewables, such as photovoltaics, wind, or geothermal energy, can at times exceed the total power needs, especially in the summer season when the demand is relatively low. When the system is not prepared for that high power, it may be necessary to limit or completely disable energy generation from RESs to stabilize the grid. The higher the share of renewables in energy production the higher the risk of overload. The growing share of unstable green energy in the system is a challenge for grid operators. Therefore, to avoid the threat of a blackout or disconnection of RESs from the grid, it is crucial to adjust energy production to its consumption profiles and to intelligently manage power supply by operators, energy producers but also by end-users. Nevertheless, future energy grids based on decentralized energy production (large PV or wind farms as well as on-site production) are one of the methods for decarbonization of energy production and, if proper management strategies are applied, they could improve the security of the energy supply and increase the building energy flexibility level. However, to maximize energy conservation, it is crucial to apply proper control systems, protocols, sensors, and communication between system elements. One of the potential strategies could be a demand response method (DR) which is a type of demand side management control [22]. In general, its objective is to flatten the demand curve, especially the demand peak, reduce load, shift load or adjust the power/heat generation profile by end-users. Depending on the main objective, two types of DR programs can be applied: price-based DR and incentive-based DR (IBDR). In the first one, different price policies are promoted to the end-users to voluntarily change their behavior in terms of electricity use patterns. However, from the perspective of energy generation and grid security, the benefits can be maximized with the IBDR. In this program, the demand load can be regulated by the third party, in exchange for some sort of compensation. In direct-load control which is a type of IBDR, depending on the agreement type between the energy provider and the customer, the program administrator has access to the user equipment and can control it or even interrupt its operation. However, a different and more complex method must be applied for proper energy profiling [23]. A schematic difference between both programs is shown in Fig. 7.17.

Both DR strategies could be applied to the systems equipped with HPs, especially integrated with any type of heat or energy storage [24–27]. During lower energy consumption and high power production from RESs, the energy surplus can be stored in TES, shifting the load and balancing the demand. Additional economical benefits for the end-users can be obtained while using grid energy during off-peak hours profiting from lower energy costs. The DR programs applied to HP's control strategy contribute to an improvement in the stability of the energy grid, help to avoid overload problems during pick demand, and improve utilization of TES. The evaluation of building energy flexibility in existing buildings equipped with HPs was studied by Mor et al. [27]. The investigation was performed at three European pilot sites and the main objective was to study and compare the flexibility parameters for different DR strategies. Regardless of the investigated building, DR strategies for HP operation improved the energy flexibility, although the full potential was not achieved. Moreover, local climate conditions together with building and system characteristics greatly determine the operating hours of a HP.

Although individual HP could provide some level of energy flexibility in the power grid, these solutions still demonstrate some limitations that need to be addressed and further investigated. The main challenge is the DR control algorithm itself. As it is targeted to optimize the energy use from the power grid, it can increase the number of times the HP is switched off leading to an unwanted excess use of the secondary energy source in

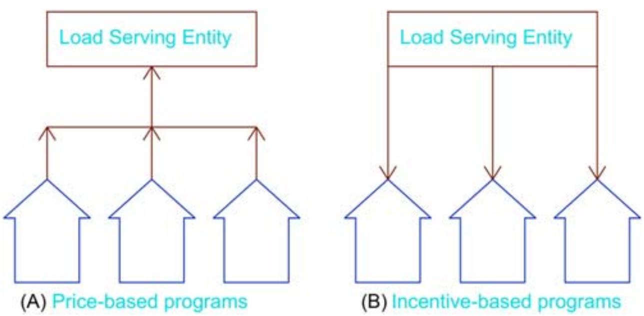

FIGURE 7.17 (A) Price-based and (B) incentive-based demand response programs. *Source: Based on Wang Y., Chen Q., Kang C., Zhang M., Wang K., Zhao Y. Load profiling and its application to demand response: a review. Tsinghua Sci Technol 2015;20 (2):117–129. https://doi.org/10.1109/tst.2015.7085625.*

hybrid systems. Consequently, it could even lead to higher operational costs. The DR strategy should be therefore focused and adapted to consumer preferences. Socio-economic studies [28] revealed, however, some level of anxiety and reluctance towards an exchange of consumer data, especially among mid-age responders.

In the current stage, these solutions are still under development however, with increasing energy prices, new energy policies such as tax reductions, in general, better financial incentives along with improvement of the control system, HPs integrated into the power network, could increase the energy flexibility of the power grid, improve its stability and could play an important role in its transformation into future smart grids.

7.4.5 Heat pumps in the low-temperature networks

Another concept for future energy grids is based on low or ultra-low district heating (ULTDH) networks. In this solution, the temperature of the water circulating in the distribution pipes is lowered even below 30°C and HPs are used to elevate the temperature to be suitable for heating purposes. HPs can be applied on a building level as well as can provide heat to building clusters (Fig. 7.18). For ultra-low temperatures, it is possible to use heat sources, characterized by lower temperatures such as geothermal or WW. Moreover, in the reverse mode of operation, HPs allow the bidirectional heat exchange with the heating network by returning heat and/or cold back to the district heating ring and consequently, transforming end-users into prosumers. However, for DHW purposes, it is necessary to use a separate HP to obtain higher water temperature at the outlet of the HP or use additionally an electric heater.

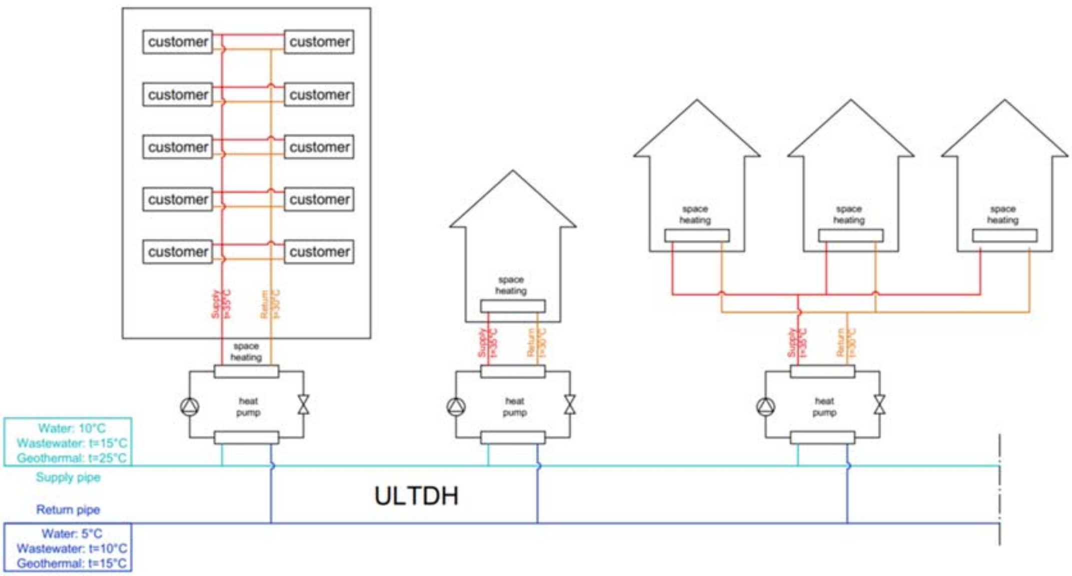

FIGURE 7.18 Scheme of the application of heat pumps in ULTDH networks for residential purposes. *ULTDH, Ultra-low district heating.*

This type of network, referred to as cooling district heating, provides flexibility in the building and grid operation. A similar system, that benefits from the flexibility of HPs, operating on a building level, is a water loop heat pump system also called water source heat pump system. It consists of water-to-air HPs connected to one hydraulic system. In cooling operation, the HP transfers the excess heat taken from the room to the water ring. In the reverse mode, HP cools water in the water ring. Circulating water acts as a medium that transports energy between zones/rooms in the building. Since individual HPs can work independently, each zone can be controlled independently, such a solution enables simultaneous use of cold and heat and therefore provides flexibility in energy demand. As the excess heat from one zone can be transferred to another one or stored in TES, the overall building energy performance increases. As the water temperature in the water network depends on the thermal balance and mode of operation of each end-user, the control strategies and smart metering systems are crucial for proper system performance.

7.5 Summary

In this chapter, the flexibility of the HPs regarding building energy needs was described. The first part focused on the systematics of HPs. It has been shown that they can be used for heating or cooling purposes locally as well as in centralized municipal systems. The scope of HPs' operation is wide, and they can be flexibly adapted to the intended purpose. The next part focused on the possibility of cooperation between HPs and other devices, such as heat sources or heat storage, at the building level. Systems in which HPs are supported by conventional or renewable heat sources were presented. The use of heat storage both on the heat source and heat sink was also shown. The multitude of solutions showed how flexible the use of HPs can be and what solution can be used to increase their work efficiency. The last part presented the use of HPs at the level of the energy systems. The use of municipal waste heat or industrial waste heat showed the potential of using these devices to achieve the objectives of the circular economy. The use of HPs is one of the basic elements of the 4th generation heating networks and is necessary to implement the assumptions of 5th generation heating networks, the basis of which is the exchange of low-temperature heat between buildings.

Despite the flexibility of HPs, the effectiveness of their use largely depends on local conditions, that is, climate or the availability of a heat source with constant and high temperature. These parameters determine the choice of the solution and the use of additional elements such as heat storage or supplementary energy sources. The HP technology is already well known, and the solutions have been available on the market for several decades, and therefore the current research is largely focused on developing appropriate control algorithms to optimize the operation of systems with HPs. The use of HPs is also very important regarding environmental aspects. The goal of achieving decarbonization of building resources by 2050 requires the use of flexible energy supply systems, which are ideally suited to HPs. Supplying these devices with electricity produced from RES or waste heat (in the case of thermal-driven HPs) creates zero-emission local or municipal energy systems. However, these activities must be preceded by appropriate financial and political support.

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CHAPTER

8

District heating and cooling for building energy flexibility

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Heating and cooling play a crucial role in the building energy sector. Enhancing the efficiency of building heating and cooling systems and reducing their CO_2 emissions are among the emerging objectives. District heating and cooling (DHC) is not a new term; however, its energy flexibility for improved building operation and demand side management has not been used widely in different countries. Renewable energy is one of the key elements in a flexible DHC system to improve the flexibility of power plants. Some equipment such as thermal storage and electric boilers are also important in these systems. Moreover, smart control can provide more flexibility by forecasting the thermal load and making appropriate decisions for peak load shaving and shifting. The relation between energy flexibility and DHC has been discussed in this chapter.

8.1 Introduction

Thermal energy, based on the latest International Energy Agency report, accounts for 46% of total global energy demand, and this figure is rising substantially [1]. As a result of this, heating and cooling systems all around the world, in buildings and industry, are one of the most significant emitters of CO_2 emissions. To strive for a completely decarbonized plan [2], a substantial paradigm shift in the way heat and electricity are produced and consumed in general, particularly in the case of a district, is required. DHC systems have higher efficiency than conventional heating and cooling systems. In addition, the greenhouse emissions of these systems are considerably low.

Meanwhile, building heating and cooling systems play an important role as thermal comfort is a key element in buildings. A proper substitute for traditional heating and cooling

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systems that has attracted significant attention over the last decades is DHC systems. DHC systems use the infrastructure to connect dwellings, buildings, or facilities within a neighborhood, district, or city to meet the heating and cooling demand [3]. In this system, water is used as the main working fluid to provide low-temperature domestic hot water, and space heating and cooling for buildings. The waste or excess heat can be used to generate electricity. The main components of a DHC system, as shown in Fig. 8.1, including heat and cold sources, customers, distribution network, and storage elements. Heat and cold sources are boilers, combined heat and power (CHP) units, and renewable energy sources such as solar panels, geothermal, and wind energy. Meanwhile, the absorption chillers and the heat and cold recovered from industrial processes can be considered secondary sources. The customers of such systems can be residential buildings, offices, and commercial buildings. Thermal storage such as thermal tanks is also used in this system.

Demand flexibility or energy flexibility refers to a building's ability to decrease, shed, shift, modify, or create power by using onsite distributed energy sources. The flexible systems can shift the heat load during peak hours via demand side management strategies to increase the efficiency of the energy systems and decrease emissions. The integration of

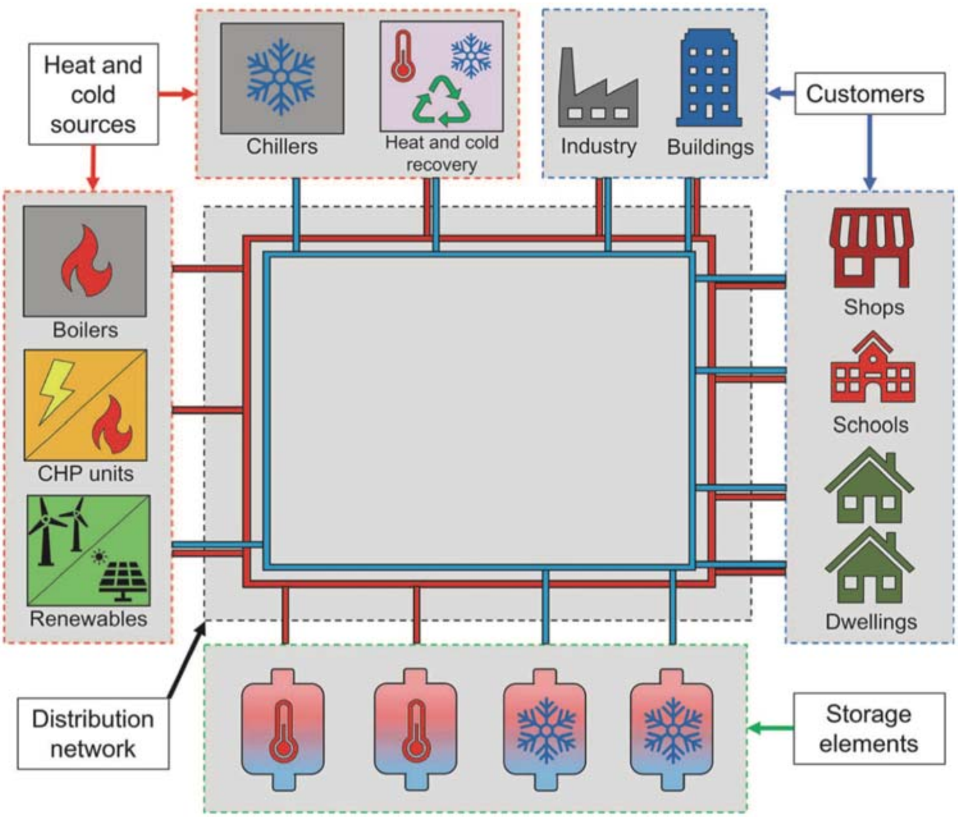

FIGURE 8.1 Main components of a DHC system [4].

DHC with energy flexibility is a trending topic that was used in the 5th generation of DHC. In these buildings, the electrical appliances, air conditioning systems, lighting systems, water pumps, and chillers are the main parts that energy flexibility can integrate with. Thermal storage devices such as thermal tanks, boilers, and thermal mass, in addition to electrical storage like the stationary battery, can also be integrated into DHC systems to increase energy flexibility. Meanwhile, the sources that can enhance flexibility are PV panels, wind turbines, CHP, and combined cooling, heating, and power. A summary of the flexible systems is shown in Fig. 8.2 for residential and commercial buildings.

Boilers in this system can be categorized into fossil fuel-fired boilers, heat recovery boilers, and waste heat recovery boilers. Meanwhile, electric boilers like electric resistances, which are coupled with water tanks and small-scale fuel power boilers, are the main heat sources in the building DHC system. In addition, various chillers have been used in DHC systems. These chillers can be categorized into three different groups, which are mechanical vapor chillers, vapor absorption chillers, and vapor adsorption chillers, based on their refrigerant cycles. The selection of thermal storage relies on different factors, including the source of energy (e.g., CHP, solar panels, wind), the aim of DHC (e.g., space heating, space cooling, providing hot water), and the working fluid in the system [4].

Some studies used heating and cooling at a district level, while energy flexibility was used to enhance the operating performance of the system. The main findings from some

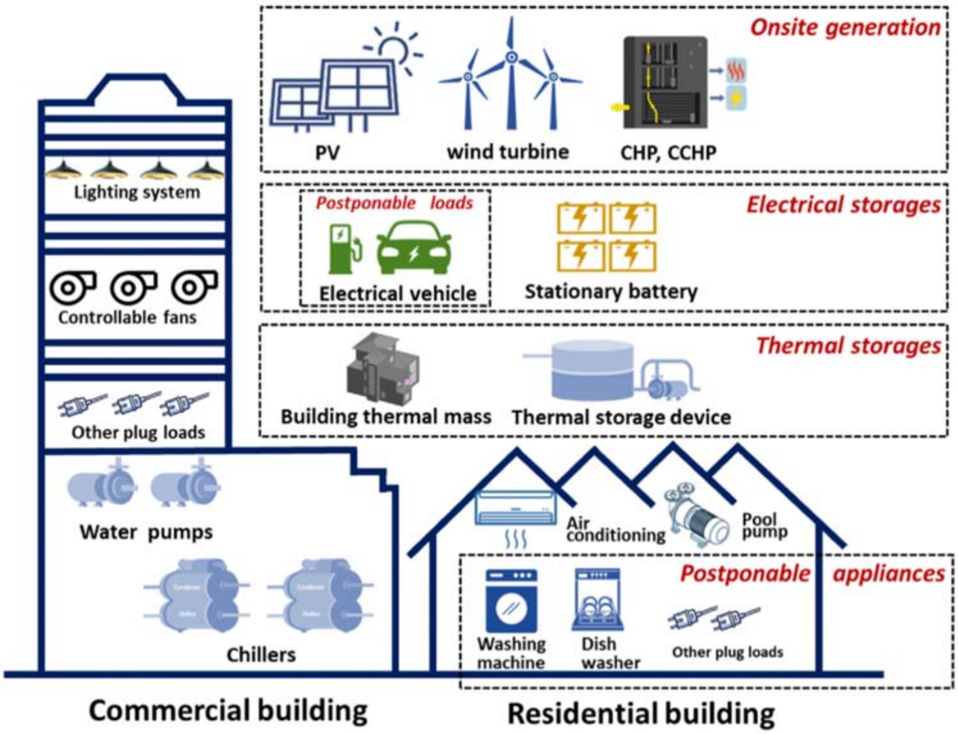

FIGURE 8.2 Sources of flexibility in commercial and residential buildings [5].

of these studies are summarized in Table 8.1. In the majority of these studies, thermal mass was used as the thermal storage, although the objectives for flexibility were different. In the studies by Luc et al. [6], Foteinaki et al. [7], Hu et al. [8], Romanachenko et al. [9], and Hedegaard et al. [10], buildings in the DHC were modeled, while Pajot et al. [11] and Nuytten et al. [12] examined the impact of heat pump and CHP on the DHC system, respectively. Luc et al. [6] studied a small district system that was connected to district heating (DH). A new rule-based control system was used to reduce total building energy consumption. The flexibility was aimed to shift and shed the peak load. The simulation lasted for 60 min, and the flexibility resulted in a 41%–51% load shifting in all schedule-based scenarios. Meanwhile, Foteinaki et al. [7] studied low-energy residential buildings which were connected to DH in Denmark. In this study, different scenarios were

TABLE 8.1 Summary of the results from the literature review.

Authors	Year	Thermal storage	Type of flexibility	Purpose of the study	Results
Luc et al. [6].	2020	✓ (Thermal mass)	Load shifting	Simulating a district in Denmark by Modelica	The flexibility reduced the energy consumption via load shifting and the use of a rule-based control system
Foteinaki et al. [7].	2020	✓ (Thermal mass)	Peak load shaving and shifting	Simulating low-energy residential buildings connected to a district in Denmark by IDA ICE	More cost reduction occurred by using dynamic temperature set-points, while the potential for load shifting was greater when using the fixed schedule temperature set-points
Hu et al. [8].	2020	✓ (Thermal mass)	Load shifting and shedding	Simulating a district cooling system in China	The weekly energy flexibility in a cluster was around 12.4% which was more than a single building that was not connected to the district
Romanchenko et al. [9].	2019	✓ (Thermal mass)	Load shifting and shedding	Modeling residential and nonresidential buildings connected to district heating (DH)	The use of demand response (DR) for space heating in DH resulted in a reduction in energy consumption
Hedegaard et al. [10].	2019	✓ (Thermal mass)	Load shifting and shedding	Modeling residential space heating DR in Denmark	A simple price–based DR resulted in decreasing in hot water consumption during peak hours
Pajot et al. [11].	2018	✓ (Thermal mass)	Load shifting and shedding	The impact of a heat pump on the DH system	Reduction of thermal discomfort might be a better option instead of load shedding. The reduction in CO_2 emission increased energy consumption
Nuytten et al. [12].	2013	✓ (Thermal mass)	–	Coupling a CHP system to thermal energy storage for DH	The central CHP and central energy storage provided maximum flexibility

examined by considering different set points in dynamic and constant electricity prices in each scenario. The result indicated that the energy consumption in the morning peak load reduced between 40% and 87% in all scenarios. In addition, preheating was one of the practical approaches to achieving load shifting and peak load reduction.

Hu et al. [8] studied occupants' behavior in high-rise residential buildings connected to DHC. A data-driven stochastic occupancy model was used to gather occupancy patterns. The result showed that the energy flexibility potential of the buildings on a cluster scale was around 12.9%, while this number was considerably higher than the flexibility in one high-rise building, which was not connected to the district.

Romanchenko et al. [9] investigated the potential of space heating demand response in buildings for DH systems. The results showed that using demand response in buildings can have a significant impact on the cost-optimal heat supply in Sweden. The demand response was used to smooth the variations in the system heating demand. The smoothing of the demand reduced the heat generation cost, and the number of starts for peaking units decreased by more than 80% in the district.

Hedegaard et al. [10] developed a model for space heating in residential buildings using DHC. The model was used to investigate the effectiveness of a price-based DR system aimed at reducing energy consumption. The outcome illustrated that the demand response in the DHC system was practical, and more flexibility in peak consumption of domestic hot water was achieved.

Pajot et al. [11] investigated the impact of heat pumps in a French residential eco-district by using a thermal model. The flexibility in this system was used for load shedding which was analyzed separately for peak shaving, thermal comfort, and CO_2 emissions reduction. The results indicated that turning off the heating supply for one hour successfully worked in the case of peak shaving. Meanwhile, thermal comfort was reduced during load-shedding hours. To solve this discomfort, a reduction in heating loads can be applied instead of shedding them. In addition, in the case of turning off the thermal loads, the duration can be changed to a shorter period. The CO_2 emissions increased from 0.06% to 0.14% in the energy-saving time in a month. Therefore, the link between energy saving and reduction in CO_2 emission needs to be chosen carefully.

Nuytten et al. [12] worked on a CHP system with thermal storage in DHC. A model that can determine the maximum energy flexibility in a district coupled with thermal energy storage was developed. In this study, a 300 kW_{th} CHP was coupled with an 800 kWh thermal energy storage system to provide flexibility in terms of heat supply. The total amount of flexibility for the centralized CHP coupled with decentralized energy storage was less than that coupled with centralized energy storage. The reason why decentralized energy storage was not practical was that the setup created a weak link between the CHP and the customer with the highest instantaneous heating demand.

8.2 District heating and cooling

The district energy system is not a newly emerged technology, and it has been used since the 19th century. The first generation of the district system (1GDH) was used from around 1880 to 1930, in which the energy source was coal, and the main fluid in this system was steam. The main reason to use the DH was to decrease the risk of boiler explosion as the system was working in very high temperatures. The second generation (2GDH) was used from 1930 to 1980. During this period, shell-and-tube heat exchangers and water pipes resulted in fuel-saving in addition to a control system for the heating demand. Furthermore, the CHP and boilers were used during that time, and the main fuel was coal and oil. In the 1970s, the idea of third-generation DH (3GDH) was developed, and it then resulted in large-scale CHP systems. In this generation, pressurized low-temperature water was used as the main fluid. In a DHC system, a central plant supplies hot or cold water through a network with underground pipes to many buildings. This system can be integrated with renewables as heat sources [13]. Meanwhile, district cooling (DC) followed the same path as DH. In the 19th century, the first DC (1GDC) system was introduced. This system included decentralized evaporators, centralized condensers, and a refrigerant like ammonia as the transport fluid. The second generation (2GDC) used chilled water as the medium, and chillers were used substantially. The third generation (3GDC) developed the idea of free cooling.

In the fourth generation of DHC systems (4GDHC), renewable energy sources and smart buildings play a significant role [4]. Renewable energy sources such as photovoltaic panels and geothermal energy (if possible) were added to the system for generating electricity, heating, and cooling. Meanwhile, smart buildings are energy-flexible as buildings can equip with penalty-aware controllers. It first requires one to choose the penalty; and then, the penalty-aware controller would be considered to provide that factor in addition to providing thermal comfort for the occupants. Firstly, the home energy management system that controls the controllable appliances should evaluate the flexibility potential of the smart home before its activation to check the availability of the appliances and to conduct a cost-benefit analysis. Secondly, the system operators need to estimate the flexible capacity of a smart home on how to react to the operators' flexibility requests. In this way, the operators can assign monetary compensation based on the available flexible capacity of the smart home. However, it would be difficult to distinguish between the household's actual load and the flexibility that is resulted from its reaction to the flexibility signals. It is worth mentioning that uncontrollable appliances cannot provide flexibility. It means that only controllable appliances can provide flexibility. However, their flexibility can be predicted by estimating the change in the operation of the controllable appliances according to their reaction to flexibility signals. For instance, in an air conditioner, the objective function for normal operation is to minimize the difference with the desired room temperature and maximize flexibility. Although the flexibility capacity of the storage-based appliances is more than the controlled ones, the impact of the controlled appliances is noticeable. The reason why the smart air conditioner is not that flexible is that this system is highly dependent on thermal comfort and occupants' behavior. Occupants' behavior depends on various factors and their interactions. For instance, these factors rely on arrivals, departures, duration of stay in the building, number of occupants, the location of the building, and the presence and absence of occupants in peak hours. In this system, thermal loss needs to be reduced considerably.

Thermal energy has a great potential for flexibility in the DH network. The thermal load can be considered as both supply and consumption of the DH systems. In space heating and domestic hot water applications, hot water is used in the DH system as the supply. However, in some industrial processes such as textiles, paper, wood, metal, and plastic, thermal heat is consumed. The reason why DH is important is that the DH system has the potential for short-term heat storage, which can assist in optimizing the CHP cogeneration in the electricity sector without compromising the heating sector. When heat storage is used in the system, the electricity produced by renewable energy sources like wind turbines or PV solar panels can be controlled by CHP. The heat can easily be supplied from the storage. In other words, when the electricity demand is higher, the CHP can increase production. Meanwhile, if the heat production is higher, the storage can be charged. This process is reversed if the heat production is lower and the storage is discharged. As a consequence, the flexibility can integrate renewable energy and can make the system more efficient not only economically but also environmentally. Short-term thermal storage can be used in three different ways. As an example, the domestic hot water storage tank is the first, which is substantially common in Danish buildings. Secondly, the utilization of phase change materials is a new trend in buildings, although it has not been a lot of research on their utilization in DHC. Thirdly, the thermal mass of the building has been proven to be the most practical and economically friendly way for thermal storage among other options [14,15].

On the other hand, DC systems distribute chilled water for air conditioning or process cooling. Cities with major downtown or commercial districts have a great opportunity for DC. The first DC system was used in Hartford in 1962. Although DH has been widely used in the countries like Denmark, Sweden, and France, DC systems are used on a smaller scale. The distribution network in DC is quite similar to that of the DH. Cold water is circulated instead of warm water on this occasion. There are two main pipes, including supply and return. Supply temperature is mostly at 6°C−7°C. Meanwhile, in the return pipe, the temperature is about 12°C−17°C. The chilled water is heated in the supply pipe with the supply air which is supplied to a building or an industrial process. Chilled water is repeatedly circulated through the cold generation plant. The plant can be integrated with both heating and cooling. Firstly, the electricity and heat are generated, and the products are then used in a feeding compression chiller or an absorption chiller [16]. The most important advantage of DC is to reduce grid power demand by providing cooling through the local power grid, shifting power demand to off-peak periods through cold energy storage, and the use of free cooling. In general, less space for cooling equipment is required in DC in addition to considerably reduced maintenance costs and electricity costs [17]. Fig. 8.3 illustrates a traditional DHC system.

The first step toward changing the traditional heating and cooling systems is to choose DHC on a large scale. Although this system has its advantages and disadvantages, the decision to choose this system is based on different factors. One of the most important advantages of DHC systems is that these systems have higher efficiency than heating and cooling in a single building [11]. Moreover, lower capital investments and fewer space requirements are among the other benefits of these systems. However, the payback period of these systems is significantly longer than conventional heating and cooling systems. Such systems are not a proper choice for sparsely populated areas.

Nowadays, European countries seem to be a pioneer in DHC around the world. As an example, Sweden has increased the usage of biomass in DH, while Poland mostly focuses on geothermal as the main source. Based on a heat and power report in Denmark, around 61% of the houses are connected to DHC, and this number is around 50% in Finland and 48% in Sweden [17].

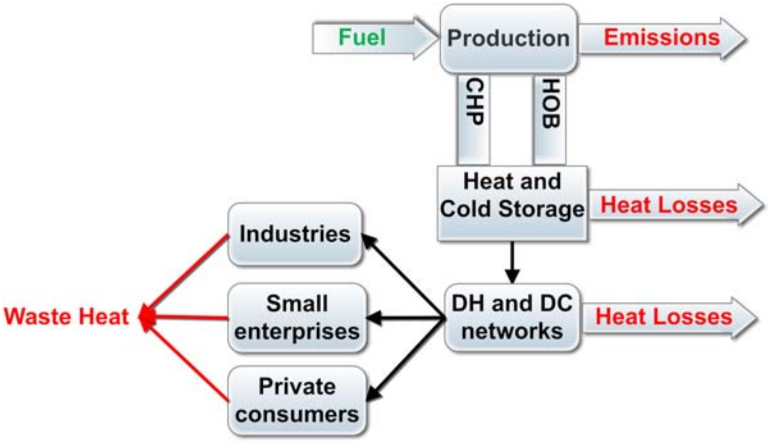

FIGURE 8.3 A traditional DHC system [17].

8.3 District heating and cooling and energy flexibility

One of the most important challenges in DHC is integrating systems with increased energy flexibility. DHC systems have already been considered a flexible part of the energy system. These systems can store heating and cooling in thermal mass and thermal storage. Two ways can make the DHC more flexible. The first step toward flexibility is to modify the primary networks of energy (power plants as described in Section 8.3.2), while the second one is to employ demand side management as a practical way in the secondary networks (as described in Section 8.3.3). Fig. 8.4 illustrates a flexible DHC system. In the flexible system, the fuels are renewable energy sources that have decreased greenhouse gas emissions. The cooling and heating which is produced by the CHP power plants, heat pumps, geothermal heat, or the industrial water heat of some factories like cement, flows in the DC and DH networks. In this phase, the customers consume the heat to maintain indoor thermal comfort. Meanwhile, as a result of DHC, hot water and cold utilities in chillers are provided. In a flexible system, the waste heat of residential buildings also plays a significant role as it can be used again for DC and DH. Moreover, in residential buildings, by using smart electrical appliances that can be controlled by a control system, smart heating, ventilation, and air conditioning, scheduling the time of the occupants' presents, and other factors, the flexibility of the system can be greatly enhanced.

8.3.1 Global sources of district heating and cooling in energy flexibility

DHC can use various energy sources. These sources can be divided into six main groups, as shown in Fig. 8.5.

The first option is geothermal or ground source heat pumps which are widely used in Poland as an example. Although this technology can provide low-cost heating and cooling for DHC, it is geologically limited and is only efficient in moderate temperature zones. The second energy source can be biomass, in which the wood or energy crop materials can be used to provide heat. Although this source is renewable and it has its advantages, the

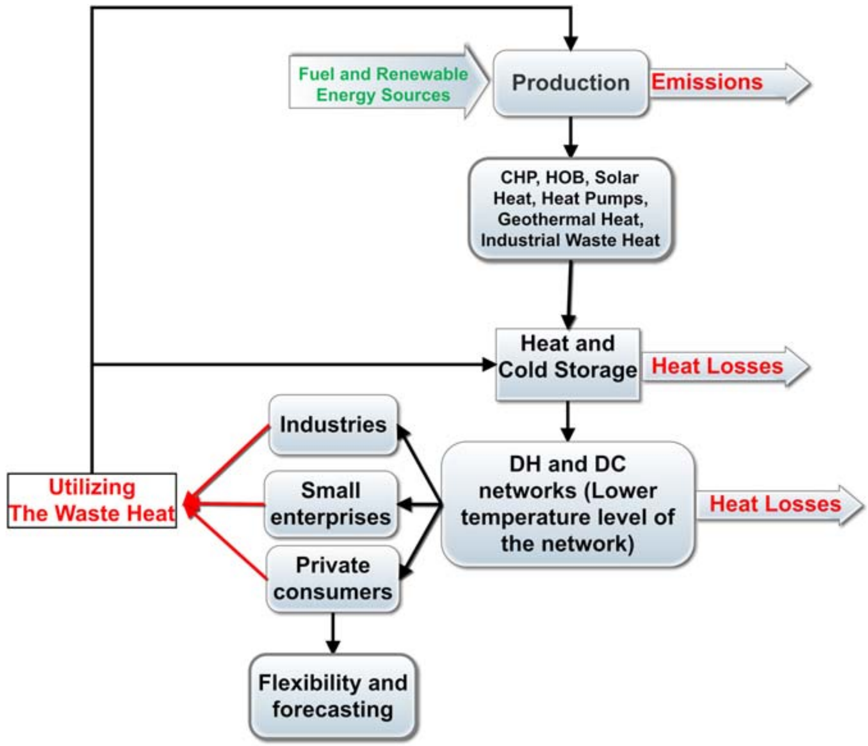

FIGURE 8.4 A flexible DHC system [17].

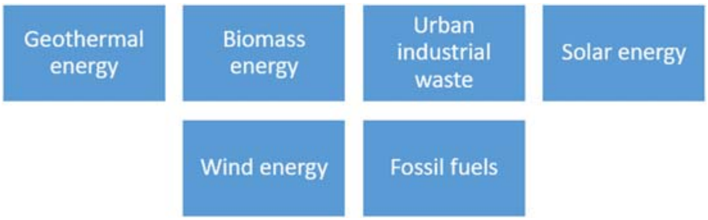

FIGURE 8.5 Sources of energy in a flexible DHC system.

availability of this source is not even in all countries. To generate electricity, urban waste can be burnt on a large scale. The generated heat can be used in DH, although it might cause some health problems. The waste heat of industrial and commercial processes can also be used in DH. This waste heat can be transformed into nearby buildings or can be coupled with the CHP system. Other forms of renewable energy sources like solar thermal panels, which generate electricity in addition to heating water or as an option for absorption chillers, are extremely practical as well. In addition, wind power can also be suitable in the CHP system which will be introduced in Section 8.3.2. Lastly, fossil fuels can generate heat by burning coal, oil, and natural gas. Fossil fuel greenhouse emission is a great issue, although the infrastructure is already in place in many countries around the world [18].

8.3.2 Primary networks of DHC and energy flexibility

8.3.2.1 CHP and energy flexibility in district heating and cooling systems

The flexibility of a power system in DH can be defined by two main aspects. The first aspect depends on flexibility which is related to technology. In this term, the distribution of heat to meet customers' needs by considering the hydraulic and thermal limits is essential. The second aspect is about economic flexibility, which aims to reduce the cost for governments and end users. The CHP and industrialized residual heat sources are the main sources of heat that are transmitted by DH. Although CHP is a common technology in the DHC system, it also has some problems. For example, in the case of overheating for a CHP generator, the room temperature increases, and as a result, the rate of energy consumption increases too. Newly emerged technologies can solve this matter; however, the combination of renewable energy sources can be practical [19].

8.3.2.1.1 Case studies related to the CHP and energy flexibility in DHC

In a study in Northern China, the potential of energy flexibility and DH has been discussed. Northern China mainly depends on coal power plants for space heating and electricity. Without any doubt, coal power plants intensify air pollution. As an example, the winter haze is a common issue in many cities around the world which makes the governments more concerned about this matter. The energy flexibility in DH can play an important role in achieving the goals of a low-carbon, safe, and clean energy sector. As shown in Fig. 8.6, this DH system includes primary networks: thermal storage tanks which are

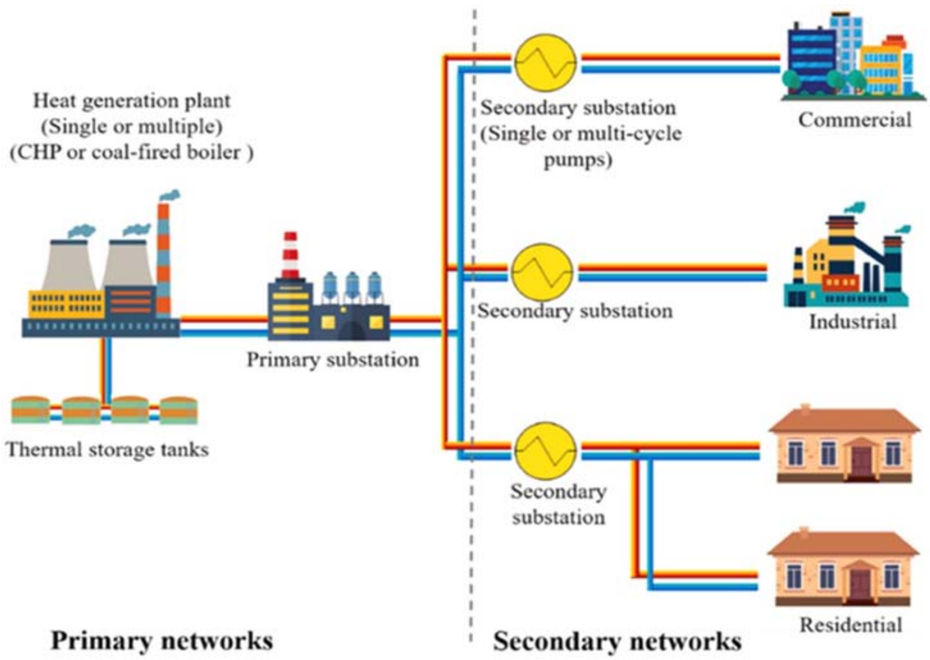

FIGURE 8.6 Composition of a DH system [13].

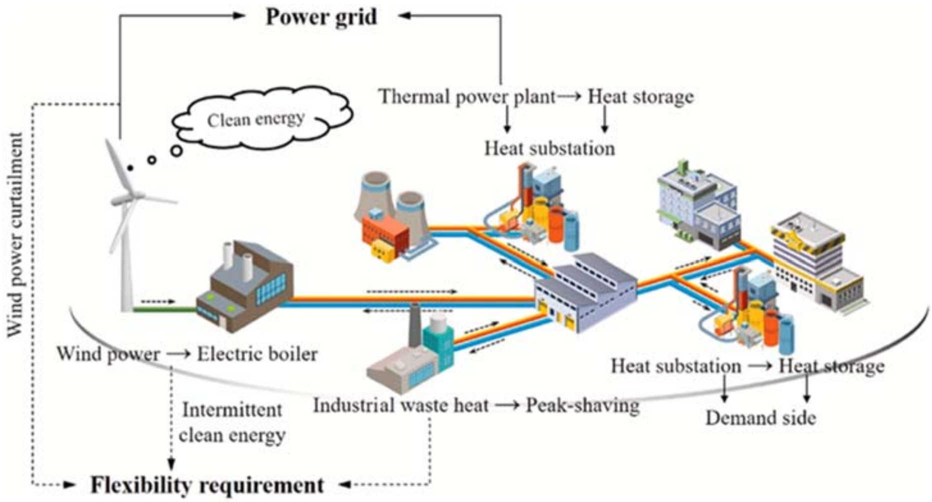

FIGURE 8.7 Flexibility requirement of DH systems [13].

connected to a heat generation plant, that is either single or multiple (CHP or a coal-fired boiler), a primary substation, and the secondary networks which include commercial, industrial, and residential end users. The medium used for heat transfer was mainly water or steam. The temperature controller, pressure differential controller, and flow rate controller were used to control the heat supply.

The district system can be divided into two main categories, the central and distributed pump systems. The flexibility of the DHC system in heat supply and demand is the main goal of this chapter. As demonstrated in Fig. 8.7, to achieve energy flexibility, the heat supply in the DHC system can be used for electricity generation or the consumption of CHP and electric boilers. However, nuclear reactors and some other renewable energy resources, in addition to the surplus heat of industrial units, can be considered the heat source in the near future [13].

To make a system more flexible and solve the problem of heating during the winter, as the heating load is the maximum, the CHP is controlled to adjust with the heating load. The minimum electricity generation of CHP limits the capacity of the integrated power of the wind. The value limits the flexibility of the CHP generator in electricity generation. By using flexibility in this system, the curtailment of wind power can be used for other purposes [13]. As an example, Wu et al. [20] considered a low-temperature tank, a high-temperature storage tank, and an electric heat pump to enhance the efficiency of a heat and power system. Fig. 8.8 illustrates the integrated electricity and heat supply system. It can be seen that the system consisted of two main parts, including the electricity network and heat network. The electricity network included thermal power plants, wind energy, biomass power, and solar energy as the sources of energy. Electrical energy storage was also part of this system. The generated electricity can be used by heat pumps and electric boilers, as explained earlier. The heat network was working with the CHP and the storage.

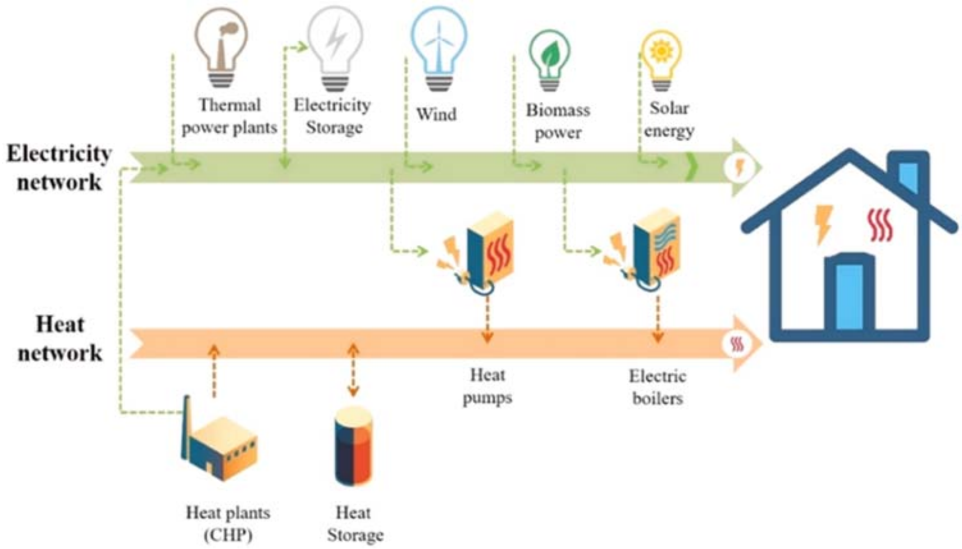

FIGURE 8.8 Integrated electricity and heat supply system [13].

8.3.2.1.2 Increasing the efficiency of thermal power plants with energy flexibility in district heating and cooling

Thermal power plants, which are mostly CHP units all around the world, are coal-fired. The flexibility in this system can be achieved if the outputs of electricity and heat can be adjusted. By considering the power plant as a heat source, the changes in the CHP unit can improve the system's flexibility. To meet this goal and the heating load, the heating capacity of the CHP unit needs to be increased while the boiler's output is reduced. As a result, the forced output of the unit will decrease as well. This flexibility can be met in three different ways to reduce the steam on the turbine and increase the heat supply and reduce the cost considerably. The first method is to bypass heating for the steam turbine, and the second method is to achieve low-pressure cylinder zero-output. The last one is to use high back pressure circulating water heating.

The flexibility in the CHP system is more dependent on the heating sector. At the same time, electric boilers with heat storage play an essential key in this system. This equipment can provide flexibility for heating sources and help the CHP unit to decrease power generation. The electric boilers are replacing the coal-fired ones, and they can use the power that is generated by wind or other renewable energies as a heat source during a low-load period and store the surplus power while the load meets the minimum demand. This system is economically and environmentally efficient. Peak shaving is a flexible method in this system [13].

8.3.2.2 Industrial heat waste in district heating and cooling and energy flexibility

Industrial waste heat accounts for more than 70% of total energy consumption in China for example, and the minimum amount of this energy that can be converted to waste heat at different temperatures is 50%. Recovery of industrial waste heat is essential for heat utilization in the DH system. However, the long distance between the industrial zone and urban DH is a great challenge as well as the costs. This technology can be used as a heat source directly for thermal power plants to generate electricity or improve the quality of waste heat utilization. As an example, Law et al. [21], Haung et al. [22], and Sonsaree et al. [23] investigated low-temperature heat waste as a source for direct heat use, and the flexibility requirement was to facilitate the access point and to control the volatility in the system caused by the heat network. On the other hand, Gu et al. [24] used natural-gas boilers with absorption heat exchangers to recover the waste heat.

8.3.3 Control systems in district heating and cooling

A control system can be added at a customer level. An example of this system is a supply temperature controller to change the set-points in different seasons based on some factors. The importance of occupants' behavior in a smart controlled system was mentioned earlier, while the control module in DHC considers climate, energy price, CO_2 emission rate, and the thermal load forecast to provide a flexible system. Moreover, the advanced control system aims to provide load shifting in the system, increase the dependency of the DHC on renewable energy sources, and decrease the operating temperature in the distribution network to ambient temperature in DH or increase it in DC to reduce thermal loss. Fig. 8.9 shows the flexible DHC system with a control system.

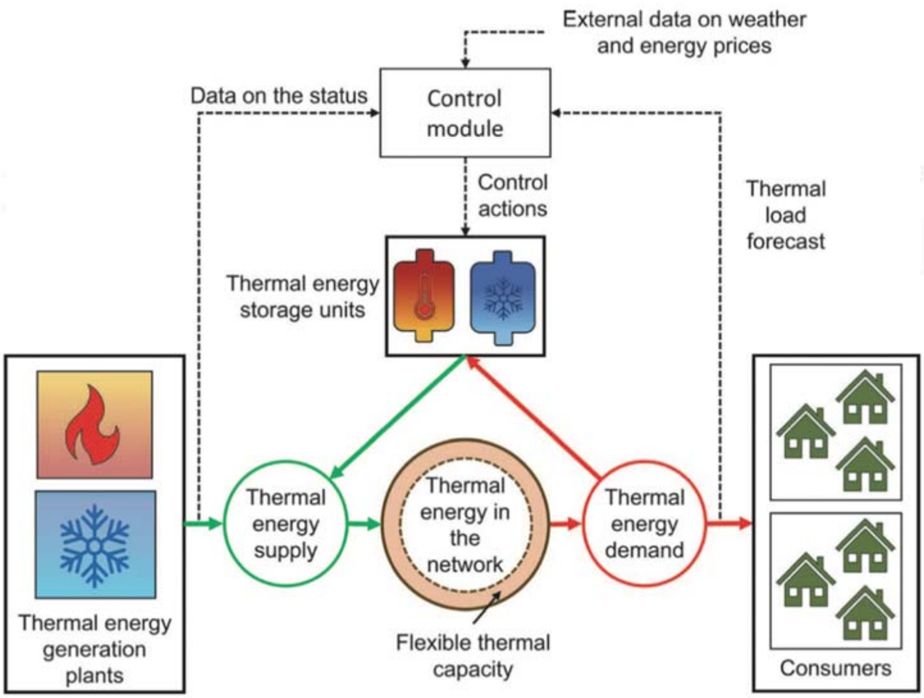

FIGURE 8.9 A flexible DHC system with a control module [4].

8.3.3.1 *A case study of a building connected to flexible district heating and cooling*

In the case study conducted by Foteinaki et al. [7] in 2020, a multifamily apartment block was designed according to Danish Building Regulation 2015 [25]. This building was connected to the Danish DHC system. The building was modeled according to the needs of the local DHC system for peak load shaving and cost reduction to support the thermal storage potential of the system. This building was well-insulated and heavy-weight. The total demand of the building for heating and cooling should not be more than 30 kWh/m^2/year, while there is a 1000 kWh/year load which was considered for heating the floor area (Table 8.2).

There are two main approaches to implementing demand response in the building sector: direct and indirect load control. In direct load control, the supplier directly controls loads of the consumers and has the right to perform load modulation to facilitate the system operation. Indirect load control refers to motivating consumers to participate in demand response by adjusting the timing and/or the magnitude of their energy use. Most often, indirect control is realized based on costs and the supplier provides variable tariff schemes to motivate consumers to benefit from low-cost periods and avoid high-cost periods. The dynamics of the tariff scheme may vary, including time-of-year (seasonal) pricing, time-of-use pricing (daily or weekly variations), critical-peak pricing, and real-time pricing. The consumers are informed about the prices one day or some hours in advance and decide whether or not to participate in this demand response activity.

Two indirect load control strategies were studied.

1. Assuming there is no communication platform between the building and the heat supplier, a constant strategy was implemented with one or two flexibility events every day during the heating season. This could be achieved with indirect control by giving monetary incentives to the occupants, for example, fixed contracts with time-of-use tariffs. The occupants set lower temperatures when there were high heating costs and vice versa. In this case, fixed schedules for temperature set-points were used, determined based on average daily profiles of the heating load of the area and the marginal heat production cost.
2. Assuming there is a communication platform between the building and the heat supplier, a signal is sent to the building from the supplier to communicate the need for load adjustment. The home management system modulates the temperature set-points according to this signal. In this case, the signal was the hourly marginal heat production cost. Two scenarios were considered in this study, including using a constant set-point of 22°C and using a variable set-point.

In the first scenario, the annual energy consumption for space heating and the peak demand was considered 12 kWh/m^2/year and 82 kWh/m^2, respectively. To evaluate the

TABLE 8.2 Building description.

Floor area	Number of floors	Numbers of apartments on each floor	Floor area in each apartment	Number and floor area of staircases	Supplied water temperature	Maximum heating power	Ambient temperature	Daily solar radiation
6272 m^2	7	8	112 m^2	4/21 m^2	45°C	14 W/m^2	−8°C	2.2 kWh/m^2/day)

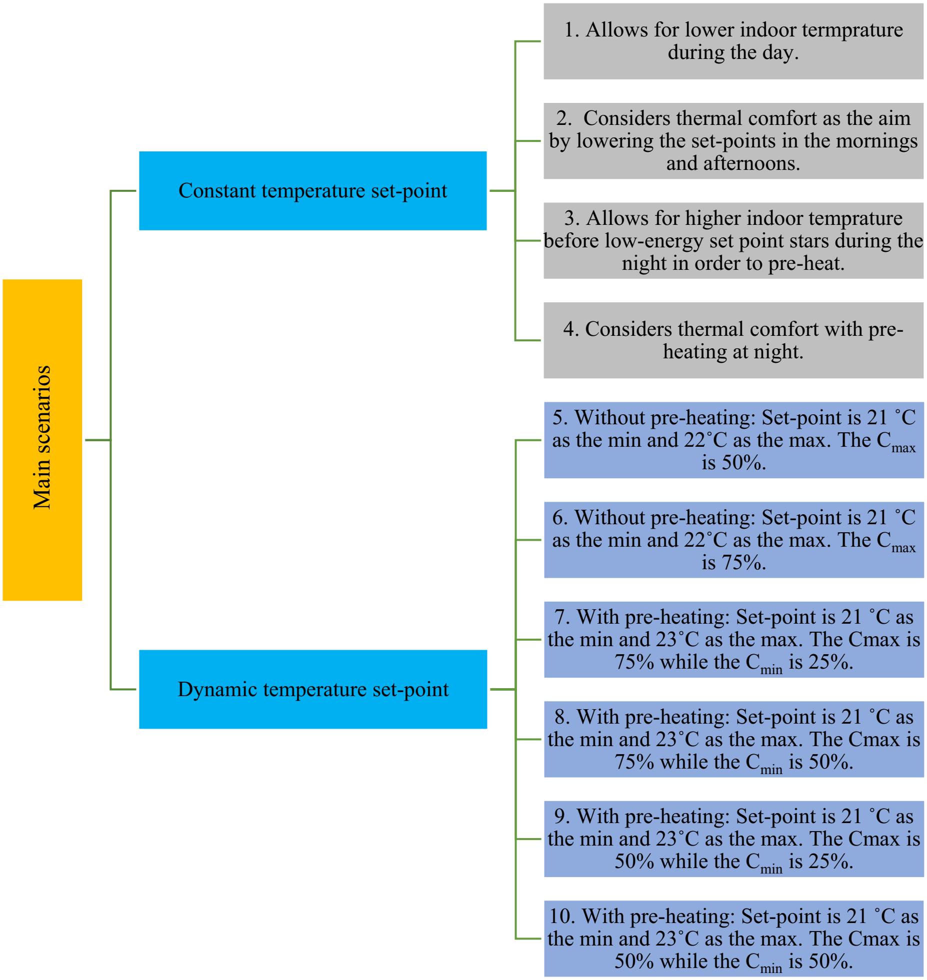

FIGURE 8.10 Summary of the scenarios considered in the case study.

different cases of thermal comfort, two temperature ranges of 21°C–23°C and 20°C–24°C were considered in this study. The main purpose was to reduce morning and evening peak loads.

On the other hand, in dynamic temperature set-points, the flexibility strategy was to shift the energy to the times that the cost of heat was the lowest. To achieve this aim, the thresholds of the heat production cost were set. In this case, the set-point varied based on the signal, while the signal was lower than the low-cost thresholds. For instance, to store the heat in the thermal mass, the set-point should be increased. Meanwhile, the set-point was decreased when the signal was higher than the high-cost thresholds to discharge heat. In Fig. 8.10, two scenarios with a constant temperature set point and dynamic temperature set points are illustrated.

Total energy used for space heating for the heating season can be calculated using Eq. (8.1), in which E_i is the energy used for space heating every hour.

$$E_{tot} = \sum_{1}^{heating\ season} E_i \tag{8.1}$$

The total heat production cost for space heating in the building connected to DH is calculated using Eq. (8.2), in which $MHPC_i$ is the marginal heat production cost for every hour.

$$MHPC_{tot} = \sum_{1}^{heating\ season} E_i \times MHPC_i \tag{8.2}$$

The indicator of total energy use during high load hours in comparison to low load hours is determined in Eq. (8.3), in which $E_{high\ load}$ is the total space heating energy used during high load hours, between 6:00 and 21:00, and $E_{low\ load}$ is the total space heating energy used during low load hours, between 21:00 and 6:00 (next morning). The range of the indicator was between $+1$ and -1. The optimal number is 1 when energy is consumed only during low load hours.

$$F_1 = \frac{E_{low\ load} - E_{high\ load}}{E_{low\ load} + E_{high\ load}} \tag{8.3}$$

The indicator of the total energy used during high production cost hours in comparison to low production cost hours is given by Eq. (8.4).

$$F_1 = \frac{E_{low\ cost} - E_{high\ cost}}{E_{low\ cost} + E_{high\ cost}} \tag{8.4}$$

$E_{high\ load}$ is the total space heating energy used during high production cost hours when the cost is higher than the median value of costs of each month, and $E_{low\ load}$ is the total space heating energy used during low production cost hours when the cost is lower than the median value of costs of each month.

The results indicated that scenario 1 was the most practical case as it had a decline of 15.5% and 10.8% in cost and energy consumption, respectively. However, thermal comfort was not considered to be important in this case while the indoor temperature was reduced by 0.6°C in comparison to scenario 4, which has the highest energy decrease of 86.5% in the peak hours and a 5.8% decline in cost. Meanwhile, scenario 3 was the most suitable scenario among the others in terms of energy flexibility in shifting load at night because the indicator was 0.79, while scenario 9 was the most proper one in the morning with the indicator value of 0.52.

Fig. 8.11 illustrates the average heat load in different loads and average operative temperatures in different scenarios and different hours.

8.4 Summary

DHC with energy flexibility have been discussed in this chapter. In conclusion, heating and cooling are vital parts of our life. Without any doubt, increasing the efficiency of

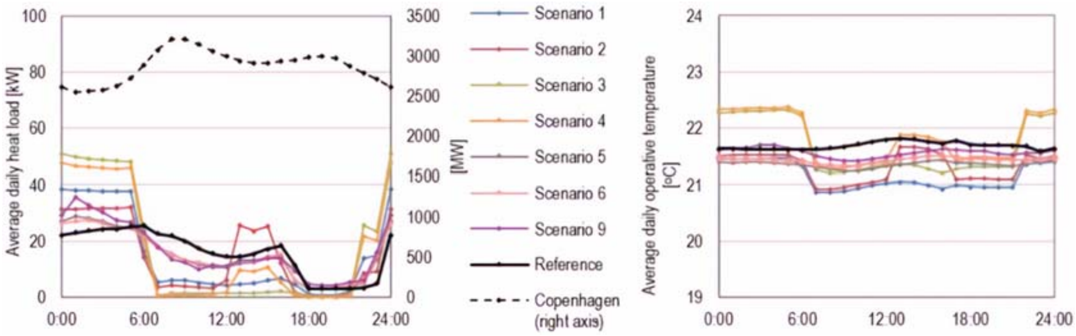

FIGURE 8.11 Average daily heating load of a low-energy building under different scenarios (*left image*) and average daily operative temperatures in comparison to the reference scenario (*right image*) [7].

this system can make a significant change. As a result of this, fewer pipelines are used, the excess heat is used in the cycle again, and the building energy consumption is managed wisely. DHC is a term to help the system to be integrated with different facilities to provide thermal comfort, reduce energy consumption and costs, and decrease CO_2 emissions.

There are two ways to increase the flexibility of the system. The first is to make the CHP power plants more flexible. This can be achieved by using renewable energy sources or using the excess heat of industrial processes. Renewable energy sources are considered a substitution for power plants to generate electricity during peak hours. The second method is to use demand response and control systems to provide flexibility by linking customers and the district system. These controllers should consider weather conditions, occupants' needs, flexibility aim, and thermal comfort.

In general, all the flexibility goals cannot be achieved at the same time. Different scenarios need to be considered. These scenarios can be categorized based on the price of electricity, types of power plants, types of buildings, and environmental aspects of interest.

The price of electricity is dynamic at high peak hours and constant during low load hours. In the scale of buildings, different set points can be proposed to save energy and costs in high peak hours. On the other hand, reducing CO_2 emissions is another purpose of the DHC system. The decision between these scenarios is mainly based on the purpose of energy flexibility and the existing facilities.

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CHAPTER

9

Smart grids and building energy flexibility

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The smart grid offers a great opportunity to move the energy industry into a new sustainable environment that provides a reliable, productive, and high-quality supply to ameliorate end users' lifestyles. This concept comprehensively covers all parts of a power system including generation, transmission, distribution, and consumption. Under such an environment, the penetration of various energy resources such as photovoltaic solar cells and wind turbines may negatively affect the energy system flexibility. Therefore, improvement in energy system flexibility is a pivotal issue in smart grids and should be taken into consideration. In this chapter, the smart energy system concept as well as the most crucial challenges and opportunities related to smart grids are elucidated. Additionally, the flexibility concept is clarified, whereas a flexibility-constrained energy scheduling problem incorporating demand response programs is also proposed. Finally, a small-scale smart energy system is introduced and used to evaluate the role of energy flexibility in the smart grid energy system.

Nomenclature

Acronyms

ADMM alternating direction method of multipliers
AMI advanced metering infrastructure
CAES compressed air energy storage
CHP combined heat and power
DERs distributed energy resources
DOE department of energy
DRPs demand response programs
DSM demand-side management

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EMS energy management system
EPRS European parliamentary research service
ESS electrical storage system
FERC energy and regulatory commission
GHGs greenhouses gases
IoT internet of things
MILP mixed integer linear programming
OMS outage management system
P2G power-to-gas
P2P peer-to-peer
PV photovoltaic
SCCs sensitivity coefficient of customers
SGSO smart grid system operator
SoC state of charge
SSESs small-scale energy systems

Indices

t, N_t set and index of time

Parameters

$G_{\max}^{CHP}$ maximum input gas of CHP unit
$G_{\max}^{Grid}$ maximum traded gas
$H_{\max}^{Grid}$ maximum traded thermal
N^W the number of wind turbines
P_{Max}^{CH} charging power of ESS.
P_{Max}^{DCH} discharging power of ESS
$P_t^{E,dem}$ electrical demand
$P_t^{G,dem}$ gas demand
$P_t^{H,dem}$ thermal demand
$P_{\max}^{Grid}$ maximum traded electrical power
P_t^{wind} the output power of the wind unit
$Pe_t^{buy,grid}$ electricity buying price
$Pe_t^{sell,grid}$ electricity selling price
$Pg^{buy,grid}$ gas buying price
$Ph_t^{buy,grid}$ thermal buying price
$Ph_t^{sell,grid}$ thermal selling price
P_r^w the nominal output power of wind turbine
SoC_{Max}^{ESS} the capacity of the ESS unit
V_C^{In} cut-in speed of wind turbine
V_C^{out} cut-out speed of wind turbine
V_c^{rated} rated speed of wind turbine
V_t^{wind} wind speed of wind turbine
ψ_{PH}^{CHP} coefficient between power and thermal
ϖ_{PH}^{CHP} coefficient between power and gas
$\varphi_{CHP}^{RDR}, \varphi_{CHP}^{RUR}$ ramp up and down rates of CHP unit
η^{DR} penetration rate of DRPs
ζ^{Flex} flexibility limit

Variables

C_t^{Elec}	electrical cost
$C_t^{Thermal}$	thermal cost
C_t^{Gas}	gas cost
$G_t^{buy,grid}$	purchased gas from the main grid
G_t^{CHP}	input gas to CHP unit
H_t^{CHP}	output thermal of CHP unit
$H_t^{buy,grid}$	purchased thermal power from the main grid
$H_t^{sell,grid}$	sold thermal power to the main grid
I_t^{DR}	a binary variable of the DR programs
I_t^{E}	a binary variable of power trading
I_t^{ESS}	a binary variable of the ESS unit
I_t^{H}	a binary variable of thermal trading
P_t^{CHP}	the output power of the CHP unit
P_t^{CH}, P_t^{DCH}	charging and discharging power of ESS unit
P_t^{Up}, P_t^{Dn}	upward and downward load shifting
$P_t^{buy,grid}$	purchased power from the main grid
$P_t^{sell,grid}$	sold power to the main grid
SoC_t^{ESS}	SoC of ESS unit

9.1 Introduction

In the last decades, conventional energy systems have been upgrading and transforming toward becoming a smart grid, which brings more privileges to power supply sections including generation, transmission, distribution, and consumption [1]. In this regard, the power grid should be comprehensively and efficiently reformed in all sections to adapt to the novel smart structure. As an illustration, energy generation, which is completely handled by conventional units in the traditional power grid, is integrated with new technologies such as renewable energy resources in smart energy systems [2]. Although an appropriate environment has been provided in the smart power grid for the implementation of all types of renewable energy resources, solar and wind power generation systems are among the most prevalent systems used. However, the stochastic nature of solar and wind energy resources leads to variability in power generation in comparison with conventional dispatchable power generation units. In fact, in contrast to generated power from conventional units, which follow market conditions, the produced power of solar and wind energy systems is highly related to weather conditions. Accordingly, such uncertainties in generated power of renewable systems can jeopardize system flexibility. Thus, various sources of flexibility such as fast ramp power plants, large-scale energy storage systems (ESSs), controllable renewable energy systems, demand-side management programs, virtual power plants, and multienergy systems have been proposed to improve the flexibility of smart power grids [3].

This chapter concentrates on the smart energy system scheduling problem associated with the flexibility concept. In this regard, the smart grid concept and different energy sections including generation, storage, and consumption are first elucidated in Section 9.2. The challenges and opportunities of the smart grid are then investigated in Section 9.3. The concept and role of flexibility in smart power systems are discussed in Section 9.4. A simple mathematical formulation of smart multienergy systems associated with flexibility constraints is also presented in Section 9.4; while the simulation results and analysis are provided in Section 9.5. Finally, the main achievements of this chapter are examined in Section 9.6.

9.2 Smart grids: concept and components

Nowadays, the energy demand is dramatically increasing, so an efficient and applicable solution is needed to overcome this challenge. A smart energy system can be considered an outstanding option to resolve this issue. Referring to European Union Commission, the smart grid concept is defined as "*an electricity* network *that can cost-efficiently integrate the behavior and actions of all users connected to it—generators, consumers, and those that do both—to ensure economically efficient, the sustainable power system with low losses and high levels of quality and security of supply and safety*" [4]. The smart grid is an exhaustive concept that covers all aspects of energy systems including energy generation, energy transmission, energy distribution, energy storage, and energy consumption.

The smart grid scheduling problem has been widely investigated from different aspects in previous studies. Some studies restricted the territory of smart grids to electrical energy carriers [5] and [6]; while others concentrated on integrated smart structures [7]. A multiobjective optimization problem was proposed in [5] to optimize the operating cost as well as the maximum demand of an electrical-based smart system. A probabilistic electrical power management model in the presence of electric vehicles, Demand Response Programs (DRPs), and smart transformers was provided in [6]. However, optimal coordination between diverse energy carriers such as electrical, thermal, gas and water can be performed in a smart multienergy system which can lead to more efficient operation. In an integrated energy structure, different types of energy can be effectively converted, stored, and distributed which are completely compatible with the development of modern urban areas [7]. Additionally, the smart grid energy system encompasses multiple Small-Scale Energy Systems (SSESs) to decentralize the operation of future smart grid energy systems as depicted in Fig. 9.1. Each of the SSESs possesses a series of generation, conversion, and storage units to satisfy different types of local demands, whereas its local controller can be communicated with the central operator of the smart grid energy system. As an example, a stochastic optimization model of SSESs associated with solar energy resources and DRPs was proposed in [8]; while a decentralized model based upon the Alternating Direction Method of Multipliers approach was provided in [9] to operate SSESs as a transactive energy framework.

To handle smart grid energy systems, different control approaches, including centralized, decentralized, and distributed, have been utilized; each of these techniques brings some challenges and opportunities to smart grid energy systems. In a centralized approach, one entity (a person or an enterprise, for example) controls the system; where this method can provide the most optimal solution, even though they are faced with some critical challenges such as scalability and information security of participants. In a distributed control approach, the central controller is comprehensively neglected and all of the entities have equal access to information which leads to more complexity in its structure. In addition, despite increasing information security due to eliminating the central controller, the convergence issue in the presence of a large number of participants is still a big challenge in distributed control methods. To fairly resolve the deficiencies and challenges of centralized and distributed approaches, the

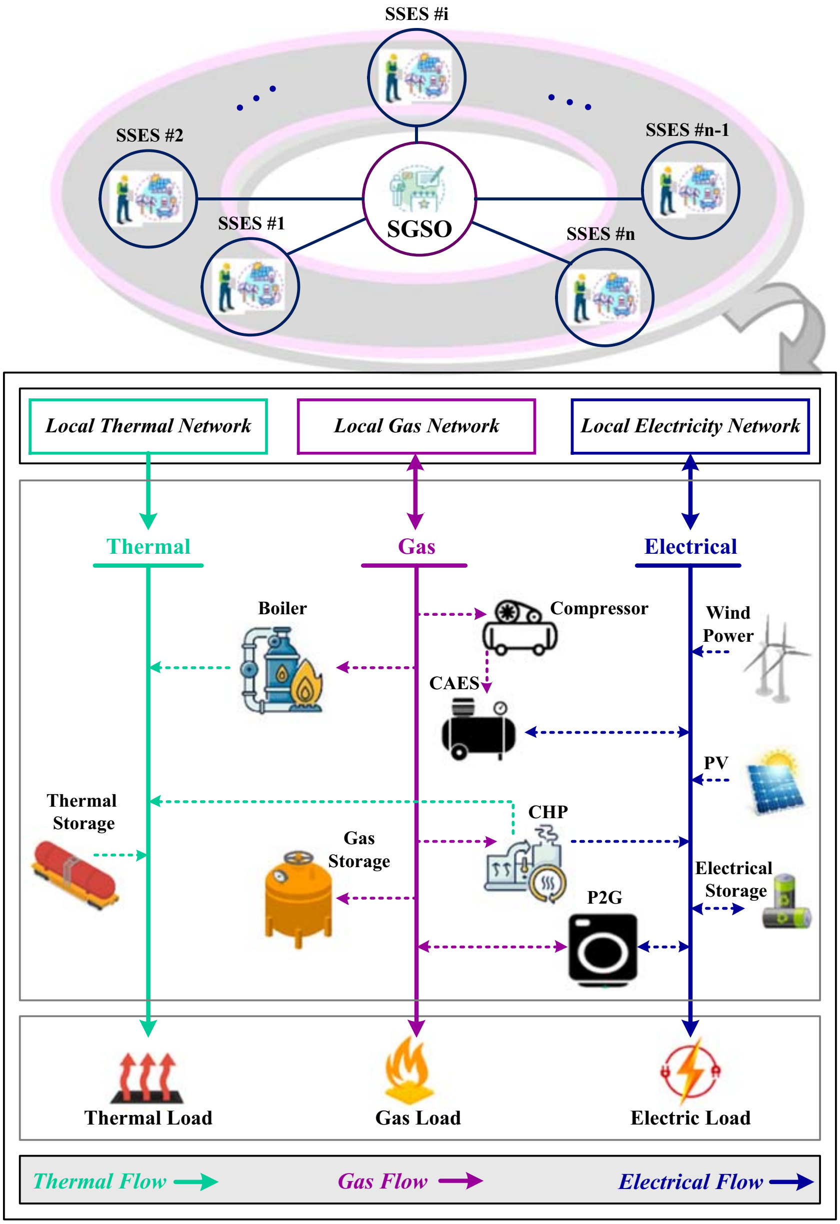


FIGURE 9.1 The smart grid energy system associated with SSESs.

decentralized approaches, as a combination of the previous methods, have been suggested. In a decentralized technique, there is no single controlling entity, and control is shared among several independent entities. The decentralized approach has a faster convergence than the distributed approach, and the scalability difficulties of centralized approaches have been resolved due to using more central controllers in decentralized approaches. However, the positive features of centralized and distributed approaches were observed at a lower level in decentralized methods. In this regard, the obtained optimal solution in the decentralized approach is weaker than the centralized structures. Additionally, the information security of the decentralized approach is slightly placed in a lower degree due to using fewer central controllers as compared with the distributed approach. However, a systematic communication infrastructure is required to efficiently implement all these control approaches.

The Internet of Things (IoT) as an efficient infrastructure can facilitate the operation of smart energy systems. Under the IoT-based systems, all effective information such as people's requirements and features, things' characteristics, and processes are competently connected to the internet to generate, collect, share and utilize information [10]. Accordingly, IoT information-based technology enables smart energy systems to share information between end-users, improve smart grid performance, and enhance the connectivity of smart grid components [11]. Therefore, energy productivity, system flexibility, and system reliability are improved by implementing DRPs, facilitating energy trading between end-users, and using the potential of storage units, electrical vehicles, charging stations, and smart homes capabilities [12]. Additionally, challenges such as environmental sustainability, stability, security, and reliability faced by conventional energy systems can be partially resolved in IoT-based smart energy systems. Moreover, the performance of Smart Grid System Operator (SGSO) in different functions of operation such as outage times management, load balancing, customer experience, line voltage, fault location, and restoration services can be ameliorated. Finally, it should be mentioned that the IoT infrastructure has been rapidly developed in recent years to support diverse functions of smart grids and this includes but is not limited to decentralized energy generation, Demand Side Management (DSM), Outage Management System, Energy Management System (EMS), real-time monitoring, and Advanced Metering Infrastructure (AMI) systems.

In the following sections, energy generation, energy storage, and energy consumption as the most important sections of the smart energy system are discussed.

9.2.1 Energy generation

Selecting efficient patterns of energy generation resources in an SSES is considered a challenging issue that can affect the performance of a smart system including flexibility, reliability, sustainability, and economic and environmental aspects. As mentioned previously, multienergy generation systems, which can consist of different energy carriers such as electrical, thermal, gas, and water energy, are considered integrated structures to provide the most optimal operation point [13]. The findings from [14] showed that the optimal design of the energy power generation side decreased the total annual costs and carbon dioxide emissions by 30% and 16%, respectively while increasing energy efficiency by 28% in a smart multienergy system. It was shown in [15] that the sustainable operation of the multienergy system can be affected by the optimal design of the energy generation system which was obtained by applying a robust optimization approach. In this regard, the optimal expansion planning of generation resources in a smart multienergy system, including energy carriers of electricity, thermal energy, and gas, was mathematically modeled in [16] to determine the optimal combination of diverse generating units, energy devices, and transmission lines.

Regarding the type of utilized primary energy sources in energy generation units, the SSESs can be investigated in two main clusters: (1) Renewable energy systems and, (2) Nonrenewable energy systems which are examined below.

9.2.1.1 Renewable energy resources

In recent years, energy security and sustainability are two crucial issues in energy studies. In this regard, electricity decarbonization is suggested by European Commission to overcome critical environmental challenges. Referring to European Climate and energy framework, the share of renewable energy resources in total energy consumption should reach up to 32% in 2030 [17]. The common types of renewable energy resources are solar, wind, geothermal, hydropower, and bio-energy; whereas solar and wind energy resources are the most popular ones used in smart grid energy systems.

9.2.1.2 Nonrenewable energy resources

A nonrenewable resource is a natural resource that cannot be facilely and quickly replaced by natural means to follow consumption [18]. Thus, this type of energy resource is not recommended by policymakers for the future of smart energy systems. However, these resources, such as combined heat and power (CHP) energy systems, have been generally used in the current smart energy systems. CHP is a technology that produces electricity and thermal energy at high efficiencies using a range of technologies and fuels. Thus, SGSO can provide more efficient control in the presence of CHP units due to the correlation between different energy carriers including electrical, gas, and thermal energy. Moreover, CHP units are usually well known as an on-site power production system which can lead to fewer energy losses.

9.2.2 Energy storage

In recent years, worldwide concerns about growing CO_2 emissions, climate change, and the security of energy supply have dramatically increased [19]. High energy consumption is presented in buildings, approximately 40% of total global consumption, providing a significant share of the global greenhouse gas (GHGs) emissions [20]. To overcome this environmental challenge, utilizing renewable energy resources is promising which can satisfy a considerable part of consumption in buildings and also relieve the network stress [21]. However, the real-time supply-demand balance may be violated by increasing the penetration rate of renewable resources such as Photovoltaics (PVs) which can undesirably affect the smart power grid flexibility. To resolve this issue, conventional solutions are not efficient, and applying effective alternatives is imperative [22]. Under the smart environment, using the fast ramp ESS incorporating accurate EMS can be considered a beneficial plan [23]; which are clustered into three main categories depending on their capacities as given in Table 9.1 [24].

Recently, various types of ESSs have been nominated and utilized in the smart power grid to enhance system flexibility. In the following subsections, three prevalent storage technologies: (1) battery storage system, (2) Power-to-Gas (P2G) system, and (3) Compressed air energy storage (CAES) system are scrutinized.

TABLE 9.1 Characteristic of ESSs based on capacity and placement, in which P is power.

Type	Capacity	Location
Large-scale technologies	$P > 100$ MW	Grid side
Medium-scale storage systems	5 MW $< P <$ 100 MW	Commercial and industrial units
Small-scale energy storage devices	$P < 5$ MW	Residential side

9.2.2.1 *Battery storage systems*

In the last few years, the dream of a highly efficient battery ESS has become a reality. Thus, the lead-acid battery-based technology has been replaced by the lithium-ion (Li-ion) technology [25]. However, the efficiency rate of the battery storage systems depends on different characteristics such as energy and power density, cost, lifetime, and response time. As an example, the long-term impacts of both Li-ion and lead-acid batteries on an isolated microgrid were investigated in [26] via a stochastic techno-economic approach. It was shown that both batteries were useful in reducing the levelized electricity cost; where they were less effective as compared with the flywheel energy storage in long-duration applications. Moreover, battery storage systems can provide a positive impact on the flexibility of smart microgrids. For instance, a bi-level optimization programming model was proposed in [27] to achieve optimal allocation of ESSs to improve grid flexibility.

9.2.2.2 *The P2G systems*

The P2G system is a flexible and advanced device for interconnection between electricity and natural gas networks. The P2G units convert surplus electrical energy (especially from renewable energy) into natural gas which is injected into the gas network. This stored energy can be used in times of need to satisfy either thermal demand or electrical demand (A gas-to-Power unit is also required). Therefore, the benefits of P2G systems become more distinguished in the smart grid with a high penetration rate of distributed energy resources (DERs) [28]. It was shown in [29] that implementation of P2G units declined the renewable curtailment by up to 87%. A multiobjective optimization problem was proposed in [30] to minimize the generated emissions and the operating cost considering a P2G unit and a wind power generation system. It was concluded that using the P2G system was more effective in cost reduction in comparison with DRPs.

9.2.2.3 *Compressed air energy storage systems*

The CAES system as an efficient storage unit uses electrical energy in off-peak periods to compress air and store it under high pressure in underground geological storage facilities. This compressed air can be released on demand to produce electrical energy via a turbine and a generator [31]. The stored energy can be utilized in peak periods which leads to emission mitigation as well as economic improvement in smart power grids. The positive environmental and economic impacts of CAES systems have been investigated in [32] and [33], respectively. Furthermore, the CAES units can be considered an efficient option to improve system flexibility via acting as a fast-response ESS [34]. Due to all these desirable features, the CAES technology has been widely addressed in smart microgrid energy system studies. A risk-based stochastic optimization model was proposed in [35] to maximize the profit of a generation company which included CAES, wind, and thermal units. The contribution of a CAES system in optimal bidding and offering strategies in an energy market considering energy price uncertainties was addressed in [36]. The impacts of a hybrid storage system on stochastic optimal operation of a smart microgrid which consisted of a solar-powered CAES system and an ice storage conditioner were examined in [37]. The results showed that the implementation of the proposed structure on the typical smart multienergy system reduced the operating costs and emissions in the day-ahead energy management by considering a solar-powered CAES system and an ice storage conditioner.

9.2.3 Energy consumption

Under the smart power grid, the demand side players can actively participate in the electricity market which can improve the system flexibility as well as market efficiency. In fact, in such an environment, the consumers can achieve efficient performance via responding to the control signals sent by the upstream smart grid's operator. The demand-side activities are well-known as DSM programs which are classified into two main categories: (1) DRPs and (2) Energy efficiency programs.

9.2.3.1 Demand response programs

Referring to Federal Energy and Regulatory Commission survey, the DR concept is defined as "*changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" [38]. The impacts of DRPs on smart power grid scheduling have been extensively evaluated from different points of view, such as *environmental impacts*, *economic benefits*, *reliability*, and *flexibility*. The environmental and economic impacts of DRPs on the scheduling of integrated electricity and heating systems were investigated in [39]. It was indicated that the electricity and thermal DRPs can improve the operating cost as well as reduce emitted GHGs without imposing additional investment costs. The effects of price-based DRPs on carbon emissions were also evaluated in the European electricity markets [40]. In [41], it was shown that the Sensitivity Coefficient of Customers in DRPs incorporating energy storage units significantly affected the energy productivity of smart multienergy systems. The impacts of reliability improvement of DRPs' implementation were evaluated in security-constrained unit commitment problems in [42]. A flexibility-oriented scheduling model was proposed in [43] to evaluate the economic and reliability indices of smart microgrids associated with incentive-based DRPs. It was concluded that the system profit increased by about 4% and 2.7%, while the reliability index was improved by 60% and 56%, in normal and resilient operating modes, respectively. The role of DRPs on flexibility enhancement was appraised in [44] whereas the maintenance cost of the smart grid also declined in the presence of DRPs. In [45], the flexibility index was integrated into the unit commitment problem incorporating wind power generation and DRPs. It was concluded that DRPs can be considered a significant source of flexibility in the smart power grid.

9.2.3.2 Energy efficiency programs

Referring to the European Parliamentary Research Service, energy efficiency is defined as "*the ratio of the output of performance, service, goods or energy, to the input of energy*" [46]. Recently, the use of energy efficiency programs in the demand side of power systems was taken into consideration as a crucial issue. In this regard, the smart grid environment can provide an appropriate structure to implement energy efficiency programs [47]. Thus, energy efficiency improvement and using high-tech appliances on the consumption side of energy systems are contemplated as pivotal challenges in the smart power grid [48]. The effects of energy efficiency programs on the improvement of the operating cost during peak periods were evaluated in [49]. It was concluded that implementing electrical and thermal energy efficiency programs declined the operation cost of the smart microgrid by 9.01% and 11.01%, respectively. The environmental merits of energy efficiency programs were examined in [50]. The results showed that the emissions and system financial burdens were reduced tangibly due to load curve modification associated with energy efficiency programs and DRPs. The benefits of these programs in reducing carbon emissions were assessed in thirty provinces of China [51]. It was concluded that when the rate of energy efficiency was below the threshold value, carbon emissions were reduced by 0.818% for every 1% increase in the rate of energy efficiency. Moreover, there is much interest in the interactions between DRPs and energy efficiency programs in smart power grid studies. The coordination between DRPs and the energy efficiency programs was handled in [52]. It was concluded that the negative and positive interactions can violate the operation of the smart power system.

9.3 Smart grids: challenges and opportunities

The smart grid concept provides an intelligent infrastructure in smart cities to reach a sustainable, reliable, and energy-efficient structure. However, investigation of different positive and negative aspects of smart power grids can be contemplated as a significant issue. In the following sections, the main challenges and opportunities of smart power systems are scrutinized.

9.3.1 Challenges

The smart power grids will face some crucial concerns which are clarified in the following subsections.

9.3.1.1 Complexity

The smart grid energy system provides a more complex physical and managerial structure as compared with the conventional structure. Smart grid scheduling is a highly complicated problem, in particular when considering diverse energy carriers in an integrated structure, which makes it even more sophisticated. Under such an environment, all parts of energy systems including generation, transmission, distribution, and consumption are efficiently altered to procure sustainable societies from technical, social, economic, and environmental aspects. However, due to the need of using a large number of smart devices in smart integrated energy systems, the social acceptance of the communities in response to the novel complex technologies becomes a highly crucial concern.

9.3.1.2 Cyber attacks

Digitalization of energy systems is one of the main features of the transition from conventional energy systems into smart energy systems; whereas AMI and IoT infrastructures are considered the backbone of smart systems. In such an environment, maintaining the information security of system users and energy system stability against cyber-attacks are contemplated as fundamental concerns. Therefore, regarding the importance of smart grid security, some studies have examined novel and efficient solutions to protect energy systems against cyber-attacks. An efficiently integrated security system was provided in [53] to support the smart energy system, whereas both supervised machine learning and heuristic feature selection techniques were used to increase the efficiency of the algorithm. An advanced approach based on a ternary Markovian model of cyber-physical components interactions was proposed in [54] to capture the subsystem layers' interactions of cyber-physical power systems. It was shown that the physical part of the smart grid was extremely affected by cyber-attacks.

9.3.2 Opportunities

Despite the aforementioned challenges, significant advantages can be brought to system users in a smart environment due to the high penetration of DERs, the active role of end-users, and the efficacious use of advanced technologies. In the following subsections, the main opportunities of a smart power grid are elucidated.

9.3.2.1 Economic benefits

A smart grid structure provides more economically efficient opportunities for all system players. The impacts of emerging business models on providing opportunities for community participants were investigated in [55]. Referring to this study, 221 active businesses were identified which were analyzed by utilizing the business model canvas framework. It was observed that platform operators, aggregators, and representatives constituted the three macro-categories of facilitating actors, complemented by retailers and grid operators in the smart grid environment. However, the smart grid energy system can be encompassed by interconnecting different smart micro multienergy systems [56]; whereas optimal coordination was performed between various energy carriers in each smart micro multienergy system. It was verified that improvement in economic benefits was more drastic in an integrated structure when compared to the separated energy systems [57]; while using high-tech devices and smart EMSs increased economic efficiency [57]. Under the smart environment, the impacts of DR programs on cost reduction of the smart multienergy system were evaluated in [58]. It was concluded that the total operation cost declined by about 9% in the presence of the DR programs. Moreover, Peer-to-Peer (P2P) energy trading can provide considerable economic and technical benefits. As an example, it was shown in [59] that P2P energy trading between agents decreased the load shedding costs by 64% in comparison to the case without energy trading.

9.3.2.2 Environmental benefits

Since electricity demand shows cyclical fluctuations, different types of generating units should be committed along a specified time horizon. Thus, to respond to the rapid increase in demand, high-emission and high-cost power plants should be committed to the conventional power system structure [60]. However, utilizing high-tech information and communication systems in both demand-side and supply-side of the smart energy systems can lead to competent management. Accordingly, a smart power grid can prevent imposing additional environmental and economic burdens, especially in peak periods due by using appropriate tools which can improve the power system operation. Smart energy systems bring distinguished environmental benefits such as reduction in GHGs and fossil fuels consumption due to increasing penetration of DERs, storage systems, and DSM programs. Referring to the Department of Energy in the United States, it was reported that extensive use of high information and communication systems will improve manufacturing production and energy efficiency by 10% and reduce emissions by 25% [61]. Furthermore, the environmental impacts of smart grid energy systems have been appraised in different studies. As an example, the positive impacts of information and communication technologies on the reduction of the emitted CO_2 as well as energy consumption in smart homes were evaluated [62]. The simulation results confirmed that the level of emissions reduction was proportional to the efficiency and share of the renewable generation resources, and grid energy dependence. The potential of advanced monitoring and control technologies was investigated in [63] to reduce energy use in smart homes as well as emission mitigation on the smart grid scale. It was shown that the coordination of smart management systems by consumer behaviors improved the chance of widespread adoption of smart monitoring and control technologies.

9.3.2.3 Social/community benefits

The life quality of end-users is a pivotal aspect to ensure the all-around development of a community. The productivity of a community will be improved by increasing the satisfaction of end-users. Under the smart environment, the possibility of using diverse high technological devices can provide such conditions which improve the satisfaction indices of end-users. In such circumstances, the role of end-users in generating, storing, and consuming energy is actively increased which leads to their active participation in local energy markets. Accordingly, the end-users can get benefits from energy exchange with other participants, the so-called P2P energy trading, or the upstream energy provider [64].

9.3.2.4 Flexibility improvement

The smart grid energy system provides an appropriate environment for the implementation of high-tech and fast ramp resources as well as efficient storage systems such as CAES and P2G to maintain the energy system flexibility. Moreover, using advanced communication infrastructure facilitates the application of DSM programs in smart power grids which can be considered an effective strategy to improve the flexibility of energy systems.

9.3.2.5 Resiliency improvement

The power demand of consumers should be satisfied continuously, even in critical emergencies. The smart grid structure can provide an appropriate environment to facilitate this crucial necessity due to rapid advancements in sensing, computing, and communications. Thus, the positive aspect of smart grids in resiliency improvement has been addressed in several studies. The process of power grid restoration will be hastened by the optimal dispatching of DERs [65]. As an example, the impacts of optimal allocation and operation of DERs on smart grid resiliency amelioration were studied in [66,67]. It was observed that the recovery time and the unserved load of the power system were significantly reduced by using the efficient allocation of DERs.

9.4 Flexibility in smart grids: definition and modeling

Grid flexibility is a crucial factor that affects smart grid functionality. In the following subsections, the concept of smart grid flexibility is elucidated. Furthermore, a mathematical model of a smart multienergy system scheduling problem concentrating on the flexibility concept is also provided.

9.4.1 Definition

The increasing penetration of DERs in the demand side of the smart power grid affects the variation rate of a net electrical load from the SGSO point of view. As an example, the installed capacity of PV systems on the demand side of California's power system has reached 5561 MW in July 2020 [68]. This issue revealed the vital role of using various sources of flexibility like fast ramp resources, energy storage, and DR programs in smart energy systems. Energy system flexibility can be defined as "*The capability to balance rapid changes in renewable generation and forecast errors within a power system*" [69] which has been scrutinized in recent studies. The role of fast ramp units in an uncertainty-based unit commitment and construction problem was evaluated in [70] to improve power system flexibility with a high penetration rate of DERs. Application of energy storage units on flexibility improvement was assessed in [71]; while positive impacts of DRPs were addressed in [72] and [73]. Moreover, the SGSO can enhance system flexibility by implementing some regulatory restrictions on the micro multienergy systems. Thus, the variation rate of energy trading in each SSES with the upstream network is limited by the flexibility constraint [68] which can guarantee the secure operation of a smart grid with a high penetration rate of DERs.

9.4.2 Mathematical modeling

Here, the mathematical formulation of a smart multienergy system aiming at evaluating the impacts of flexibility indices on the optimal operation was proposed. DRPs and a battery storage system as part of smart grids' capability were appraised to improve the system's flexibility. The proposed optimization model has been implemented in the General Algebraic Modeling System (GAMS) environment and structured as a Mixed Integer Linear Programming problem. The GAMS is a high-level modeling system for mathematical optimization problems. This optimization platform can competently solve linear, nonlinear, and mixed-integer optimization problems.

The economic objective function of the proposed model is given in Eq. (9.1), where the costs of buying/selling electrical and thermal energy from/to the upstream electrical and thermal networks are represented by Eqs. (9.2) and (9.3), respectively. The cost of the required gas procurement from the upstream gas network is determined by Eq. (9.4).

$$Min \sum_{t=1}^{N_t} \{C_t^{Elec} + C_t^{Thermal} + C_t^{Gas}\} \tag{9.1}$$

where:

$$C_t^{Elec} = Pe_t^{buy,grid} P_t^{buy,grid} - Pe_t^{sell,grid} P_t^{sell,grid} \tag{9.2}$$

$$C_t^{Thermal} = Ph_t^{buy,grid} H_t^{buy,grid} - Ph_t^{sell,grid} H_t^{sell,grid} \tag{9.3}$$

$$C_t^{Gas} = Pg^{buy,grid} G_t^{buy,grid} \tag{9.4}$$

The objective function is subjected to the following constraints.

1. Networks constraints:

Simultaneous buying and selling of electrical energy and thermal energy from the upstream network are restricted by Eqs. (9.5)−(9.6) and Eqs. (9.7)−(9.8), respectively. Moreover, the input gas from the upstream gas network is limited by Eq. (9.9).

$$0 \le P_t^{buy,grid} \le I_t^E P_{\max}^{Grid} \tag{9.5}$$

$$0 \le P_t^{sell,grid} \le (1 - I_t^E) P_{\max}^{Grid} \tag{9.6}$$

$$0 \le H_t^{buy,grid} \le I_t^H H_{\max}^{Grid} \tag{9.7}$$

$$0 \le H_t^{sell,grid} \le (1 - I_t^H) H_{\max}^{Grid} \tag{9.8}$$

$$0 \le G_t^{buy,grid} \le G_{\max}^{Grid} \tag{9.9}$$

The energy balances of the electrical load, thermal demand, and gas requirement are satisfied by Eqs. (9.10)−(9.12), respectively. Besides the energy trading, the electrical output energy of the CHP unit, the amount of charging and discharging of battery storage, the level of DR programs' participation, and wind power generation are considered in Eq. (9.10). Moreover, the thermal output energy of the CHP unit is determined using Eq. (9.11). In Eq. (9.12), the purchased gas from the upstream gas network and the gas consumption of the CHP unit are contemplated.

$$P_t^{buy,grid} - P_t^{sell,grid} - P_t^{CH} + P_t^{DCH} + P_t^{CHP} + N^W P_t^{wind} + P_t^{UP} + P_t^{Dn} = P_t^{E,dem} \tag{9.10}$$

$$H_t^{buy,grid} - H_t^{sell,grid} + H_t^{CHP} = P_t^{H,dem} \tag{9.11}$$

$$G_t^{buy,grid} - G_t^{CHP} = P_t^{G,dem} \tag{9.12}$$

2. CHP constraints:

The relations between the input gas and output heat and power in the CHP unit are shown by Eqs. (9.13) and (9.14). Eq. (9.13) is used to satisfy the relation between thermal and power outputs of the CHP unit; while the relation between gas consumption and the output power of the CHP unit is formulated by Eq. (9.14).

Eqs. (9.15)–(9.16) stand for the ramp-up and ramp-down rates of the CHP units, respectively. Moreover, Eq. (9.17) is used to limit the input gas of the CHP unit.

$$H_t^{CHP} = \psi_{PH}^{CHP} P_t^{CHP} \tag{9.13}$$

$$G_t^{CHP} = \varpi_{GP}^{CHP} P_t^{CHP} \tag{9.14}$$

$$P_t^{CHP} - P_{t+1}^{CHP} \le \varphi_{CHP}^{RDR} \tag{9.15}$$

$$P_{t+1}^{CHP} - P_t^{CHP} \le \varphi_{CHP}^{RUR} \tag{9.16}$$

$$0 \le G_t^{CHP} \le G_{\max}^{CHP} \tag{9.17}$$

3. Battery storage system constraints:

The operation limits of the battery storage system are formulated by Eqs. (9.18)–(9.21). The State of Charge (SoC) of the battery storage is shown by Eq. (9.18), in which the hourly SoC is limited by Eq. (9.19). Moreover, the amounts of hourly charging and discharging power of the ESS unit are restricted by Eqs. (9.20) and (9.21), respectively.

$$SoC_t^{ESS} = SoC_{t-1}^{ESS} + P_t^{CH} - P_t^{DCH} \tag{9.18}$$

$$0 \le SoC_t^{ESS} \le SoC_{Max}^{ESS} \tag{9.19}$$

$$0 \le P_t^{CH} \le P_{Max}^{CH}(1 - I_t^{ESS}) \tag{9.20}$$

$$0 \le P_t^{DCH} \le P_{Max}^{DCH} I_t^{ESS} \tag{9.21}$$

4. DRPs constraints:

The limitations of DRPs are modeled by Eqs. (9.22)–(9.24). Eq. (9.22) states that the total amount of upward and downward load shifting in DRPs should be equal; whereas the level of upward and downward DR programs in each period is limited by the part (η^{DR}) of the electrical demand.

$$\sum_{t=1}^{N_t} P_t^{Up} = \sum_{t=1}^{N_t} P_t^{Dn} \tag{9.22}$$

$$0 \le P_t^{Up} \le I_t^{DR} \eta^{DR} P_t^{E,dem} \tag{9.23}$$

$$0 \le P_t^{Dn} \le (1 - I_t^{DR}) \eta^{DR} P_t^{E,dem} \tag{9.24}$$

5. Wind turbine constraints:

The output power of a wind turbine depends on the wind speed. The relations between wind speed and output power of the wind turbine are formulated as Eq. (9.25), according to the literature [74].

$$P_t^{Wind} = \begin{cases} 0 & V_t^{wind} < V_C^{In} \text{ or } V_t^{wind} > V_C^{out} \\ \dfrac{V_t^{wind} - V_C^{In}}{V_c^{rated} - V_C^{In}} & V_C^{In} \le V_t^{wind} < V_c^{rated} \\ P_r^w & V_c^{rated} \le V_t^{wind} \le V_C^{out} \end{cases} \tag{9.25}$$

6. Flexibility constraints:

The flexibility constraint of a smart multienergy system is modeled by Eq. (9.26); where the difference between the amount of traded energy with the main grid in successive periods should be lower or equal to the flexibility limitation [68]. Since Eq. (9.26) is a nonlinear equation, it can be correctly approximated by linear equations as shown in Eqs. (9.27)–(9.28).

$$\left|\left(P_t^{buy,grid} - P_{t-1}^{buy,grid}\right) - \left(P_t^{sell,grid} - P_{t-1}^{sell,grid}\right)\right| \le \zeta^{Flex} \tag{9.26}$$

$$\left(P_t^{buy,grid} - P_{t-1}^{buy,grid}\right) - \left(P_t^{sell,grid} - P_{t-1}^{sell,grid}\right) \le \zeta^{Flex} \tag{9.27}$$

$$-\left(P_t^{buy,grid} - P_{t-1}^{buy,grid}\right) + \left(P_t^{sell,grid} - P_{t-1}^{sell,grid}\right) \le \zeta^{Flex} \tag{9.28}$$

9.5 Case study and discussion

Here, the performance of the proposed model was examined using a typical small-scale multienergy system implemented in the GAMS modeling language and solved using Cplex 12.8.0.0. To scrutinize the impacts of the flexibility constraint on the optimal operation of the small-scale multienergy system, four different scenarios presented in Table 9.2 are taken into account.

9.5.1 System data and parameter settings

The proposed flexibility-based optimization problem was applied to a simple small-scale multienergy system as depicted in Fig. 9.2. The scheduling horizon was 24 hours. The demands of electricity, thermal, and gas of the small-scale multienergy system are given in Fig. 9.3 whereas the electricity and thermal selling prices are shown in Fig. 9.4 [74]. Moreover, it was assumed that the electrical and thermal buying prices from the upstream grid were 10% higher than the selling prices.

The wind speed in the small-scale multienergy system was considered and is shown in Fig. 9.5 [74]. Referring to Fig. 9.5, it can be observed that the highest wind speed was at the beginning and end hours of the day. The other required data was taken from [74] and is presented in Table 9.3.

TABLE 9.2 Statement of scenarios.

Scenario	DRPs	Flexibility constraint
#1	×	×
#2	✓	×
#3	×	✓
#4	✓	✓

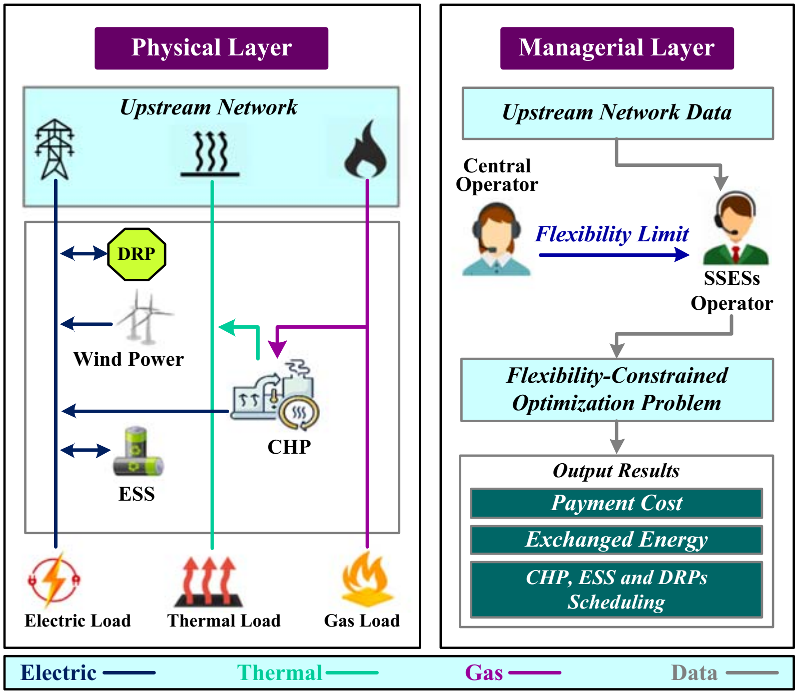


FIGURE 9.2 Illustration of a simple small-scale multienergy system.

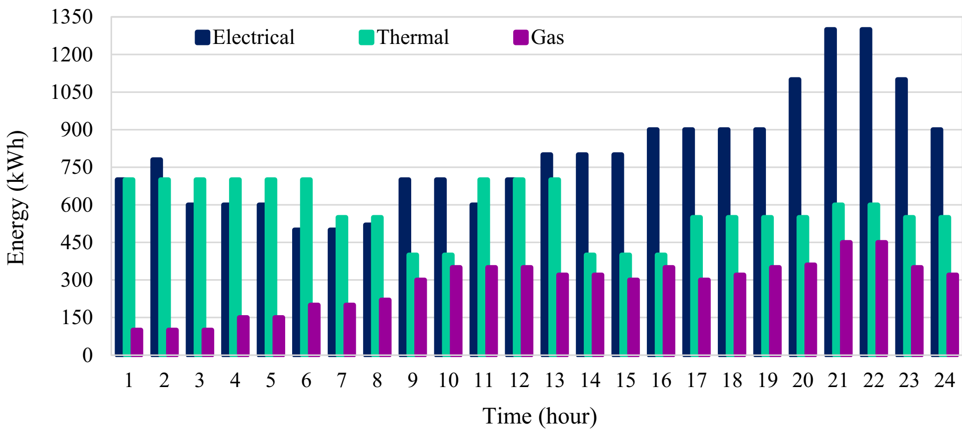


FIGURE 9.3 The electrical, thermal, and gas load profiles over the scheduling horizon.

9.5.2 Simulation results and discussion

By applying Cplex 12.8.0.0, the small-scale multienergy system scheduling problem was handled and the operation costs were calculated and are provided in Table 9.4. It can be seen that the implementation of DRPs decreased the financial burden which was $20.3

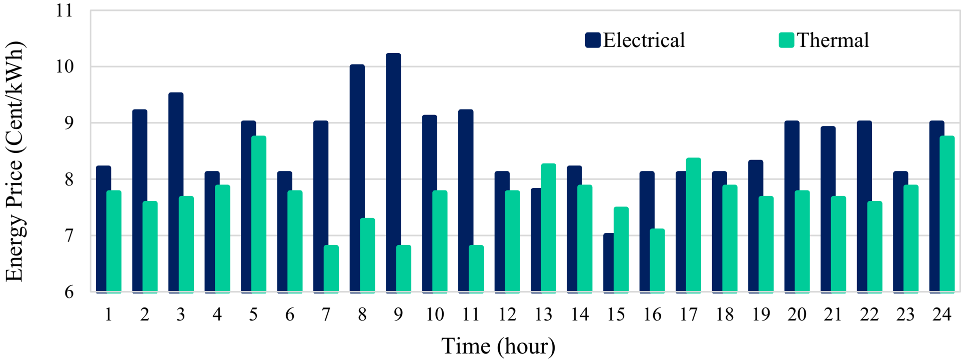


FIGURE 9.4 The electrical and thermal selling prices over the scheduling horizon.

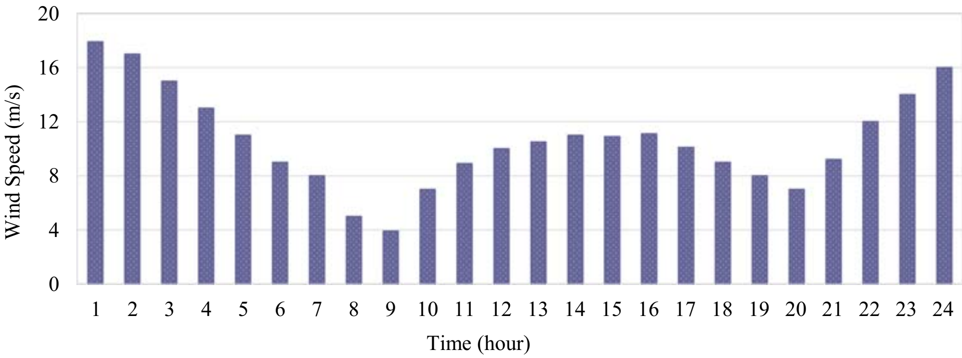


FIGURE 9.5 The wind speed over the scheduling horizon.

TABLE 9.3 The input parameters of the small-scale multienergy system.

Parameter	Amount	Parameter	Amount
$G_{\max}^{Grid}$	1800 (kW)	SoC_{Max}^{ESS}	300 (kWh)
$G_{\max}^{CHP}$	800 (kW)	V_C^{In}	4 (m/s)
$H_{\max}^{Grid}$	1000 (kW)	V_C^{out}	22 (m/s)
N^W	3	V_c^{rated}	10 (m/s)
P_{Max}^{CH}	80 (kW)	ψ_{PH}^{CHP}	1.2
P_r^w	100 (kW)	ϖ_{GP}^{CHP}	0.4
$P_{\max}^{Grid}$	1100 (kW)	$\varphi_{CHP}^{RDR}, \varphi_{CHP}^{RUR}$	50 (kW)
P_{Max}^{DCH}	80 (kW)	η^{DR}	0.2
$Pg^{buy,grid}$	7.2 (cent/kW)	ς^{Flex}	500 (kW)

TABLE 9.4 Total operation cost over the scheduling horizon in different scenarios.

Scenario no	Operation cost ($)	Changes (%)
#1	662.54	–
#2	642.23	−3.6
#3	716.38	8.12
#4	654.26	−1.24

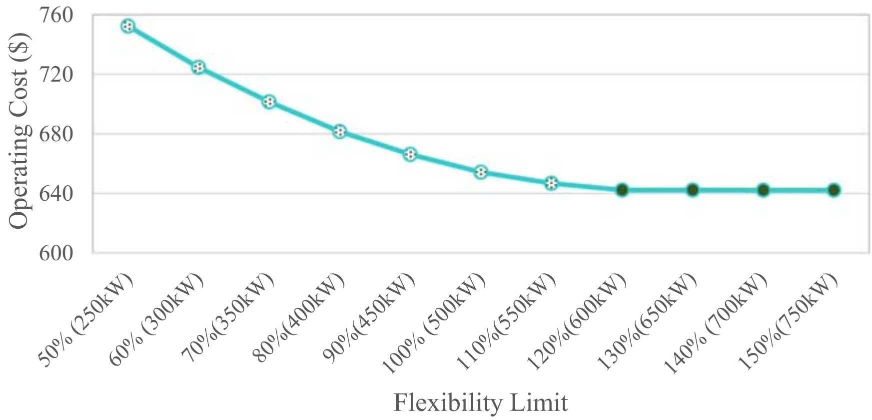


FIGURE 9.6 Operation cost variation in response to flexibility limit changing.

lower than the operating cost in Scenario #1. However, the operation cost was increased by $53.8 in Scenario #3 when compared to that in Scenario #1, due to imposing the flexibility constraint which affected the level of traded energy with the main grid. Referring to Scenario #4, it can be concluded that DRPs can cover the additional cost which was imposed on the energy system as a result of considering the flexibility limitation.

Referring to Table 9.3, it can be observed that the flexibility limit was considered equal to 500 kW which dramatically affected the operating cost of the SSES. Thus, the impact of the flexibility limit, specified by the system operator of the upstream grid, on the operating cost of the SSES was evaluated and the results are provided in Fig. 9.6. It can be seen that the lower the flexibility limit was selected, the higher the operating cost was imposed on the SSES. In addition, it can be concluded that the rate of the operating cost reduction was discontinued when the flexibility limit reached up to 600 kW, that is 20% (100 kW) higher than the initial amount (500 kW).

The amount of energy carriers which was exchanged with the upstream grid over the scheduling horizon in Scenario #4 is shown in Fig. 9.7. It can be seen that the SSES sold the excess electrical energy to the upstream grid in hours #1 to #12; while importing the shortage energy from the upstream in hours #13 to #24. This energy trading occurred due

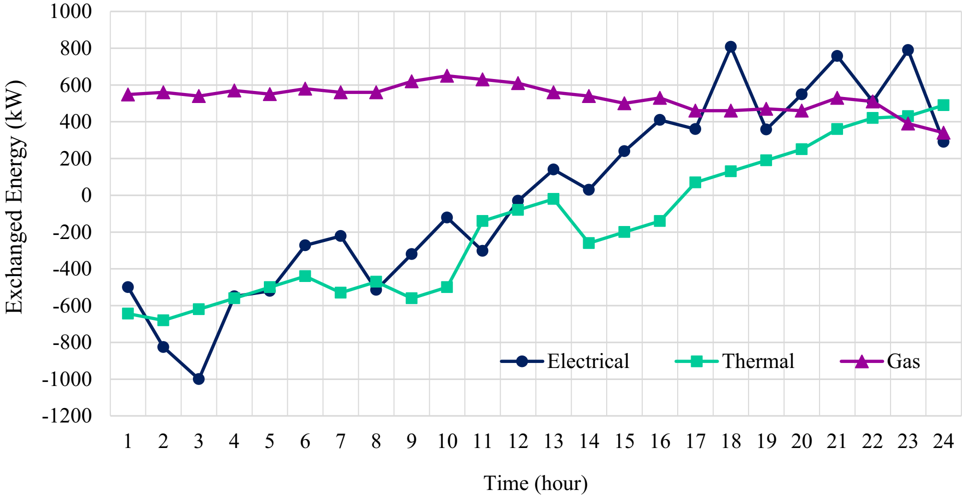


FIGURE 9.7 Level of exchanged electrical, thermal, and gas energies with the upstream grid.

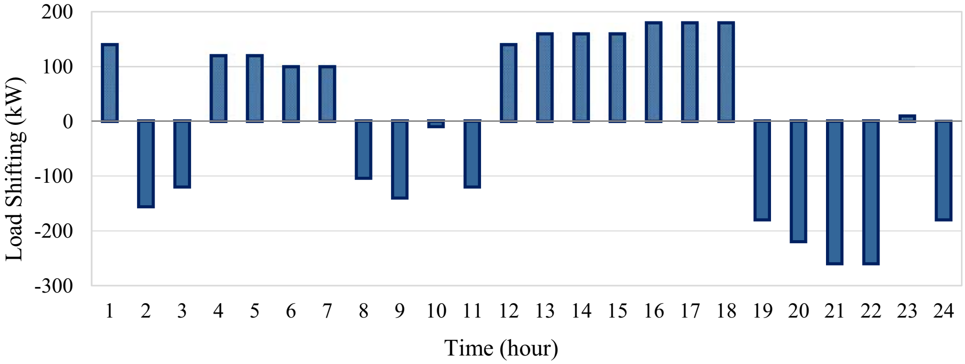
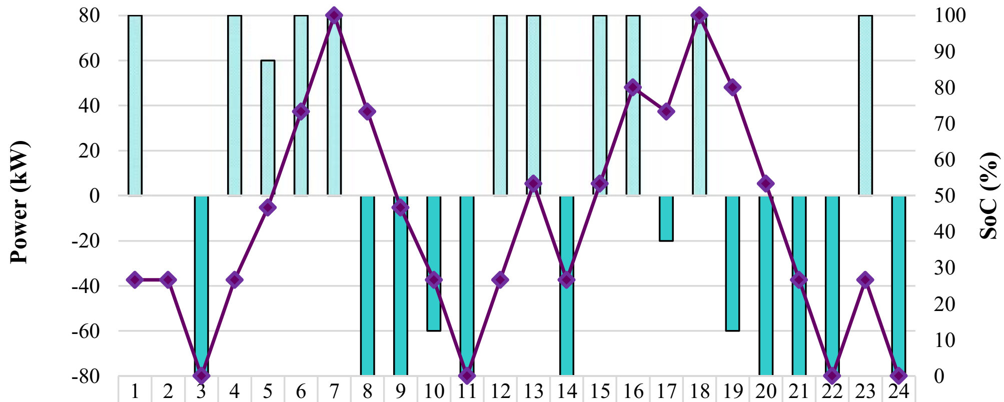


FIGURE 9.8 The hourly load shifting associated with DRPs.

to different variations of the electricity selling price over the scheduling horizon. Additionally, the CHP unit as the main energy resource of the smart SSES affected the amount of traded thermal energy and gas energy. As an illustration, the generated power of the CHP unit was high in the first hours of the scheduling horizon which led to a high generation of thermal energy as well as considerable consumption of the gas demand.

The hourly shifted load as a result of DRPs implementation is portrayed in Fig. 9.8. Here, the positive and negative values represented the amount of the upward and downward load shifting, respectively. It can be seen that the electrical load was shifted down in the high load hours, that is hours #19–24. However, the electricity demand was satisfied by the upstream grid in hour #23 since the electricity price was too low.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	80	0	-80	80	60	80	80	-80	-80	-60	-80	80	80	-80	80	80	-20	80	-60	-80	-80	-80	80	-80
SoC (%)	27	27	0	27	47	73	100	73	47	27	0	27	53	27	53	80	73	100	80	53	27	0	27	0

FIGURE 9.9 The hourly charging and discharging patterns of the ESS unit.

Fig. 9.9 demonstrates that the hourly charging and discharging of the ESS unit are dependent on the electricity price and demand over the scheduling horizon. Thus, the ESS unit was charged during the hours with the lowest electricity prices (e.g., hour #1) and discharged in the hours with the highest prices (e.g., hour #8).

9.6 Summary

This chapter concentrated on the flexibility concept of smart power grids. Firstly, the definition of a smart grid and its components were clarified. Then, the main challenges and benefits of smart power systems were addressed. It was shown that DERs, DSM programs, and ESSs can be efficiently implemented in a smart power grid which positively affects system flexibility as well as system management. However, the growing penetration rate of DERs in smart energy systems can lead to flexibility violations. To overcome this challenge, the SGSO can increase the penetration rate of DRPs as well as the capacity/number of ESS and fast ramp resources in the smart grid which will impose a considerable investment cost on the system. To avoid such financial burdens, implementing flexibility limitations can be promising to ensure the secure operation of the system. To investigate this issue, a flexibility-constrained energy scheduling model associated with DRPs was proposed in this chapter which was tested on a small-scale multienergy system. The following achievements have been concluded:

1. Considering the flexibility constraint increased the operating cost of the SSES by 8.12%.
2. The implementation of DRPs can be contemplated as a beneficial policy to eliminate the flexibility constraint consequences on the operating cost.
3. Sensitivity analysis showed that the operation cost of a smart SSES was significantly dependent on the flexibility limit.

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CHAPTER

10

Building energy flexibility analysis: case studies and demonstration

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A transition to a renewable energy future with intermittent and fluctuating power generation calls for a paradigm shift in electrical power systems. Enabling this shift requires demand that can be adjusted according to the available power, and this is termed energy flexibility. A wide range of sustainable energy technologies have been developed to achieve flexibility within building energy systems to reduce operating costs and support the operation of the power grid. This chapter first provides an overview of recent case studies using different technologies to improve building energy flexibility. A case study of a net-zero energy office building is then presented to demonstrate both how to effectively use photovoltaic (PV) panels and an electric battery to improve building energy flexibility, and how to quantify the energy flexibility that they can offer. Lastly, the potential of using other energy flexible measures present in the building to enhance energy flexibility is discussed.

10.1 Introduction

The penetration of renewable energy technologies in buildings provides an opportunity to achieve net-zero emissions. However, the inherent unpredictability of power generation from renewable energy resources and the uncertainty of power demand make it challenging to accurately match energy supply with demand [1]. In this context, energy flexibility was proposed as an effective solution to address the challenges faced by future energy systems.

Building energy flexibility is highly reliant on energy flexible systems, such as renewable energy generation combined with energy storage, either electrical or thermal. When these flexible sources are deployed, appropriate demand response (DR) strategies can be developed and used to actively manage energy supply and demand, balancing the needs of the power grid, occupant thermal comfort, and other numerous operating constraints.

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The DR strategies were generally developed based on optimization algorithms and can potentially improve power grid balance significantly and reduce building energy costs. However, the flexibility potential and impact of DR strategies within a building are governed by its available flexible sources and their implementation. A range of case studies using different energy flexible sources have been developed to demonstrate how energy flexibility can be achieved and how it can significantly reduce building operational costs and ultimately reduce carbon emissions.

10.2 Case studies to enhance building energy flexibility

In this section, an overview of recent case studies using different energy flexible sources to improve building energy flexibility is provided. The case studies were mainly categorized based on the energy flexible sources used.

10.2.1 Case studies using Heating, Ventilation, and Air-conditioning systems and thermal energy storage as main flexible measures

Heating, Ventilation, and Air-conditioning (HVAC) systems consume significant energy as they manage indoor thermal loads to maintain thermal comfort in buildings. They offer great potential for flexibility improvement if the full range of thermally comfortable temperatures is exploited. Potentially HVAC systems can control power consumption via temperature setpoint adjustment answering the requirements of both the power grid and occupant thermal comfort. Many studies have investigated how to effectively use HVAC systems to increase building energy flexibility. Wang et al. [2], for instance, presented a control strategy aimed at reducing energy use by proper adjustment of the chilled water flow rate setpoints to achieve the same indoor temperature rise among different zones, while simultaneously shutting down some chillers in response to short-term DR events. It was reported that this proposed strategy can reduce power consumption by about 11.2%, compared with the use of conventional control strategies. Kou et al. [3] developed a model-based control method to optimize the operation schedule of the HVAC systems in residential buildings. In this control method, an optimization function was developed to minimize the electricity cost, the violation of indoor thermal comfort, and the violation of the contracted demand limit. The method considered external disturbances including electricity tariff, forecast weather, and the nonresponsive electricity demand of the building. The simulation results showed that this method can reduce total operating costs of the HVAC systems by 34.16% when compared with the use of conventional control strategies.

Integrating HVAC with thermal storage (e.g., building thermal mass, phase change material storage systems, water tanks) can further improve building energy flexibility through appropriate DR control. Lizana et al. [4] proposed a framework, as shown in Fig. 10.1, which used a heat pump and a latent thermal storage system to improve building energy flexibility. According to the predicted future energy demand, weather data, occupancy patterns, and the electricity tariff evolution, the settings of operating

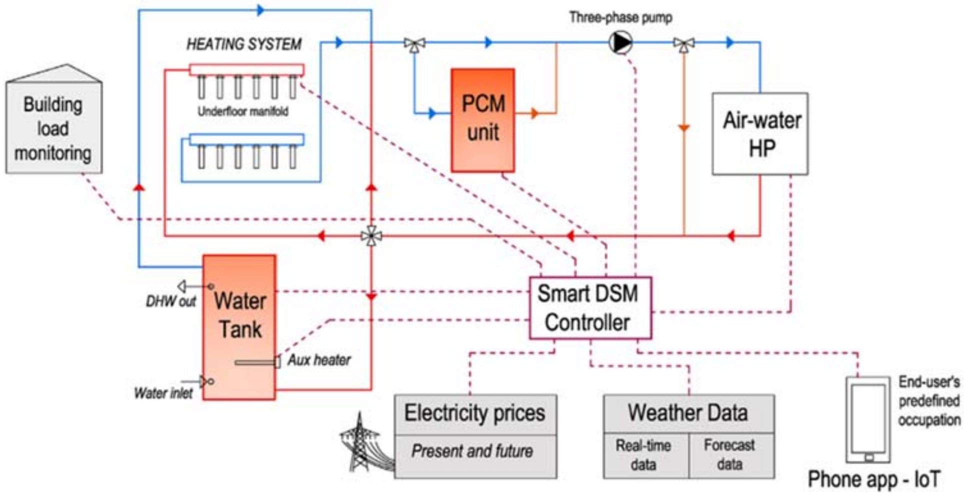

FIGURE 10.1 Heating and domestic hot water supply system presented in Ref. [4].

parameters and modes of the system were optimized to reduce building power consumption during the high electricity price periods. The results from the one-year simulation showed that the electricity bills of both the end-users and retailers were reduced, although there was a slight increase in the final energy consumption when this new control strategy was implemented. Liu et al. [5] integrated a cold energy storage tank within an HVAC system to achieve cooling energy flexibility. During the period of the "valley" electricity price, considerable cooling energy from chilled water was used to charge the storage tank. During the peak electricity price period, the storage tank was discharged to meet the building's thermal load and reduce the power demand. The results showed that the average-to-peak ratio of the HVAC power consumption increased from 40.9% to 83.3%. Similarly, Hammer et al. [6] improved the energy flexibility of a district heating network using decentralized heat storage systems to switch off the heating networks during the low load period and the demand can be served by the previously charged heat storage system. In doing so, it can avoid system operation at a low-temperature difference and thus a low efficiency during the low load period. The one-year simulation showed that annual network losses could be reduced by up to 34%.

Sehar et al. [7] improved the building energy flexibility of an office building using PV, ice storage integrated with packaged air-conditioning units, and end-use loads. DR strategies were developed according to the demand reduction signal and different working conditions. The results showed that the proposed DR strategies can achieve both building peak demand reduction and energy consumption reduction. The use of ice storage increased the total energy consumption of the building however it contributed to a significant reduction in peak demand. In Ref. [8], PV panels, a heat pump, a thermal storage system, an electrical energy storage system, and shiftable loads were used as the flexible sources (Fig. 10.2) to improve building energy flexibility. A cost-optimal control was used to minimize electricity cost by employing spot electricity price and reducing the grid

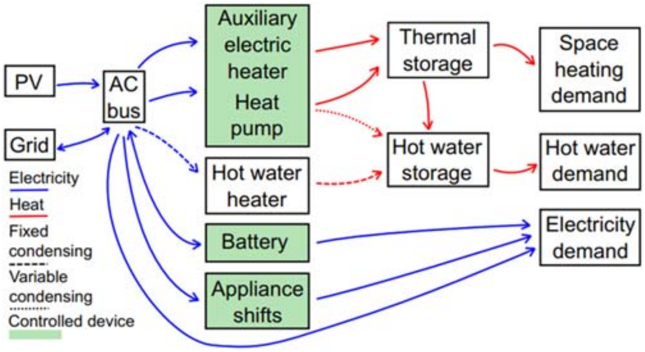

FIGURE 10.2 Flexible energy sources and energy flows in the system used in Ref. [8].

power import, while a rule-based control was used to maximize PV self-consumption. It was revealed that the proposed strategy can reduce annual electricity costs by 13%–25% as compared with the reference control which employed a constant electricity price.

Ren et al. [9] proposed 40 alternative designs to combine the utilization of a photovoltaic-thermal (PVT) system, a heat pump, a phase change material (PCM) thermal storage system, and different demand-side management strategies to improve the energy flexibility of a net-zero energy house. The results showed that PV power can provide 79% of heat pump energy consumption when an appropriate demand-side management strategy was considered. Using thermal energy storage could further increase solar contribution to nearly 100%. Shakeri et al. [10] presented an energy management strategy that purchases electricity for battery charging during off-peak hours, while during peak hours, the battery released the stored energy to buildings. Concurrently, temperature setpoints of air-conditioning systems were optimized to reduce power consumption. It was shown that the proposed strategy can reduce operational cost with a minimum sacrifice in thermal comfort.

Niu et al. [11] studied the flexibility potential of building cooling systems with building thermal inertia and battery storage. A mixed-integer linear model was developed to optimize dispatching and the operating cost of building energy systems. However, a case study using this method for cost reduction showed that the unilateral pursuit of maximum operational cost reduction resulted in a large peak-valley difference in the power import from the grid.

In Ref. [12], the flexibility of an HVAC system using building thermal mass was investigated. A daily cost-optimal strategy was developed to optimize the parameter settings for preheating, precooling and night ventilation according to operating conditions and electricity tariffs. This strategy was implemented in five different residential buildings, and the results indicated that this strategy can achieve 18.1%–26.1% energy savings using optimized insulation thickness and good quality windows. Lu et al. [13] proposed a rule-based control strategy to improve the energy flexibility of a cooling system using building thermal mass as energy storage in an office building. A lower indoor air temperature was used to charge the building thermal mass during the off-peak periods and the thermal mass released the stored heat to the building during the peak periods. It was reported that the flexibility provided by thermal mass was significantly influenced by the thermal capacity of the building structure, internal heat gains, and the types of cooling terminals used, rather than the envelope insulation levels. However, a different conclusion was obtained in a case study of indoor heating in a Danish house, where building heating energy flexibility using thermal mass as a flexibility measure was studied [14]. The setpoint of the HVAC system was increased to accumulate heat in the thermal mass when the electricity price was low, and the setpoint was decreased to reduce power consumption during high electricity price periods. It was shown that the envelope insulation level was an essential factor affecting the heating energy flexibility. In addition, indoor items and furniture also played a significant role in enhancing energy flexibility, which can achieve an increase of up to 21% in the energy flexibility potential for the building with a low thermal mass envelope. Foteinaki et al. [15] presented a method that can shift the energy use of district heating systems from peak electricity tariff hours to low ones. The setpoint was increased to store heat in the building's thermal mass when the electricity price was low. Likewise, the setpoint was decreased to release the stored heat when the electricity price was high. It was shown that preheating was a highly effective method in building demand shifting and peak demand reduction. The proposed method can achieve an energy consumption reduction of up to 87% during morning peak hours.

Considering that both building thermal mass and decentralized thermal energy storage systems can facilitate flexible energy dispatching in buildings, some studies focused on using these two measures together to enhance building energy flexibility. In Ref. [16], a partial thermal storage system that can cover a fraction of daily space heating demand was integrated with a direct electric space heating system in combination with building thermal mass to improve building operational flexibility. A DR strategy was designed to shift the power demand from the peak price hours to off-peak. An unusual winter day with a lot of volatility in spot prices was used in the performance testing of this strategy. It was found that building thermal inertia and the partial thermal storage system with a storage capacity of 20% of the full day thermal demand can contribute to a 38.2% energy saving.

10.2.2 Case studies using electrical appliances as the main flexible measure

Electrical appliances have been used as an effective measure to improve building energy flexibility due to their time-shiftable nature. Fig. 10.3 shows the operation characteristic of the time-shiftable devices, where red boxes indicated the original user-preferred start time and green boxes presented allowable delays, providing "flexibility windows" for the operation of the appliances. These flexible windows can enable schedule optimization of the appliances and thereby reduce the operation of these appliances during peak hours. On the supply side, PV and batteries were commonly used as flexibility measures in buildings, where PV represents renewable power generation that can reduce the grid power consumption and the operation of the battery can achieve temporal energy shifting and balance supply and demand in energy networks.

Zhao et al. [18] proposed a convex optimization algorithm to minimize the electricity cost and the peak-to-average ratio (PAR) of power consumption of electrical appliances. This method adjusted the operating power of the adjustable appliances considering the

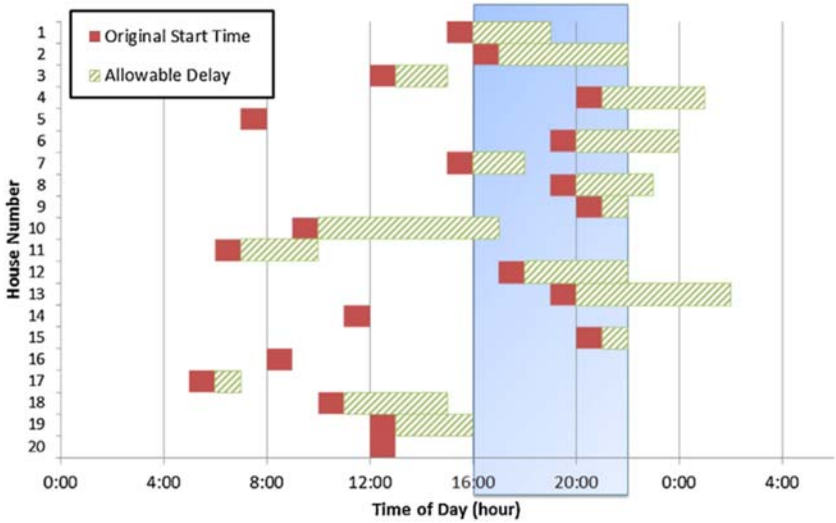

FIGURE 10.3 Acceptable delays of using different electrical appliances at different hours, where the blue box indicated the peak demand period [17].

usage profile of those nonadjustable ones and the real-time electricity price by solving the convex objective function at each time interval. The results showed that this algorithm can effectively reduce the electricity cost and the PAR of power consumption of the appliances. D'hulst et al. [19] conducted a large-scale pilot test to investigate the flexibility potential of delayable and buffered appliances in residential buildings. In this study, 418 delayable and buffered appliances were selected from 186 households to support "flexibility window" based operation. Two scenarios were used as the reference electricity consumption to investigate the flexibility potential at different periods. The first scenario was to postpone the use of all appliances as much as possible and the second scenario was to use all the appliances as early as possible according to the given flexibility window. The results revealed that the thermal buffered appliances and electric vehicles showed a significantly higher flexibility potential than the wet appliances (e.g., dishwashers, washing machines) in DR programs.

10.2.3 Case studies using other flexible sources and measures

Energy sharing among different buildings is another area of interest to increase energy flexibility. For instance, waste heat collected from data centers can be used to provide heating directly, or potentially used to drive cooling systems (e.g., liquid desiccant cooling) for neighborhood buildings. Appropriate DR strategies along with thermal energy storage systems can greatly increase the level of operating flexibility via appropriately using the waste heat collected. Ma et al. [20] proposed an energy management model to control the operation of PV and electrical appliances in a group of buildings, where all participating buildings can share their generated power or feed the power back to the grid when the PV generation was surplus. It was reported that the proposed model reduced the peak-valley difference in the net building load more reliably than the scenario where the participating buildings were independently considered for load shifting, which was found to result in even larger peak-valley differences when compared with the original curve.

Some studies aimed to improve energy flexibility by analyzing occupant behavior and electricity consumption patterns in buildings. Afzalan and Jazizadeh [21], for instance, proposed a data-driven segmentation approach to identifying user consumption patterns. A metric that considered different load features was proposed to identify users with load shifting and shedding potential. A total of 360,000 households in Austin were used as a city-scaled assessment. It was estimated that when 20% of households with high demand reduction potential participated in a DR event, significant energy reductions were possible across end uses, for example, air-conditioning units (100.2 MWh), electric vehicles (41.7 MWh), dryers (11.2 MWh), dishwashers (3.2 MWh) and washing machines (1.8 MWh).

Perez et al. [17] proposed a centralized model predictive control method to minimize the HVAC peak power consumption by adjusting the thermostat setpoints in individual homes of a community. Meanwhile, the operating schedules of the time-shiftable appliances were optimized to reduce the peak power consumption of the community. It was found that adjusting thermostat setpoints alone can achieve an 18.8% reduction in the peak electricity consumption and shifting the use of appliances can reduce the peak load by 5.1%.

The main findings from the foregoing studies are summarized in Table 10.1. The above results demonstrated that flexibility in buildings significantly relies on the use of energy storage systems, such as batteries, thermal storage systems, and building thermal mass. DR strategies can be developed to shift building demand from peak hours to off-peak hours by appropriately using energy flexibility offered by different energy flexible sources. Although in some cases, energy flexibility based on these measures was restricted by some factors, such as indoor thermal comfort requirements, uncertainty in building demand variation, and urgent requests from the power grid. Nevertheless, energy flexibility is a useful and important resource to manage building demand and ultimately support power grid operation.

10.3 Energy flexibility analysis of a case study building

10.3.1 Description of the case study building

The object of the study is the Sustainable Buildings Research Center building at the University of Wollongong, Australia. This net-zero energy office building has a total floor area of 2600 m^2, comprising two interconnected wings, as shown in Fig. 10.4.

The southern wing has two stories, with an open-plan office on the first floor and the ground floor consisting of exhibition space, laboratories teaching spaces, and amenities. The northern wing accommodates a high bay laboratory space, which is naturally ventilated. To achieve net-zero energy consumption, a wide range of renewable energy technologies and energy-efficient systems were used including a mixed-mode HVAC system controlled by occupancy, PV arrays, a PV-thermal system, a ground source heat pump system, an air source heat pump system, thermal slabs, cool roofs, and transpired solar

TABLE 10.1 Summary of findings from a range of studies on improving building flexibility using different energy flexible systems, including building thermal mass (BTM), electrical appliances (EAs), occupant behaviors measures (OB), energy storage (ES), and renewable energy power generation systems (RE).

		Energy flexible systems/ measures implemented							
Refs.	**Buildings**	***HVAC***	***BTM***	***EAs***	***OB***	***ES***	***RE***	**Objectives/DR strategies**	**Results**
[2]	Commercial buildings	√						Shut down some chillers to reduce power consumption during short DR events and properly control the temperatures of different zones	Energy savings during the DR event were 15.3% and a fast power reduction of 39% was achieved once the proposed DR control was activated
[3]	100 residential houses	√						Optimize the operation schedule of the HVAC systems considering electricity tariff, forecast weather data, indoor thermal comfort, etc.	Reduced the average electricity cost of the HVAC system on a test day from $3.55 to $3.27
[4]	A Scottish residential building	√				√		Shift demand from peak hours to off-peak hours by considering restrictions on environmental conditions, electricity tariffs, and expected occupancy patterns	Reduced the electricity for consumers (20%) and retailers (25%)
[5]	A commercial building	√				√		Shift electricity demand of the chiller from peak to off-peak hours using thermal storage tanks	Increased the average-to-peak ratio of chiller power consumption from 40.9% to 83.3%
[6]	District heating networks	√				√		Temperature setpoint control to reduce thermal loss in small load conditions	Reduced total network heat consumption by up to 6%
[7]	An office building	√		√		√	√	Reduce energy and peak power consumption based on combinations of DR, PV, and an ice storage system	The highest peak load reduction was 89.5%
[8]	A low-energy house	√		√		√	√	Appropriate control to minimize the system operational cost and maximize PV self-consumption	The PV power self-consumption can reach 88%
[9]	A net-zero energy house	√				√	√	Reduce building energy consumption and operational cost by using demand management strategies, based on PVT, a heat pump, and a thermal storage system	The use of PVT and PCM storage can improve solar contribution to the power consumption of the heat pump by up to 100%

(*Continued*)

TABLE 10.1 (Continued)

		Energy flexible systems/ measures implemented							
Refs.	**Buildings**	***HVAC***	***BTM***	***EAs***	***OB***	***ES***	***RE***	**Objectives/DR strategies**	**Results**
[10]	A residential house	√		√		√	√	Battery charge and discharge along with temperature setpoint adjustment of thermal appliances according to the time of use (TOU) electricity prices	Reduced 20% of daily electricity cost
[11]	A factory building	√	√			√	√	Battery charge and discharge along with optimizing the temperature setpoints of the HVAC system according to TOU electricity prices	Using a battery can achieve 5.3% of operational cost savings and using building thermal mass can further contribute to 4.0% of cost savings
[12]	Five residential buildings	√	√					Optimize parameter settings for preheating, precooling, and night ventilation according to user occupancy and electricity tariff	Reduced the heating cost (3.2%) and the cooling cost (8.5%)
[13]	A nearly zero-energy office building	√	√					Charge or discharge thermal mass through controlling the indoor temperature setpoint of HVAC systems to reduce the power consumption during peak hours	Reduced peak power consumption by 55.6%
[14]	A Danish house	√	√					Indoor temperature setpoint control according to the external price signal in a building with PCM wallboards	Achieved up to a 35% increase in the energy flexibility index when the house was built with a high-insulation and lightweight envelope
[15]	An apartment block	√	√					Indoor temperature control shifts heating load from peak load periods to less expensive heat production periods	Achieved up to 87% reduction in energy consumption in morning peak hours
[16]	A simulated house	√	√			√		Shift power demand from peak price hours to low-cost hours based on available storage systems	Storage size of 40% of the full day heating demand achieved 46% energy cost savings
[17]	A group of 40 houses	√		√				Use model predictive control to minimize the HVAC peak power consumption by adjusting thermostat setpoints and rescheduling the operation of electrical appliances	Reduced the average daily peak load by 25.5% for a group of 40 houses

(*Continued*)

TABLE 10.1 (Continued)

		Energy flexible systems/ measures implemented							
Refs.	**Buildings**	***HVAC***	***BTM***	***EAs***	***OB***	***ES***	***RE***	**Objectives/DR strategies**	**Results**
[18]	A residential site	√		√				Change operation of adjustable appliances according to price signals considering power usage profiles of nonadjustable appliances	Reduced the cost by 25% and the PAR of electricity consumption by 63%
[19]	Residential buildings in Belgium			√				Reschedule the operation of postponable appliances	Postponable appliances per household can increase power consumption by up to 430 W at midnight and can reduce the power consumption by 65 W in the evening
[20]	Smart building cluster			√			√	Price-responsive strategy to control PV power distribution and the scheduling of appliances	Reduced the total cost of the building cluster by 4.6% when the shiftable loads accounted for 25% of the total load profile
[21]	Residential buildings in Austin	√		√	√			Use load pattern identification and user segment to evaluate load shifting/shedding potential	160 MWh power consumption can be reduced through 20% participation of the selected flexible loads during a 2-h event

collectors (TSC). The PV arrays consist of 596 panels with a capacity to generate 160 kW at the design conditions. An electrical energy battery with a capacity of 39.6 kWh was designed to increase building energy flexibility. Among these systems, the PV arrays, PV-thermal system and TSCs are driven by solar energy and are the potential flexible sources of the building. The building has a mixed-mode ventilation system consisting of natural ventilation through a window modulation system and mechanical ventilation through an air distribution system. The building is also equipped with an electric vehicle charging station with two DC fast chargers, as shown in Fig. 10.5. The control of the building energy systems is achieved through a Building Management System (BMS).

The energy consumption of the building is segmented into computer power, lighting power, HVAC power, plug-in power (including electric car charging power and experimental facility power), and other power including lift power, overhead crane power, etc. The breakdown of energy consumption by different systems is shown in Fig. 10.6, which

FIGURE 10.4 Illustration of the case study building.

FIGURE 10.5 Electric car charging station.

was generated based on one-year data from 2021. It can be observed that the HVAC system is the largest energy consumer of the building, consuming 41.3% of total building energy, followed by plug-in power (21.8%), computers (15.3%), lighting (11.9%), and other power (9.7%). Fig. 10.7 illustrates the energy usage profile of each energy system on a work day (using the electricity consumption data of 9 February 2022). It can be observed that the HVAC system consumes more power during the daytime and electric car charging can result in short-duration peak power consumption. The peak power of the HVAC system can reach 50 kW, and electric car charging can enlarge this value to around 80 kW. When comparing the magnitudes of segment energy use (e.g., HVAC power to lighting

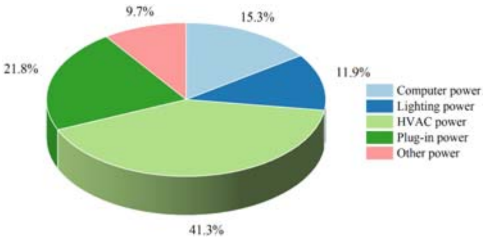

FIGURE 10.6 Breakdown of energy consumption of the building.

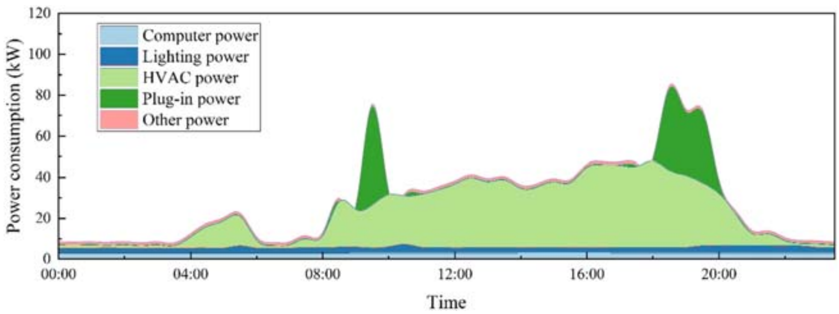

FIGURE 10.7 Daily power consumption profiles of different energy systems (stacking).

power) it is important to remember that the building is a highly advanced net-zero energy building, and not a typical commercial or office building.

10.3.2 Energy flexibility analysis

Energy flexibility potential can be quantified either using building simulation tools or monitoring data from BMSs. While the case study building is equipped with several energy flexible systems, in this analysis only the energy flexibility offered by PV panels and the electric battery was quantitatively analyzed. Energy flexibility offered by other systems such as thermal slabs, natural ventilation, PV-thermal system, and TSCs was briefly discussed. The overall method used in this analysis is shown in Fig. 10.8. In the first step, the energy flexible sources were identified from the available energy systems using domain knowledge. Once identified, historical time series data for the energy flexible systems and building demand were collected from the BMS. Data cleaning was then implemented to detect outliers and fill in missing data. As different time intervals were used to record historical data of different energy systems, linear interpolation was used to process the datasets and synchronize time intervals and timestamps. In the second step, the flexibility indicator(s) were first selected and the energy flexibility quantification method was then formulated. Based on the available flexibility, a DR strategy was also designed to enhance PV power self-consumption and shift the grid power demand from peak periods to off-peak periods as much as possible. After implementing the DR strategy, the results were generated and interpreted in the last step, and the flexibility potential was evaluated using the flexibility quantification method and flexibility index used.

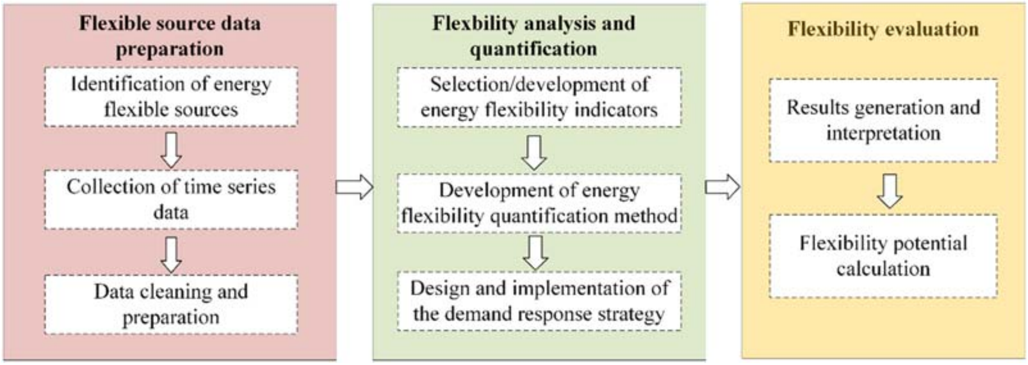

FIGURE 10.8 Energy flexibility analysis method.

10.3.2.1 Flexibility indicators and quantification method

The flexibility indicator used in this study is presented in Eq. (10.1) [14]. This indicator can provide an overall insight into how much energy can be shifted during a DR event and quantify the energy flexibility level after implementing the DR strategies. It is noteworthy that in some studies, multiple flexibility indicators were used to quantify building energy flexibility. In these cases, a flexibility quantification function should be developed to aggregate these indicators into a flexibility matrix or factor. Furthermore, building energy flexibility quantification methods need to consider a range of factors such as operating constraints (e.g., indoor thermal comfort), flexibility types (e.g., load shifting, load covering, load shedding, load modulation), and external conditions (e.g., weather conditions), so that the quantification results can provide an insight into how much a certain type of flexibility can be achieved under specified operational constraints and external conditions. However, the development of a detailed quantification method that simultaneously considers the above factors is still an open research problem, and thereby such a quantification method was not considered in this study. Since only one indicator was used in this analysis, this indicator was directly used as a flexibility quantification function to evaluate building energy flexibility.

$$F = \frac{1}{2}\left[\left(1-\frac{E_{\text{high}}}{E_{\text{high, ref}}}\right)+\left(1-\frac{E_{\text{medium}}}{E_{\text{medium, ref}}}\right)\right]\times 100\% \quad (10.1)$$

where E_{high} and E_{medium} are respectively the energy used during peak and shoulder price periods when the flexible operation is enabled, $E_{\text{high, ref,}}$ and $E_{\text{medium, ref}}$ are the energy used during peak and shoulder price periods without implementation of energy flexible measures (i.e., reference scenario). The flexibility index becomes zero if the energy use in the scenario implemented with flexibility measures equals that in the reference scenario, which indicates that the flexibility measures implemented do not improve building energy flexibility. If grid power is not consumed during peak and shoulder price periods after implementing the flexibility measures, the flexibility index becomes 100%, which means that the system has achieved full flexibility under the current electricity tariff.

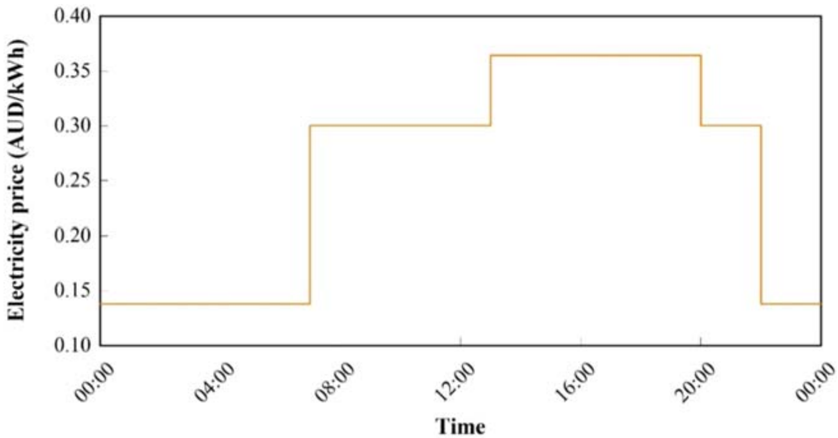

FIGURE 10.9 TOU electricity prices used in Wollongong, NSW, Australia [22].

10.3.2.2 Time of use electricity prices

The TOU electricity prices are the main indicator of the congestion level in the electrical networks and motivate consumers to adjust electricity consumption. TOU electricity prices are therefore a key consideration in the control strategy design to flexibly reduce the power network congestion and building operational costs. The TOU electricity prices for small business buildings in Wollongong, New South Wales (NSW), Australia were used in this analysis and they are illustrated in Fig. 10.9.

10.4 Flexibility demonstration and discussion

10.4.1 Energy flexibility improvement using photovoltaics and electric battery

The PV system and the electric battery were selected as flexible measures as a simple demonstration of analysis and quantification of energy flexibility. In this example, a rule-based control strategy was designed to maximize the PV electricity self-consumption and reduce the grid power consumption during peak and shoulder hours. This control strategy enables the system to charge the battery using grid power during the off-peak hours or surplus PV power during shoulder hours, and utilize the energy stored in the battery during the peak and other shoulder hours when PV generation is insufficient to minimize electricity costs. It is noteworthy that the stored power was not prioritized to be used only during peak hours. Instead, the battery was discharged when PV generation cannot meet building demand either during shoulder hours or peak hours, whichever comes first, although this was not the optimal way to use the stored energy in the battery. To increase energy flexibility, the following assumptions were used.

- PV power will be supplied to the building to meet the electricity demand when the PV power is available. Any surplus will first be used to charge the battery and the extra power will be fed back to the grid once the electric battery is fully charged.

- If available PV power cannot meet building energy demand, the battery will be discharged to supply a fraction of the building energy demand. Once the battery is fully discharged, grid power will then be used to provide additional power to meet the demand.
- During the off-peak hours, if it is predicted (ideal prediction was assumed in this study) that the PV generation during the shoulder and peak hours will be much less than the demand during these hours and the battery has not been fully charged, the grid power will be used to charge the battery to reduce the grid power consumption during peak and/or shoulder hours.

Based on the control strategy and the TOU electricity price mentioned above, the historical data of the building electricity consumption and PV power generation from 31/01/2022 to 04/02/2022 was used to illustrate how to evaluate building energy flexibility potential. The building electricity demand and the PV power generation profiles for the five consecutive days are illustrated in Fig. 10.10A). It can be seen that both the electricity demand and the PV power generation were much higher during the daytime (i.e., the periods with peak or shoulder electricity tariff) than that during the nighttime. The building is primarily occupied during the day, and as a net-zero energy building, the PV generation should exceed consumption. The PV generation cannot, of course, provide power to meet demand without sunlight overnight or on cloudy days such as the third day in Fig. 10.10A.

To demonstrate the opportunity of using PV and the electric battery as flexible measures to increase energy flexibility and PV self-consumption and reduce the grid power, three different scenarios were considered in this study for comparison. In Scenario I, neither PV nor battery was used as an energy flexible measure while in Scenario II only PV was used as an energy flexible measure. In Scenario III, both PV and the battery were used as energy flexible measures. The grid power consumption profiles under these three scenarios are presented and compared in Fig. 10.10B, in which positive values indicate power import from the grid while negative values indicate PV power export to the grid. It can be seen that in Scenario II the grid power consumption was significantly reduced when compared with that of Scenario I. PV power can meet the majority of the building's electricity demand during the daytime, and extra PV generation was fed back to the power grid in Scenario II. However, during the peak demand hours on some days, the PV power cannot meet the building demand due to low solar radiation. The comparison between Scenario II and Scenario III showed that the use of the battery further reduced the grid power consumption during shoulder and peak hours and also increased the self-consumption of the PV power. This can thereby result in the lowest grid power consumption among all the scenarios considered. The battery charging and discharging processes during the five days are presented in Fig. 10.10C with positive values for battery charging and negative values for battery discharging. It can be observed that the battery was charged when there was extra PV power and all the stored power was released and supplied to the building when the PV power was not enough to meet the demand, which increased the self-consumption of the PV power. On the days when it was predicted that there would be no extra PV power to charge the battery (e.g., third day), the battery can be charged during the off-peak hours by using the grid power, and the stored power was released during the shoulder hours to reduce the consumption of the grid power with a higher electricity price. Again, this may not be optimal as in this case, the battery may have

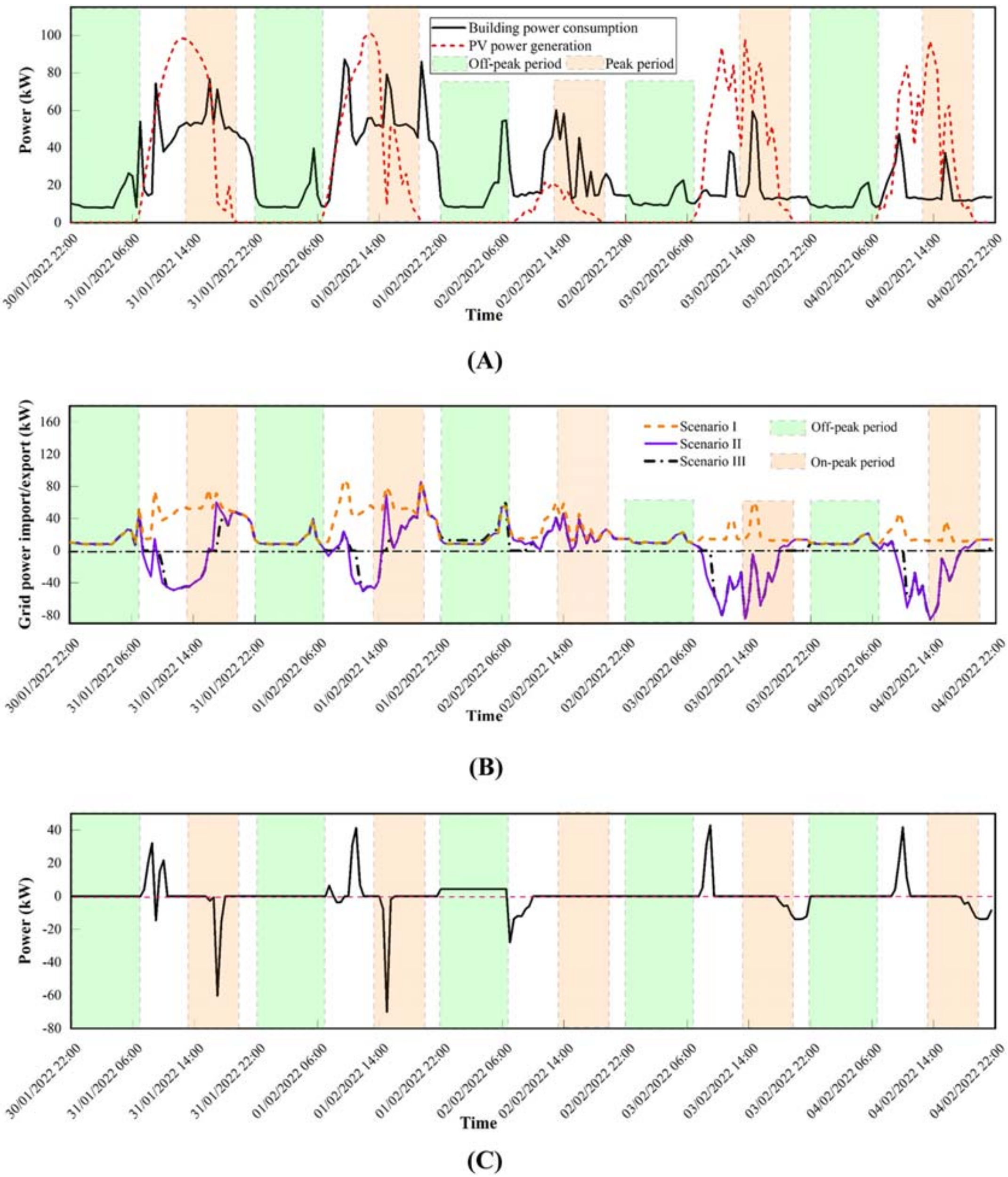

FIGURE 10.10 Simulation results under three different flexibility scenarios: (A) Five-day electricity demand profile of the building and power generation profile of the PV system; (B) grid power consumption profiles under three different scenarios; (C) electric battery charging and discharging profiles when using PV and battery as the flexible measures (Scenario III).

already been fully or partially discharged during the shoulder hours and may not be able to provide sufficient power required during peak hours.

The grid power consumption during shoulder, peak, and off-peak hours in the proposed three scenarios is compared in Fig. 10.11A. It can be observed that the use of PV can significantly reduce the grid power consumption during shoulder and peak hours because of the large PV power generation during these periods. The use of the battery can further reduce the power consumption during shoulder and peak hours since it can store part of the extra PV power when the PV power is surplus or store grid power during off-peak hours and use it during peak and shoulder periods. As shown in Fig. 10.11B, Scenario III which used both PV and battery can increase PV self-consumption and reduce grid export by 169 kWh compared with Scenario II using PV alone during the shoulder hours.

Under Scenario III, PV alone can achieve a flexibility index of 61%, and the use of the battery can further contribute a 9% increase. The use of the PV system alone can improve flexibility by reducing the grid power consumption during peak hours but integrating the PV with the battery can result in reduced peak power consumption and also contribute to achieving the following benefits. Firstly, a fraction of electricity demand from shoulder or peak hours was shifted to off-peak hours, thereby further reducing grid power consumption during shoulder or peak hours. Secondly, a fraction of extra PV power was stored in the battery when the PV generation was surplus during the shoulder hours and the stored energy was used during peak or other shoulder hours.

It is noteworthy that, in this study, the flexibility potential of the case study building was quantified using a single flexibility indicator, which indicated the amount of energy that can be shifted during a DR event. However, there are also other flexibility indicators focusing on different performance aspects, such as response time which focuses on how much time a flexible system can last in response to the grid power requirement, and committed power which quantifies the potential of power reduction during a DR event [23]. In many cases, multiple flexibility indicators may be required and in that case, a trade-off has to be made to balance different performance objectives.

10.4.2 Improving building energy flexibility using other flexible systems

As indicated in Table 10.1, the use of HVAC systems has shown great potential in improving building energy flexibility via load shifting and demand reduction. Within the case study building there are two identical ground source heat pumps (Fig. 10.12) and one air source heat pump that were used to provide hot and cold water used in air handling units, variable air volume units, and a thermally activated slab system on the first floor of the building (Fig. 10.13).

There are three different opportunities using the HVAC system to enhance the energy flexibility of the building.

- Load shifting via preconditioning the building during off-peak hours: Using the HVAC system and thermal slabs during the early morning period (i.e., off-peak hours) to precondition the building will shift part of the HVAC energy consumption from peak and shoulder periods to the off-peak ones.

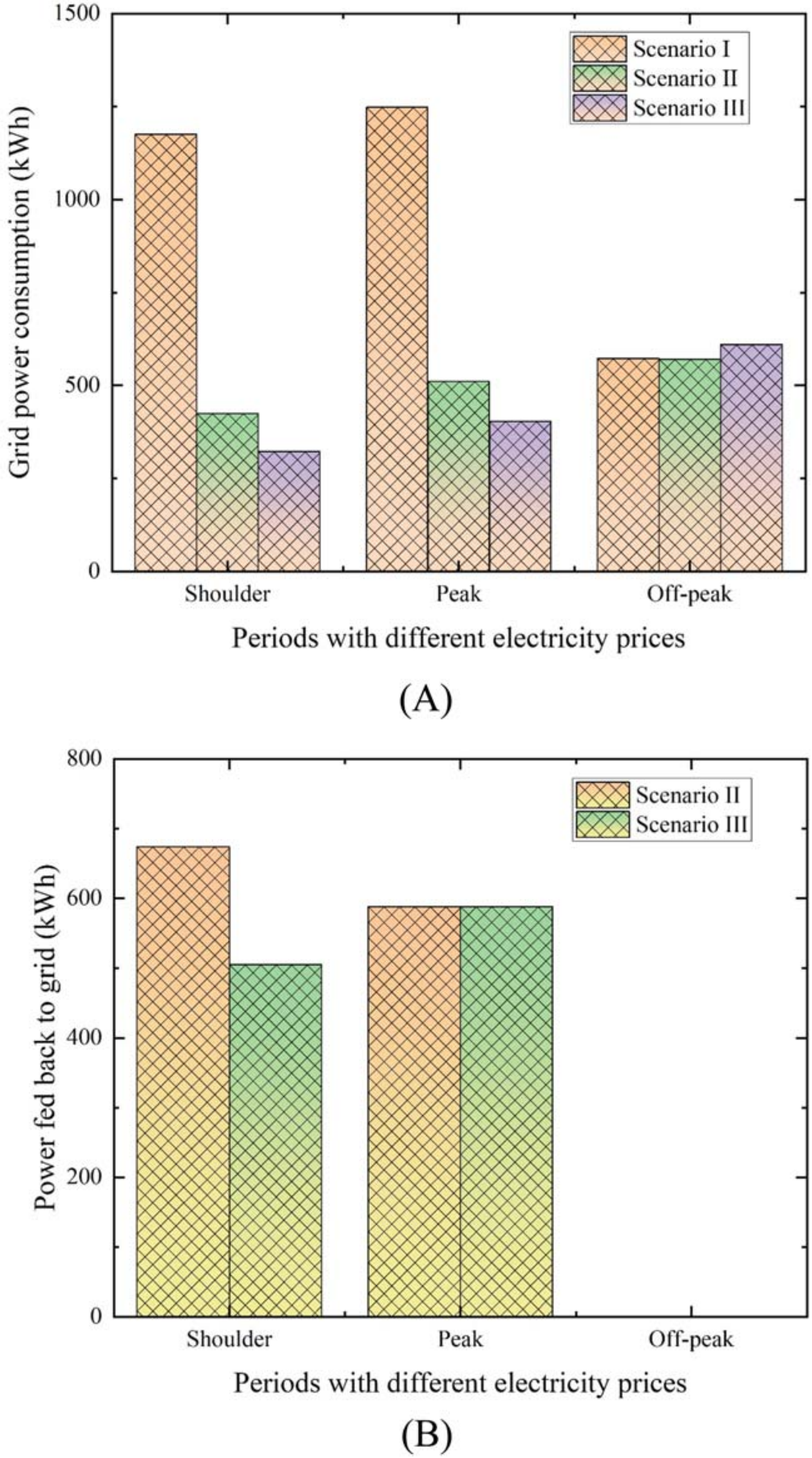

FIGURE 10.11 Comparison of flexibility performance between different scenarios: (A) power consumption during different periods under different scenarios; (B) power fed back to the grid during different periods under different scenarios.

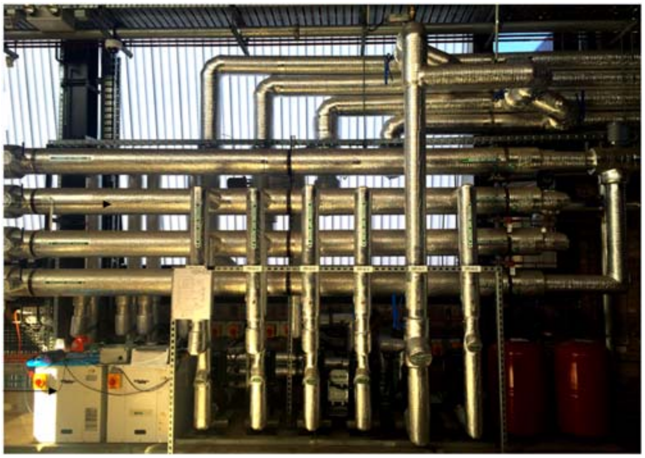

FIGURE 10.12 Ground source heat pumps and HVAC water distribution system.

FIGURE 10.13 Thermal slabs during installation under the first floor of the building.

- Load shifting via the use of the thermal mass of the conditioned space: The HVAC system can achieve this in winter by increasing the indoor temperature setpoint during the shoulder hours, and then lowering it during peak hours. Consequently, the indoor air temperature can drop to, or even slightly below the original setpoint as the thermal mass of the space discharges, and thus the HVAC system will reduce heating input. The same approach can be used during summer cooling conditions, albeit by reducing the indoor temperature setpoint first. With careful management, the indoor temperature can be controlled between the upper and lower thermal comfort limits during the whole process. Thermal slabs can also perform this function due to their large natural inertia, offering greater potential for increased energy flexibility.
- Demand reduction via natural ventilation: The case study building is located on the east coast of Australia (34S, 151E) and experiences a mild climate throughout the whole

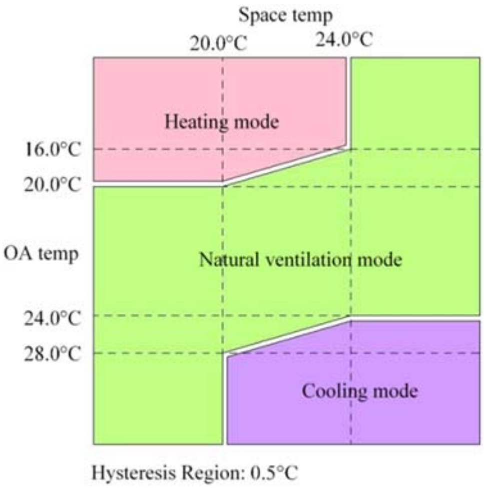

FIGURE 10.14 Building ventilation control strategy.

year. Natural ventilation is used with a mixed-mode HVAC strategy to increase building energy flexibility and reduce operational costs through automatic window modulation and the use of outside air in air handling units. The mixed-mode ventilation control strategy is shown in Fig. 10.14. Natural ventilation is enabled when the outside air is within the defined comfort band (in this case 20°C−24°C) or in the unusual cases that the building is too hot in winter or too cold in summer. Outside of these cases mechanical ventilation is activated, providing heating or cooling to the building through an air distribution system. In the natural ventilation mode, the window position is set in proportion to the amount of outside air required to bring the space to the center of the comfort band (22°C), and this is modified by the presence of high winds or wind with rain.

The building is equipped with a TSC (Fig. 10.15) on one section of the north-facing wall of the building. The TSC system was developed based on a solar wall cavity, which is around 100 mm deep and consists of two sections including a small section (1.8 m wide) on the east side and a large section (3.3 m wide) on the west side, respectively. The exterior of the TSC was made of perforated corrugated steel sheets, on which a matrix of small holes with a diameter of 1.35 mm was used for air intake. The back wall of the TSC was insulated by laminating an insulation layer of 200 mm to reduce the heat loss of the TSC to the indoor space.

Although the TSC system installed in the building is a small-scale system for demonstration purposes, in principle, this technology can be used to increase building energy flexibility and reduce building energy consumption. For instance, under the right conditions (e.g., sunny but cool winter day), TSC will harvest solar energy at a very low energy cost, reducing the energy demand of the HVAC system. During summer nighttime, it can be used for precooling the building so that a fraction of cooling demand during daytime can be shifted to nighttime. If it is appropriately designed and integrated with buildings with high thermal mass or buildings incorporated with PCMs, a high level of energy flexibility can be achieved by using the energy storage capability of building envelopes.

FIGURE 10.15 Illustration of the TSC system installed in the building.

FIGURE 10.16 The rooftop PVT system installed in the building.

The building is also equipped with a roof-mounted air-based PVT system, as illustrated in Fig. 10.16. Similar to the TSC system, the thermal energy harvested by the PVT system can be directly used for space heating when needed and in this case, it is supplied to the first-floor space via an air handling unit. It also offers the potential to be used to drive desiccant air-conditioning systems for space cooling [24] or facilitate building ventilation [25]. The PVT system also generates power as a normal PV system, supplying building power demand and increasing power self-sufficiency. PVT technology can also be used in combination with thermal energy storage or electrical energy storage to further increase the energy flexibility potential of the building.

Cool roofs are roofing materials with high values of total solar reflectance and high thermal emittance and have shown great benefits in reducing HVAC energy consumption and improving indoor thermal comfort in cooling-dominated climates [26]. Two cool roof products with different coating materials were implemented on the rooftop of the high bay laboratory space. Although the cool roofs did not contribute to reducing the HVAC energy consumption of this building as the high bay workshop space is naturally ventilated, the cool roofs installed can reduce heat transfer to the building during hot summer days and thus assist in maintaining good indoor thermal comfort. In principle, this technology can enhance the level of building energy flexibility when used in appropriate climate zones in combination with HVAC systems.

10.5 Summary

This chapter first provided an overview of the existing case studies focusing on improving energy flexibility in buildings. A wide range of energy flexible resources such as PV, battery, thermal storage, thermal mass, and HVAC systems along with different DR strategies have been investigated and used to improve building energy flexibility. The energy flexibility potential of a net-zero energy office building using PV and an electric battery was quantified and the energy flexibility potential offered by other energy flexible systems was discussed. A DR strategy was also used to increase PV self-consumption and reduce grid power consumption. It was found that the PV system can improve the flexibility index by 61%, largely reducing power consumption during peak hours and shoulder hours. The use of a battery along with PV can further increase the flexibility index of the building up to 70%. This analysis showed appropriate use of energy flexible systems in buildings can greatly increase their operating flexibility and achieve significant cost savings.

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CHAPTER

11

Energy flexibility in grid-interactive and net/nearly zero energy buildings

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Building energy flexibility can not only reduce the energy demand and fossil energy consumption of buildings but also assist in the stable operation of the power grid and the consumption of renewable energy. It is one of the important technical paths to reduce the overall social carbon emissions. This chapter first discusses the market mechanisms and flexible interaction between buildings and power grids, and the research and application of building load regulation for increased energy flexibility are then explored. Current challenges and opportunities related to building energy flexibility are also discussed. As a demonstration, the engineering design, construction, and operation of a nearly net zero energy building are then introduced by analyzing the application characteristics and key technologies used to increase building energy flexibility and achieve nearly net zero energy consumption.

11.1 Background

11.1.1 Demand for flexible resources of power grids

The construction of new power systems with renewable energy as the main energy source is an important direction for the transformation and upgrading of existing power systems. It is also a key approach to achieving the strategic goal of "carbon peak and carbon neutrality." The large-scale access to renewable energy sources will lead to changes in power system characteristics. The power system must have strong and flexible adjustment capabilities to ensure that large-scale renewable energy sources are connected to the grid to achieve a balance of generation and consumption, and provide end-users with a stable and continuous power supply.

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The traditional supply and demand balance of the power system is dependent on the power supply side, and that is, the mode of "the source follows the load." In this way, the ability of a power plant to compensate for and adjust the fluctuation of renewable energy sources is very limited. For instance, restricted by resources, China's power systems have a shortage of flexible power sources. In 2019, flexible power sources such as gas and pumped power storage stations accounted for only 6% of China's installed power supply, far lower than 17.5% in Germany and 48.7% in the United States [1]. Therefore, traditional power generation has a large gap in flexible power resources, and it is more difficult to meet the regulation needs of new power systems with a high proportion of renewable energy in the future. The problem of the adjustable resource gap is particularly prominent in developed areas such as Shenzhen and Shanghai in China, where limited local power resources are available and have a high proportion of imported electricity [2].

On the other hand, buildings showed great potential for load adjustment as they can increase or decrease the power demand at a specific time. In buildings, loads such as air conditioning, fresh air systems, lighting, hot water systems, electric vehicle charging facilities, and uninterrupted power source energy storage showed superior regulation potential. With the rapid development of information and communication technology, the controllability of the power demand side can be significantly enhanced, and the load adjustment potential of the demand side can be tapped to realize "the load follows the source." This will become an important way to efficient consumption of renewable energy and safe operation of new power systems in the future.

As indicated in the previous chapters, buildings consume a large amount of global energy usage and this is particularly true for megacities, where the electricity demand from buildings accounts for a significant amount of the total electricity demand of the city [2]. In many cases, there is a high degree of overlap between the building peak demand period and the power grid peak generation time. If building energy flexibility can be appropriately used for load adjustment (e.g., load shifting, load shedding), it will offer great opportunities to support power grids to optimize their operations. Compared with the flexibility transformation of existing power plants, building energy flexibility is one of the flexible resources with the highest quality and has lower investment costs. As a natural aggregate of various flexible loads, public buildings are the "cornucopia" of flexible resources that can be tapped by new power systems.

Building load resources can be aggregated to form virtual power plants and participate in interactive services such as peak shaving, frequency regulation, and as backup power. Through load adjustment, the building load curve could match the peak-shaving and valley-filling demand of power grids. Taking Shenzhen, China as an example, the peak-shaving periods of the power grids are 10:00−11:00 and 15:00−16:00, and the valley-filling periods are from 4:00 to 6:00 [3]. Buildings can play a major role and provide high-quality adjustable resources by changing the peaks and valleys of the building load curve.

11.1.2 Development of net/nearly zero energy buildings

Building energy efficiency is one of the key resources to reduce building energy consumption and greenhouse gas emissions. However, building energy efficiency alone cannot achieve carbon neutrality in the building sector [3]. Over the last several decades, building practitioners have made significant efforts to develop and test the performance of various building energy-saving technologies. Traditional energy-saving technologies including passive and active ones, mainly emphasize reducing building energy consumption and improving self-supply by using renewable energy. For instance, active and passive energy-saving technologies such as high-performance doors and windows, external sunshades, high-efficiency air conditioners, energy-saving elevators, and energy-saving home appliances have been extensively used to reduce building energy consumption with various payback periods. In the meanwhile, building-integrated renewables have been widely used to improve building's renewable energy supply. However, the use of renewables in buildings highly depends on local climate conditions and available spaces. For instance, solar panels cannot generate sufficient electricity on cloudy or rainy days and there is no generation during the nighttime. This means that to fully cover the electricity demand, buildings should be grid-connected or should use electrical energy storage to meet power demand during the nighttime or in situations where solar radiation is not sufficient.

Promoting net/nearly zero energy buildings to participate in grid interaction has become an urgent need for building energy conservation and carbon reduction. Building energy efficiency is one of the important areas of dual-carbon work. For example, in April 2021, the China Academy of Building Research led the development of "Technical standards for zero-carbon buildings" [4]. Compared with previous building energy efficiency standards, this new standard introduced green power certification and carbon trading mechanisms in the definition of zero-carbon buildings. This change means that building energy efficiency has changed from "opening sources and reducing expenditures" to interacting with the power grid. The change of thinking allows buildings to achieve the goal of net/nearly zero energy operation by participating in the consumption of renewable energy on the grid side or the carbon trading market. Therefore, building-grid interaction technology is conducive to the coordinated development of new power systems and net/nearly zero energy building construction with significantly increased energy flexibility.

11.2 Research and application of building load regulation for increased energy flexibility

In recent years, with the rapid development of demand response programs and the advancement of power market reform, the significant load regulation potential of buildings is being continuously tapped to participate in the interaction of supply and demand in the power system. In the following subsections, a brief overview of the research and application of building load regulation is provided.

11.2.1 Texas building air conditioning load management project

Load management of building air conditioning in Texas, USA, is a typical example of load control in demand response. During the peak load in summer, the end-users can set an acceptable comfortable temperature range in advance according to their preferences. The installed automatic temperature controller can cyclically control the air-conditioning temperature of a large number of users in the building, and reduce the peak load without affecting the comfort of users. At present, Texas has installed 8600 smart thermostats, forming a load regulation capacity of about 90 MW [5].

11.2.2 Japan building automatic demand response project

Kyocera Corporation, Japan IBM Corporation, and Tokyu Community Group Corporation implemented an automatic demand response (ADR) project for building load control to balance power supply and demand. There was a total of 25 demonstration sites including 10 commercial facilities and 15 general residences in this project [6]. The ADR project was based on the international standard OpenADR2.0 profile for ADR. When the supply of the power system cannot meet the power demand, a demand response signal will be sent to the end-users. Once the building users receive the signal, the installed energy management system is then used to automatically control the power consumption. When the demand response is completed, the demand response status is then automatically reported. However, at present, most of the demand response projects in Japan are invitation-type demand responses.

11.2.3 Shanghai commercial building load regulation demonstration project

Shanghai Electric Power Co., Ltd. commenced to tap the load regulation resources of commercial buildings in 2018 and has developed a corresponding virtual power plant system [7]. As of May 2021, it aggregated about 50 MW of power from 150 buildings. Among them, Shanghai Minhang Mixc City is a large-scale urban complex covering shopping malls, hotels, exhibition spaces, and office buildings. The maximum daily load reaches 11.0 MW. Through the refined management of the energy consumption systems, it now has a peak shaving capacity of 1.0 MW and a valley filling capacity of 4.0 MW. With the maximum load adjustment potential, the Mixc City participated in the 2-hour peak-shaving or valley-filling demand response, and a single response was able to obtain subsidy incentives of 18,000 and 28,000 RMB, respectively. The annual electricity bill was reduced by about 400,000 RMB.

11.2.4 Tianjin commercial building load regulation demonstration project

Tianjin Electric Power Co., Ltd. also has a city-level commercial building virtual power plant relying on the Tianjin Electricity Demand Response Center [8]. As of May 2021, it is connected with six commercial buildings in the urban area to build a building-level virtual power plant to improve energy efficiency and power demand response of buildings. Taking one building as an example, efficient building energy use and participation in power demand side management can reduce electricity bills by about 200,000 RMB per year.

11.2.5 Demonstration project of building energy-saving renovation in Hubei, China

Hubei Electric Power Co., Ltd. provides energy-saving renovation services for large commercial buildings [9]. As of November 2021, a total of 147 renovation projects were implemented in different cities in China, with a single-building energy-saving rate of more than 5%. Taking a large-scale commercial complex as an example, through its analysis of the power consumption structure, combined with the collected power consumption data, an exclusive energy-saving renovation plan was formulated. By optimizing the start and stop time of the air conditioning systems and the lighting of the underground parking lot, 2,928,400 kWh of electricity in half a year was saved, which reduced the electricity bill by 2,049,900 RMB.

11.2.6 A building energy-saving renovation project of China Southern Power Grid

China Southern Grid Integrated Energy Co., Ltd. adopted the energy custody service model to undertake energy-saving renovation services for office buildings, public institutions, and commercial buildings. The current service area is 3.4 million m^2. The annual electricity consumption before the renovation was 487 million kWh, and the average annual electricity cost saving was 70.6 million RMB. Some representative examples of their initiatives are highlighted below.

One office building has 53,000 m^2, and the annual electricity consumption before the renovation was 9.183 million kWh. After the energy-saving renovation, the annual electricity saving was up to 13.8%, which was about 1083 million RMB. Another example is 19 buildings with a total construction area of about 200,000 m^2. The air conditioning systems used in these buildings were quite old and the annual electricity consumption before the renovation was about 17.569 million kWh. After energy-saving renovations (e.g., improved control, LED green lighting renovation, energy-saving management of air conditioning systems and lighting equipment, online monitoring, and analysis of building energy efficiency), about 14% of energy savings were achieved.

Guangzhou Power Supply Company Office Building has a construction area of 53,000 m^2. Before the renovation, the annual electricity consumption was 13.55 million kWh. In 2016, the energy-saving rate reached 32.3% after the energy-saving renovation, and the annual electricity cost was saved by about 4.04 million RMB. Dongguan Power Supply Bureau Office Building has a construction area of 47,000 m^2. The annual electricity consumption before the renovation was 8.88 million kWh. After the renovation in 2016, the energy-saving rate reached 4%, and the annual electricity cost was saved by about 402,700 RMB.

11.3 Current challenges and opportunities

11.3.1 Problems and challenges

The core of the interaction between flexible resources such as buildings and the power grid is the creation and rational distribution of value. The power grid guides flexible resources such as buildings through the power market to provide interactive services such as peak shaving, frequency regulation, and backup power source, and provide reasonable profit compensation for trading behavior.

At present, the power market provides profitable market products and related mechanisms, but the application scale of building load regulation is still small at this stage and end-users are not willing to participate. The direct reason is that end-users do not know how to participate in the electricity market and how to save energy costs. In other words, how to "make money" as much as possible, and how to "save money" as much as possible, remain unclear for end-users, so they cannot evaluate the investment return of this transaction. Therefore, the demand response market is very difficult to attract end-users of existing buildings. The energy-saving market can easily attract customers as they provide clear information about the return on the investment. However, for the demand response market, there is a lack of in-depth research on the interaction technology between buildings and power systems, and a lack of clear discussions on the value of building load regulation for the economic and safe operation of new power systems. The development of an economical and reasonable market is therefore needed to provide building users with a low-cost way to participate, allow end-users to "save money," and formulate supporting subsidy policies to allow end-users to "earn more money." This can in turn motivate building loads to participate in the formation of a large-scale interactive market for the power grid, thereby promoting the iterative upgrading of technology and fostering a good interactive ecology between buildings and power grids. The specific problems and challenges faced are as follows:

1. Building load is not "transparent." From the perspective of building users, individual buildings have different adjustment capabilities, and the grid adjustment scenarios that they can participate in are different. At this stage, the building load lacks a refined analysis model that can include quantitative indicators such as adjustment depth, response speed, and duration. Building owners can't evaluate their adjustment ability, and it is also not clear about the transformation cost that needs to be invested in participating in the power market. Therefore, it is impossible to evaluate the scenarios and investment benefits that can offer via participating in the power load adjustment.
2. The power grid is not "measurable" for buildings. From the perspective of the power grids, they do not understand the adjustment capability of buildings. There is no engineering model for building equivalent power dispatching available in the current market. The planning and dispatching system of power grids cannot quickly and effectively evaluate the response capacity and resource scale of each building block, so it cannot effectively guide the planning and scheduling of the distribution network that can cover flexible resources.
3. There is a lack of building load control strategies closely coupled with value formation and benefit distribution. On the one hand, the first purpose of building load is to improve user comfort, and the regulation of building load may bring a loss of user comfort. On the other hand, the existing building energy-saving market has formed stable services, products, and economic benefits in the building industry. It is necessary to study economical building load operation regulation strategies to maximize investment returns. After subsidizing the loss of user comfort and covering energy-saving gains, there is still a reasonable profit surplus, to promote building load regulation to stand out in the market and be applied on a large scale.
4. There is a lack of a sound market mechanism. Buildings, as natural load aggregators, can adapt to the requirements of the speed and depth of system adjustment, and have unique advantages in participating in the power market. However, the current market cannot fully reflect the characteristics of building load regulation in terms of the price mechanism. The fundamental reason is that the current "considerable" capacity for

building resources is poor. After achieving a considerable regulation capacity, the characteristics of resources can be summarized, and matched with the needs of the power system, to provide market products and set market rules that are more suitable for building load regulation. The establishment and improvement of a clear market mechanism will fully mobilize the enthusiasm of building owners to participate.

5. There is a lack of identity authentication mechanisms for electricity-carbon coupling and linkage. Building load can actively assist the grid in absorbing clean energy by participating in the flexible adjustment of the power grid. Currently, there is a lack of electricity-carbon coupling and linkage for building load regulation. The lack of an identity authentication mechanism and channels results in an absence of social responsibility and a driving force for users to reduce carbon emissions. If the contribution of the power grid to the building is proved in the form of a green certificate, the circulation and certification mechanisms of the green certificate in the carbon market will be established and the enthusiasm of the building sector to participate in the grid consumption of clean energy will be improved.

11.3.2 New trends and opportunities

Various load regulation and demand response programs have been developed or are being developed to promote the use of building energy flexibility and reduce building operating costs.

1. Requirements and incentive policies for demand response in the power market. To support the development of the industry, the power market has lowered the entry threshold for demand-side participation and expanded the scope of participation, but the requirements for the response time and the load regulation speed are higher. To fully integrate demand response into the power market and effectively compete with traditional generator sets, market-oriented policies in various regions have been developed and set higher requirements in terms of load aggregation and load regulation. For instance, demand response in Guangdong, China, requires a load response capacity greater than 0.3 MW and a response duration greater than 2 hours [10], while Zhejiang, China, requires the regulation power to be greater than 5 MW and the response time to be greater than 1 hour [11]. In terms of load regulation accuracy, Shanxi, China, requires that the deviation of the response capacity should be within 15%, and the response time should be less than 2 minutes, while Guangdong, China, requires that the deviation of response should be within 20%, and the response time should be less than 1 minute [12]. It can be seen that to reduce the challenge of power grid regulation, there is a development trend that the market is inclined toward high-quality resources. Therefore, it is urgent to establish an economically complete set of technical solutions for resource screening and resource aggregation that consider resource regulation capabilities.

2. At the same time, to fully stimulate large-scale users to participate in the demand response market, many places have proposed higher subsidy standards for load regulation. The subsidy for demand response in Guangdong, China can be up to 3.5 RMB/kWh while the subsidy for demand response in Zhejiang, Tianjin, and Shandong, China, for instance, can be up to 4 RMB/kWh [12]. It can be seen that vigorously tapping the load regulation potential and participating in the grid supply and demand interaction can achieve a win-win situation for the grid load. Driven by future market-oriented policies, the potential of building load flexibility is expected to accelerate.

3. Photovoltaics, energy storage, direct current (DC), and flexible loads-related technologies have been actively promoted by the policy, and the industry has entered a period of rapid development. These systems and technologies enable buildings to transform from simple energy consumers to a "three-in-one" role of energy consumption, production, and energy storage at the same time. The DC system has received widespread attention due to the advantages of improving the utilization efficiency of photovoltaics, facilitating the flexible adjustment of photovoltaics, energy storage, and electricity load, and improving the safety of electricity consumption [13].
4. With the development of building energy-saving targets from low energy consumption to net/nearly zero energy operation, energy-saving technologies have also been developed from traditional means such as high-efficiency doors and windows, walls, and energy-saving appliances to renewable energy technologies such as integrated utilization of building photovoltaics and remote renewable energy. However, due to the asynchrony between renewable energy production capacity and building energy consumption on the time scale, if generation and storage are not properly adjusted and controlled, buildings cannot use renewable energy efficiently. Therefore, to achieve maximum utilization of renewable energy in buildings and achieve a true net/nearly zero energy operation, building flexible adjustment technologies will be essential. The grid side supports the friendly interaction between the building and the grid and consumes a high proportion of renewable energy on the grid side. Therefore, photovoltaics, energy storage, DC, and flexible loads can support buildings to efficiently utilize their own photovoltaics and grid-side renewable energy at the same time and are among the key technologies for developing grid-friendly net/nearly zero energy buildings.

11.4 Technology demonstration of a grid-interactive and nearly zero energy building

Net/nearly zero energy buildings (NZEBs) have become a new trend globally to significantly reduce building energy consumption and achieve net/nearly zero emissions. This section introduces the design of a novel nearly zero energy building in Shenzhen, China as an example, which used a 100% DC power distribution system. This nearly zero energy demonstration building has 6259 m^2 and is an eight-floor office and research building (Fig. 11.1). It is located in the hot summer and warm winter climate zone in China (equivalent to ASHRAE climate zone 1) and was designed to research NZEBs with very low energy demand. The building is also the world's first building to use 100% DC power distribution to provide electricity for all its end-user demands. The building employs both passive and active energy-saving technologies as well.

This case building, called "Zero Carbon Module," is located at the southeastern corner of a building block cluster and contains the Shenzhen Institute of Building Research's research and development office space. Table 11.1 provides basic information about the building.

FIGURE 11.1 Illustration of the DC-powered building complex.

TABLE 11.1 Case building information.

Design-build model	Steel construction
Floor space	8 floors with 6259 m^2 of gross area.
Use purpose	Office, laboratory, and meeting rooms
Cost	574 USD/m^2 (286 USD/m^2 for construction, and 288 USD/m^2 for electrical system and installation)
Construction/occupied date	2017/2020

11.4.1 Building energy performance

The building was designed to achieve nearly zero energy performance. The overall objective of the nearly zero energy design was to employ passive building envelope technologies such as shading and natural ventilation to provide acceptable daylight and reduce the building cooling load. The overall designed annual energy consumption intensity is 49 kWh/m^2/year, with a 387 kW total rated electrical load.

Photovoltaic panels with a total rated power of 150 kilowatts peak (kWp) were installed primarily on the rooftop to maximize renewable electricity generation. Distributed battery storage, with a total capacity of 250 kWh, is used to improve the reliability of the power supply and increase building energy flexibility. The total PV-generated electricity is 134,244 kWh/year. Renewable energy generation offsets the building's energy use intensity to 29 kWh/m^2.

The heating, ventilation, and air conditioning (HVAC) consumes 42.98% of the building's energy usage, and a great deal of that is attributable to cooling in the summer. The rest of the energy is used by lighting (13.70%), plug loads (27.76%), and elevators (15.56%). PV generation generally provides roughly half of the building's electricity consumption. In summer, the daily average energy use and PV generations are 1635.6 and 826.9 kWh, respectively. In winter, the daily average energy consumption and generation are 1026.5 and 440.1 kWh, respectively. Fig. 11.2 shows the energy demand and PV electricity generation on the typical summer and winter days.

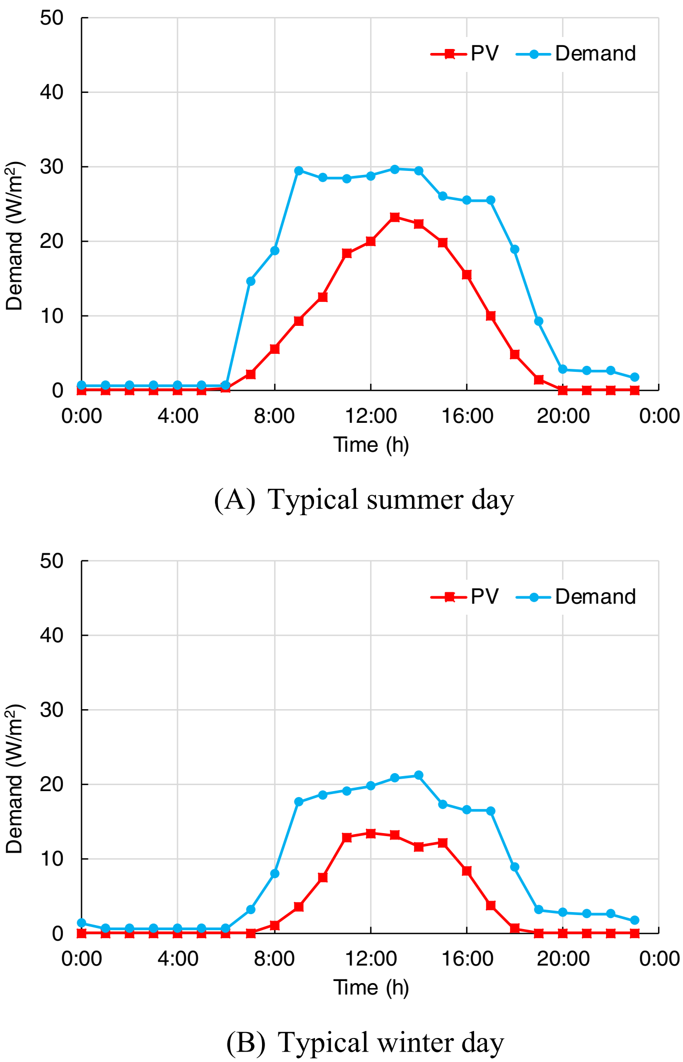

FIGURE 11.2 Energy demand and PV generation profiles on summer and winter days.

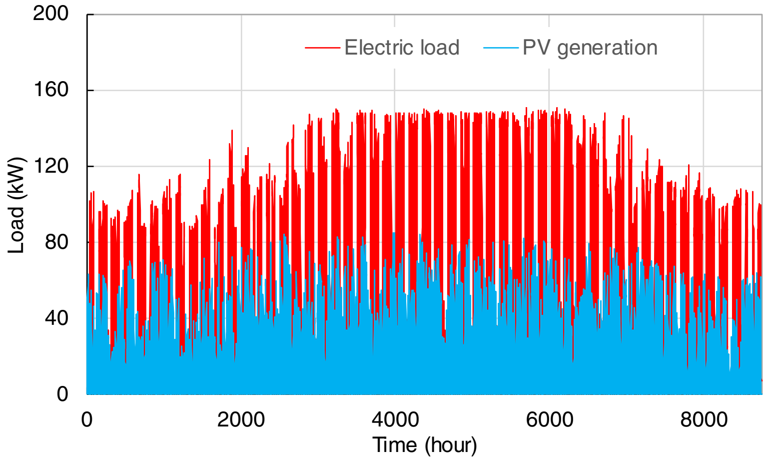

FIGURE 11.3 Annual building electricity demand and PV power generation.

The installations of 150 kWp of PV panels and 250 kWh of battery storage are used to curtail the building's peak electricity demand. The generated PV power is consumed by the building locally, and any surplus from the PV generation is used to charge the battery. The battery storage is also dispatched to discharge during the afternoon to offset the building's peak electricity purchase from the grid. The building only uses electricity for energy and has no fuel energy consumption. Fig. 11.3 shows the annual building energy demand and PV generation.

11.4.2 Overview of green building features

Several high-performance building technologies were adopted in this nearly zero energybuilding to reduce energy demand. Table 11.2 lists the main green building technologies used.

11.4.2.1Building envelope and natural ventilation

Curtain walls are used as the major components of the building envelope. Integrated exterior shading, green roofs, and vertical vegetation are used to reduce solar heat gain and visual glaring. The glass façade has a U value of 2.5 $W/(m^2 \cdot K)$. The movable modular external shades are 40 cm outside of the façade (Fig. 11.5). The modular shades can be reconfigured by the building owner and can change from vertical vegetation to blinds or vertical fins, or even to a PV module. The reconfigurable external shading components can be adjusted to optimize natural ventilation for the building office space during the shoulder seasons and maximize daylighting to provide good visual comfort.

11.4.2.2Heating, ventilation, and air conditioning system

A high-performance variable refrigerant flow (VRF) system was installed to provide air conditioning for the building. The coefficient of performance of the VRF system is 3.3 at

TABLE 11.2 High-performance building design features used.

Features	Description
Environment	• Indoor decoration with green building materials • Carbon dioxide (CO_2) and carbon monoxide (CO) monitoring • Air filtration and cleaning for outdoor air • Independent control of indoor temperature and humidity • Optimization of wind, light, and sound environment in building design
Resource-saving	• Water-saving fixtures • Nontraditional water reuse • Modular and variable indoor office space planning • Modular, all-steel structure
Active and passive energy saving	• High-performance curtain wall with operable windows • Integrated exterior shading • Photovoltaic roof • Green roof • Vertical vegetation façade
Energy management	• PV integrated DC variable frequency variable refrigerant flow system • 100% DC building microgrid integrated with PV and battery • Smart DC power distribution, control, and power management
Ecological construction site	• Green space corridor (Fig. 11.4) • Space green vegetation demonstration zone • Water permeable pavement • Solar reflective cool pavement

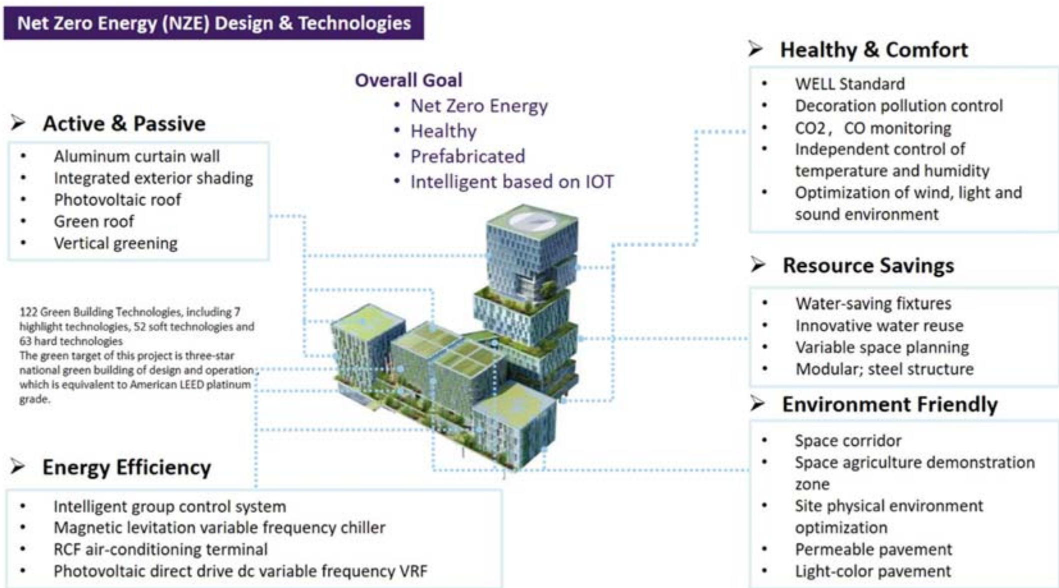

FIGURE 11.4 Building elevated floors with sustainable landscaping.

FIGURE 11.5 External shading (*left*) and large patio space on the 7th and 8th floors (*right*).

FIGURE 11.6 Outdoor units in the VRF (*left*), and fan coils and duct systems (*right*).

the design conditions. As the building is fully powered by DC distribution, all indoor and outdoor units of the VRF system are powered by a DC power supply. The outdoor units, each 12.5 kW, are connected to the 750-volt DC (VDC) bus bar through + / − 375 VDC (Fig. 11.6 *left*). The outdoor air system fan on each floor is also controlled via a viable frequency drive with a DC power supply (Fig. 11.6 *right*).

11.4.2.3Direct current power electrical system

The building is equipped with a novel DC power distribution system. A core design goal of the DC power system is to enable the building to be less dependent on the power grid. It can draw relatively constant power from its utility. Therefore, even if the building's total rated electrical load is 387 kW, the DC power system only connects with the utility AC grid through two 100 kW AC/DC converters. Based on the traditional building electrical system design, this building would need a 630 kVA utility transformer. However, the building connects to the grid via a 2 × 100 kW AC/DC converter, which greatly reduces the impact of the peak load of the building on the power grid. The 150 kWp rooftop PV panels and 250 kWh battery storage are connected to the building's DC power bus to provide the building with an additional energy supply beyond the utility grid. The voltage level of the DC bus is ±375 VDC, a plus-and-negative bipolar DC power system. The combination of a ±375 VDC backbone can provide the building with a 750 VDC power supply for large-capacity DC equipment such as HVAC systems. Each floor is powered either by +375 VDC or −375 VDC. The building can balance the +375 VDC electrical loads equally with −375 VDC loads and thus maintains the voltage stability and load balance across the DC power backbone. Table 11.3 shows the building's DC electrical loads. The core DC power technologies and equipment used are shown in Fig. 11.7.

The DC power system schematic used in the building is shown in Fig. 11.8. The high-voltage DC loads are directly fed through the + / − 375 VDC backbone. Power distribution to the low voltage loads is achieved by first converting the 375 VDC power to a lower voltage level of 48 V [14]. Then a local voltage converter can convert the 48 V DC power into 24, 20, and 5 V to meet different voltage needs of the end-user devices (Fig. 11.9). A smart DC/DC power converter, namely "The Box," is used to achieve the high voltage 375 V to low voltage 48 V DC/DC power conversion (Fig. 11.10). "The Box" feeds low voltage power for the end-user devices and allows smart metering and control over the device's power use. The Box's internal battery allows the converter box to operate a local power distribution

TABLE 11.3 Electrical loads and bipolar system connection of the building.

#	Name	Load (kW)	Units	Pole
1	LED lighting	4.4	3	+ 375 V pole
2	48 V plug load	4.4	3	
3	375 V plug load	10	3	
4	DC EV charger	30	2 (reserve)	
	Subtotal	116.4 kW		
5	LED lighting	4.4	3	− 375 V pole
6	48 V plug load	4.4	3	
7	375 V plug load	10	3	
8	Datacenter	40	1 (reserve)	
9	Public lighting	4	1	
10	Emergency lighting	4	1	
11	Security system	8	1	
	Subtotal	112.4 kW		
12	DC VRF	Total: 159 kW		750 V bus
	Total	387.8 kW		

FIGURE 11.7 Controller cabinet for DC distribution: (A) battery storage, (B) AC-DC rectifier, and (C) power distribution controller.

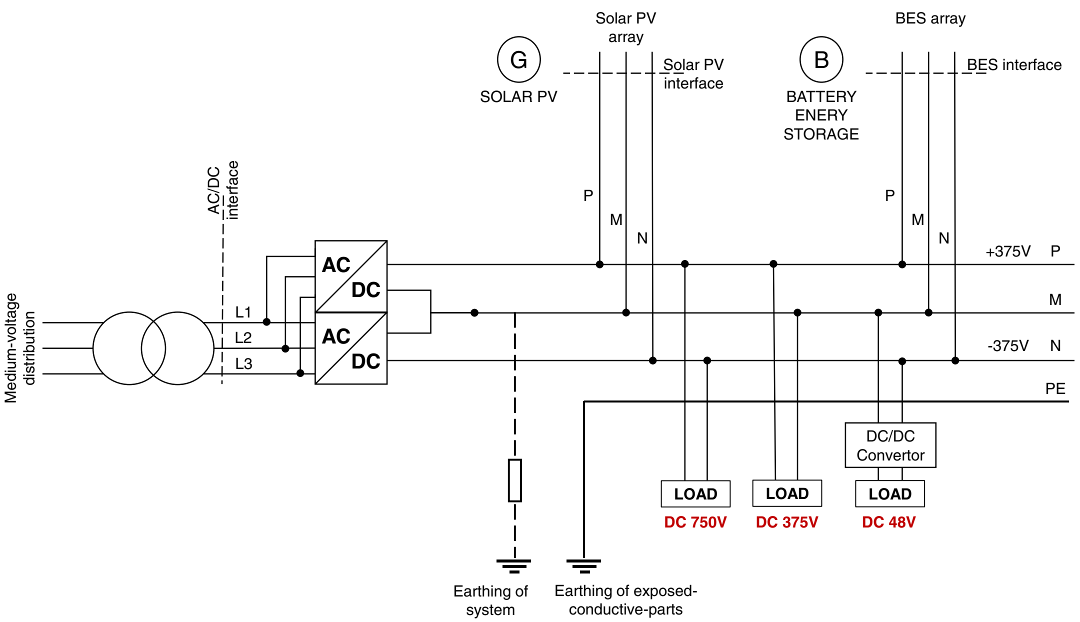

FIGURE 11.8 Schematic of a DC power distribution system used in the building.

network as an island in the building. It can also allow "The Box" to perform demand response and coordinate different end-user loads in that branch or across different branches.

The protection of the DC power system is achieved by using large impedance earthing, also known as IT earthing. The earthing mechanism can effectively isolate an occupant if an electrical

FIGURE 11.9 Low voltage DC socket to support multiple DC voltage levels for end-user devices.

FIGURE 11.10 Commissioning of a smart DC/DC power converter box (*left*); and illustration of a DC power converter as installed (*right*).

shock happens at the one-pole level, and this will not cause any closed-loop electrical shock current. In addition, the system is installed with a DC insulation monitoring device and residual current device. These devices enable insulation fault alerts and detect the fault's location.

Another focus of the demonstration is on the use of DC power to electrify building end-use technologies. The building has a DC power kitchen with DC appliances, including a refrigerator, a rice cooker, an electric stir-fry pan, an induction cooktop, disinfection cabinets, and microwaves (Fig. 11.11). The full electric DC kitchen shows that even if the building is used for office purposes, it is feasible to apply a similar DC power solution to residential houses.

11.4.3 Load flexibility and grid-interaction

Flexibility and grid interaction are among the design principles of the DC power system in the building. The use of smart power electronic devices can effectively manage end-user devices to act as flexible resources that respond to power grid signals. To respond to grid signals, the DC power bus voltage level can be adjusted through the AC/DC

FIGURE 11.11 Electrification of cooking with a DC power appliance.

converter. The flexible resources of the building can respond to the variable bus-line voltage and optimize its operation.

The control system of the DC network is designed to maintain the system's voltage stability. Several disruptive event tests were performed to evaluate the voltage level fluctuation. These tests included: (1) switch on/off large capacity end-user devices, (2) grid-connected and island mode switch, and (3) double pole switch to single pole operation. The tests showed that the DC bus-bar voltage fluctuations were within 5% of its bus-bar voltage, which will not affect the system's normal operation.

The building also provides DC chargers for electric vehicles (EVs). The DC EV chargers are designed to be 20 kW each, with a bidirectional charging function that also enables the EVs to discharge their batteries back to the building and function as a flexible electricity storage technology (Fig. 11.12). The charging and discharging strategies are smartly managed through building PV generation and local battery storage capacity.

11.4.4 Benefits and lessons learned

The first advantage of DC power is to reduce the energy loss from power conversion [13]. Traditional AC power design in buildings requires a large number of power adapters for end-user devices such as laptops and computers. An increasing number of end-user devices are internally DC. In addition, clean energy technologies such as PV, battery storage, and EVs are also natively DC. As such, the use of DC power to connect the load, renewable generation, and storage can provide significant energy efficiency benefits to building owners.

FIGURE 11.12 DC bidirectional EV chargers.

FIGURE 11.13 DC lighting with a 48 V DC naked copper bus bar.

Significant safety benefits of using low voltage power distribution at the end-user sockets and plugs can also be achieved. Using a 48 V or 24 V voltage level can significantly reduce the chance of electrical shock as compared with the traditional 120 V or 220 V AC power distribution [15]. This advantage can enable power engineers to use a more flexible wiring design, such as naked wire for lighting and other technologies in buildings, and reduce electrical system installation costs (Fig. 11.13).

Another advantage of the DC power system is that a DC system can easily integrate power distribution with metering and smart control in one system. This approach can significantly enhance the smart devices connected to buildings and better participate in demand response. With the acceleration of the Internet of Things in buildings, DC power distribution systems can greatly facilitate the ability of end-user devices to connect and interact with the power grid.

The DC power system of the building was commissioned to be grid responsive. The grid demand response can be achieved through programmable power electronic devices to control end-user devices. Another idea is to enable power electronic devices to manage the DC bus bar voltage levels, so the end-user devices can directly respond to a voltage drop or rise.

In DC power design, a large current should not be transmitted over the low voltage distribution system, which could potentially cause significant energy loss in the wires. One design idea is to position the backbone (375 VDC in this case) DC/DC converter close to each low-voltage end-user desk and therefore reduce the wiring distance from the 48 V or 24 V power supply (Fig. 11.14).

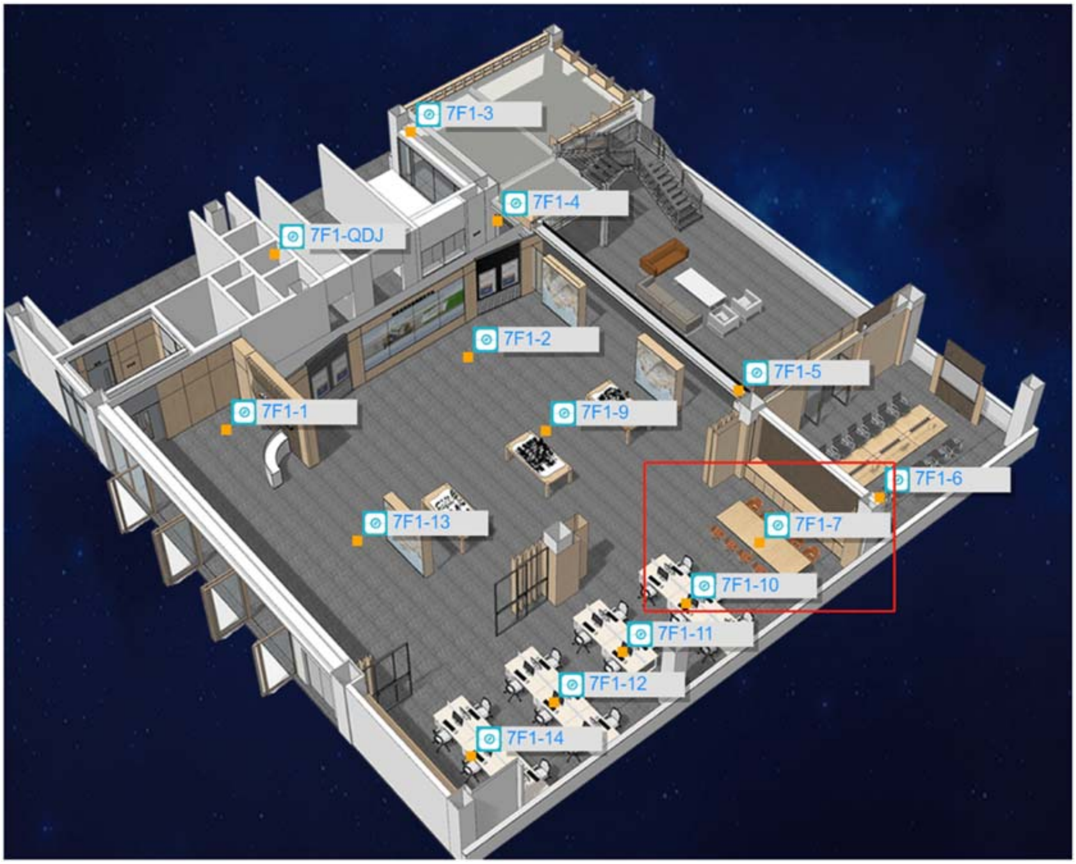

FIGURE 11.14 Locations of the DC/DC converters on the 7th floor of the building.

11.5 Summary

The concept of net/nearly zero energy building development has been recognized in many countries, and some countries have formulated development plans and goals, but there is no consensus on the definition and specific calculation methods of NZEBs. There is a consensus that apart from achieving the goal of net zero energy consumption for low-density and low-floor residential buildings, the "high-density and high-volume" buildings in most parts of urban areas are not suitable. Although buildings use comprehensive passive and active means to reduce energy consumption, it is still difficult to only use building renewable energy itself to balance energy consumption and achieve net/nearly zero energy consumption. Building load can be highly adjustable, even in the absence of energy storage, and the thermal inertia of the building and the tolerance of people to temperature changes are the potential sources to respond to active peak shaving at the supply side of the power grid. Although the influence and contribution of a single building to the power grid are very weak, under the urban form of "high density and high volume ratio," significant environmental values can be produced if a large number of buildings can be aggregated.

Faced with the above problems, we have to rethink whether we should consider the significance of NZEBs, explore the technical path of NZEBs from a broader scale, and consider the role of building energy consumption in the whole social energy system.

The realization of the goal of buildings with net/nearly zero energy consumption depends on the change of the whole energy system and the combination of information technology and energy technology. The understanding of the concept of buildings with net/nearly zero energy consumption should not be confined to the level of building terminal energy consumption, but be defined from the perspective of the relationship between buildings and urban energy systems. It is an opportunity for the construction industry to undertake the goal of the energy revolution and integrate it with information technology depth.

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BUILDING ENERGY FLEXIBILITY AND DEMAND MANAGEMENT

Building Energy Flexibility and Demand Management looks at the implementation and integration of intermittent renewable energy sources and the need for increased demand flexibility. Ensuring electrical power systems adapt to dynamic energy demand and supply conditions, this book supports the transition to a renewable energy future with increasing fluctuating power generation. By facilitating the penetration of renewable energy sources into the building sector, and balancing electricity supply with demand in real-time, this book will provide fundamental concepts, theories, and methods to understand, quantify, design and optimize building energy flexibility. The book provides case studies with emerging technologies to enhance building energy flexibility and demonstrates how demand management strategies can utilize energy flexibility for demand reduction and load shifting. This is a useful resource for researchers and engineers working in flexible energy systems and advanced demand side management strategies for achieving deep decarbonization in the building sector.

Key Features

- Focuses on how renewable energy and storage technologies can be appropriately designed and optimized to increase building energy flexibility.
- Discusses how building energy flexibility can contribute to reduced operating cost and grid optimization.
- Details how to effectively implement building energy flexibility for demand response, peak demand reduction, and peak load shifting.

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