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

Natural Energy, Lighting, and Ventilation in Sustainable Buildings

Springer

Indoor Environment and Sustainable Building

Series Editors

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The book series "Indoor Environment and Sustainable Buildings" publishes insights and latest research results on indoor environment and sustainable building, and aims to provide a more energy-efficient, safer and healthier space engineered for human to live and work. The intent is to cover all the technical contents, applications, and multidisciplinary aspects of the engineering techniques for improving indoor environment quality and the energy efficiency of heating, ventilation, and air conditioning (HVAC) systems, as well as the smart home devices, sustainable architectures and buildings.

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Natural Energy, Lighting, and Ventilation in Sustainable Buildings

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Preface

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

Southfield, MI, USA Morteza Nazari-Heris

About the Book

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

Contents

About the Editor

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

Chapter 1
Sustainable Buildings: A Comprehensive Review and Classification of Challenges and Issues, Benefits, and Future Directions

Mehrdad Ghahramani, Daryoush Habibi, Mehran Ghahramani, Morteza Nazari-Heris, and Asma Aziz

Abstract During the last few years, the importance of moving toward sustainable industries has been recognized by everyone, which has a significant influence on global warming. One of the most important objectives of sustainability is to reach energy efficiency and reduce carbon emission. Due to the importance of this issue, a huge amount of valuable studies have been done in this field, and a significant number of studies still are required to investigate the limitations of this topic. This study aims to have a comprehensive review of sustainable buildings from various perspectives. The most important contribution of this chapter is to study the challenges, obstacles, objectives, interests, and preferences of sustainable buildings from the perspective of different stakeholders. The review process involved analyzing papers published on three scientific and reliable databases, including review articles, conference proceedings, and journal papers. The papers focused more on the details of different aspects of improving energy efficiency and energy reduction to minimize the environmental, economic, social, and other impacts of fossil fuels. The outcomes of this study provide a valuable reference for stakeholders, including governments, policymakers, researchers, and decision-makers, and offer suggestions from the selected past studies. The review highlights the need for researchers to consider the challenges, benefits, and recommendations for future work in this area. The paper provides motivation and attracts future research endeavors to enhance energy efficiency in buildings and achieve sustainability.

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1.1 Introduction

Global warming has been one of the most significant environmental issues in recent decades. As a result, humans have been working diligently to develop innovative solutions in various industries to reduce their carbon footprint [1]. The scientists from various fields, especially from power, civil, and mechanical engineering, have developed smart grids [2], renewable energy sources [3], electric vehicles [4], and sustainable buildings [5]. The movement in the approach of utilizing sustainable, clean, and energy-efficient technologies can lead to sustainable future [6]. Using smart energy systems [7], renewable-based energy sources, demand-side management programs [8], and sustainable buildings [9] have the ability to make great influences in addressing global warming and air pollution.

1.1.1 Sustainability

The concept of sustainability proposes a balance between current and future needs. It addresses various challenges arising from managing structures, organizations, and resources in both the short and long term. Sustainable construction is defined as an infrastructure project or development that fulfills present requirements while preserving the capacity of future generations to meet their own needs. In many developing countries, such as Iran, construction heavily relies on traditional methods, making it challenging and stressful to incorporate advanced techniques [10]. Despite a desire for sustainable construction in the industry, clients and major stakeholders often reject innovative methods, which is a significant barrier to achieving sustainability. Contractors also face difficulties in implementing sustainable practices, and the industry is reluctant to exceed client requirements, making it challenging to operate. In addition, professionals in the construction industry often lack adequate training in sustainable construction principles, further exacerbating the situation [11].

1.1.2 Sustainable Buildings

Green and sustainable buildings are structures that are designed, constructed, operated, and maintained using environmentally responsible and resource-efficient practices. These practices aim to reduce negative environmental impacts, promote human health and well-being, and optimize economic benefits over the entire life cycle of the building [12]. Such buildings integrate sustainable site selection, water efficiency, energy efficiency, materials selection, indoor environmental quality, and innovation in design and operation. In addition, they prioritize using renewable energy sources, minimize waste generation, and promote the conservation of natural resources [13]. The important objective that sustainable buildings seek is to prepare a positive and productive environment for their occupants. The conception of this structure is based on minimizing negative effects and maximizing positive effects on various aspects of human life. In order to reach these goals, green and sustainable buildings utilize various design strategies, including passive solar design [14], high-performance insulation [15], energy-efficient lighting [16], advanced HVAC systems [17], rainwater harvesting [18], and greywater recycling [19]. By prioritizing sustainability and human health, these buildings offer a promising path toward a more resilient and sustainable future.

1.1.3 Motivations

The crisis of air pollution and global warming makes scientists and researchers seek methods for solving these problems [20]. According to the fact that buildings consume a huge amount of world's energy and produce a huge amount of emissions, it is necessary to pay more attention to the concept of sustainable building [21]. The researchers aim to develop the knowledge of sustainable buildings by implementing renewable technologies like solar panels [22] and wind turbines [23] and make these structures more positive and renewable. With the increase in the world population, it is more important than before to work on sustainable buildings to find the solutions to save the world from energy and pollution crises. Among the sectors with the highest energy consumption, the building sector consumes approximately 20–40% of this energy [24]. This sector is also one of the biggest producers of waste and every year produces a huge amount of harmful substances [25]. Therefore, developing the industry of sustainable buildings can decrease the side and negative effects of this industry and the development and encouraging the practices of sustainable building can offset the detrimental effects of buildings on the natural environment, economic stability, and societal well-being [26].

Some industry practitioners and researchers have provided a definition for sustainable buildings, labeling them as "green" buildings that surpass conventional buildings in reducing emissions and can achieve the Net-Zero Carbon Buildings Commitment [27]. In green and sustainable buildings, energy efficiency is a crucial component, if not the central element. Improving energy efficiency in both new and existing buildings presents a swift solution to reducing various negative impacts on the society, economy, and environment that this sector can have [28]. To achieve the practices of sustainable building, researchers should emphasize implementing higher levels of energy efficiency. This cannot be achieved unless by utilizing energy efficiency assessments [29], adopting energy efficiency strategies [30], integrating rooftop wind turbines [31], employing an integrative approach that utilizes multi-objective search [32], conducting energy modeling [33], integrating building-integrated PV facades [34] and installing PVs [35], upgrading luminaires [36], and employing energy-efficient building enclosures [37] and eco-friendly building materials [38], among others. The building sector remains a hot topic for researchers worldwide, with energy conservation, energy efficiency, optimization, preservation, and alternative energy sources.

1.1.4 Contributions

Despite the numerous studies conducted by research institutions, universities, and governments, a systematic review and a new perspective in this area is lacking. The objective of this chapter is to examine and offer valuable perspectives on the different areas of environmentally friendly buildings by consolidating and synthesizing findings by a comprehensive overview of the obstacles, objectives, interests, and suggestions of sustainable buildings, thereby identifying the relevant characteristics and benchmarks that define this field of inquiry. The selected studies of this chapter provide suggestions for stakeholders such as designers, manufacturers, users, researchers, and policymakers and can be utilized for further advancements by providing a framework for future progress. Proposed avenues for future research serve as a guide for upcoming researchers as they seek to address any outstanding issues that remain unresolved, using a range of techniques, methods, instruments, and tactics to achieve their objectives.

1.1.5 Chapter Organization

The chapter is organized into several sections. The second section presents a literature review of the obstacles and challenges that impede the development of sustainable buildings, such as cost and prices, the complexity of the construction process, and bureaucratic and governmental processes, as well as inadequate awareness and inadequate information. In addition, the second section delves into the objectives of the studies of sustainable buildings, which include examining environmental impacts, energy consumption, and energy efficiency in sustainable buildings. The third section further explores the interests of various stakeholders in sustainable buildings, such as governments and policymakers, producers and manufacturers, users and occupants, and environmental and social stakeholders. The preferences and suggestions of different perspectives, such as researchers, users, professionals, consultants, investors, governments, and policymakers, are presented in the last section.

1.2 Literature Review

In this section, the existing literature was reviewed to identify potential challenges, objectives, and interests that any stakeholder may encounter in sustainable building processes. In addition, suggestions and required topics for future studies will be discussed.

1.2.1 Obstacles and Challenges

Numerous obstacles were encountered and addressed in this part, as disclosed by researchers preoccupied with realizing efficient energy consumption in newly constructed and pre-existing structures to achieve sustainability.

As shown in Fig. 1.1, some of the key challenges identified during the study of various articles on sustainable buildings include the high costs that building a sustainable structure can impose on the builder or the buyer and the elevated expenses related to manufacturing and material procurement, the complexity of the bureaucracy and the process of the construction, inadequate information, and inadequacy in awareness and information of the sustainability processes.

1.2.1.1 Costs and Prices

One major challenge is the higher cost of green building materials and processes, which can range from 1% to 25% more than conventional buildings. Adopting sustainable construction materials incurs an additional 3–4% cost compared to conventional building materials though there is general lack of quantifiable information regarding the financial and economic impacts of sustainable buildings.

This poses challenges to sustainable project manufacturers as they are accountable for managing and delivering their initiatives within a pre-set budget. The primary objective of Table 1.1 is to provide an overview of the scholarly literature on the challenges associated with sustainable buildings, with a specific emphasis on the discourse surrounding cost and prices. According to the literature reviews, Life cycle assessment [39], economic evaluation [40], environmental price premiums [41], and multi-criteria design approaches for energy systems [42] are some of the measures that can be employed to reduce operating costs and achieve cost-saving.

Fig. 1.1 Obstacles and challenges related to sustainable buildings

Table 1.1 Challenges according to costs and financial issues

Costs and financial issues	References
In China, the sustainability challenges of residential buildings stem from various factors, such as financial limitations, high urban density, and construction methods	[43]
Building owners encounter challenges in attracting tenants seeking low operational costs and rent. This poses a significant obstacle to achieving sustainability goals for green buildings	[44]
Academic units within educational institutions lack motivation to conserve energy resources, as no financial benefits are associated with such actions	[45]
The Egyptian government is grappling with the challenge of managing the costs associated with energy subsidies, which has resulted in a growing concern over the associated budgetary costs	[46]
Applying green building technologies is often perceived as costly, and the lack of information and awareness of such practices is a significant barrier to their adoption	[47]
There is a tendency to overstate the potential issues associated with sustainable buildings, such as increased expenses during the construction phase, which may result in building owners being careless about future costs and benefits	[48]
The certification process for green buildings has several barriers which may result in economic challenges due to upfront costs for project owners	[49]
In Indonesia, adopting sustainable techniques is impeded by the higher costs associated with such initiatives and a lack of knowledge and awareness about them	[50]
It is essential to identify and evaluate sustainable construction approaches during the design phase in tropical regions, with a specific focus on office buildings	[51]
Older buildings often suffer from high energy consumption and cost overruns	[52]

1.2.1.2 Complexity of the Construction Process

Another challenge is the limited understanding of sustainable building design options and the complexity of the construction process, which may involve complicated technologies, procedures, and skilled workforce. Lack of communication about these complexities early on can compromise the overall performance of sustainable projects. Construction materials, technology choice, and their affordability pose challenges especially when there is a limited supply of local indigenous sustainable materials and are supplied at higher prices and with long lead times. The primary purpose of Table 1.2 is to critically evaluate and synthesize the extant literature regarding the complexities inherent in achieving sustainable buildings, paying particular attention to the salient issues of the construction process.

1.2.1.3 Bureaucratic and Governmental Processes

Long bureaucratic regulatory processes can also pose challenges. Embracing the adoption of novel and advanced technologies in construction projects may prolong the project completion timeline. The lengthy approval procedures that project managers need to go through to obtain acceptance of their construction methods are also included. Table 1.3 serves as a comprehensive analytical tool, systematically

Table 1.2 Challenges according to construction complexity

Design and construction complexity	References
Theoretical and practical application of sustainable building certification systems in Indonesia	[53]
These buildings have high degrees of installation and employ sophisticated structure systems	[54]
China's residential buildings face sustainability challenges, including financial constraints, high population density, construction techniques, and limitations in achieving high-performance standards	[55]
A model for scheduling is employed to guide and develop sustainable designs that balance two primary objectives: maximizing environmental efficiency during operation and minimizing the overall costs	[56]
A quantification and optimization approach can be used to assess the influence of users' choices on construction complexity	[57]
Active house standard methodology can provide a comprehensive assessment of building quality	[58]
A methodology for assessing and predicting classroom natural lighting levels can be evaluated using performance metrics derived from LEED criteria	[59]
In the climatology field, finding a widely accepted classification method is difficult	[60]

Table 1.3 Challenges according to bureaucratic and governmental processes

Bureaucratic and governmental processes	References
LEED certifications take time in Turkey	[61]
Professionals' participation in green building certification has a bureaucratic process	[62]
Having sufficient technical expertise and knowledge about the green building certification process	[63]
In Korea, evaluating policies and strategies is important to recognize and find out the areas in which an improvement is needed in sustainable building practices	[64]
Since the early 2000s, the Chinese government has been working on finding the best places for allocating financial budgets to support the development of the green building system	[65]
In India, there are various programs that are working on process-efficient energy, but most of these programs should be reviewed for their bureaucratic processes	[66]
Finding approaches to encourage the local governments is important to increase and foster the utilization of sustainable buildings in China	[67]

reviewing the scholarly discourse on the multifaceted challenges associated with sustainable buildings, with specific attention paid to the intricate matters of bureaucratic and governmental processes.

1.2.1.4 Inadequate Awareness

Lack of knowledge about sustainable technology and inadequate education on sustainable building techniques, materials, and processes can adversely affect the project's success and effectiveness. Moreover, insufficient dissemination of information

Table 1.4 Challenges according to inadequate awareness

Description	References
Activities that lack energy consciousness	[68]
Potential for energy conservation in architectural design	[69]
Benefits of clean technologies	[70]
Handling conflicting and cross-functional objectives	[71]
Information system on emission reduction technologies	[72]
Insufficient knowledge to implement sustainable construction methods with advanced technologies	[73]
Insufficient knowledge and education on the benefits and implementation of sustainable building practices	[74]
Limited knowledge of sustainable practices	[75]

to the public about the benefits of sustainable construction, coupled with a shortage of research on sustainability issues, also contributes to the challenge. Through a rigorous analysis of scholarly literature, Table 1.4 examines the vexing obstacles that impede the attainment of sustainable buildings, with an overarching focus on the intricate aspects of inadequate awareness.

1.2.1.5 Inadequate Information

Insufficient knowledge about sustainable materials and construction practices that can support sustainable building construction is another challenge for various stakeholders of sustainable buildings. This requires continuous interaction with specialists who have such knowledge. The primary purpose of Table 1.5 is to illustrate the intricacies associated with achieving sustainable buildings, drawing upon a range of scholarly sources and providing a nuanced evaluation of the multifaceted challenges related to inadequate information.

1.2.2 Objectives

Articles that study sustainable buildings mainly pursue some general goals and objectives, as demonstrated in Fig. 1.2, for example, objectives based on environmental impacts and reducing energy consumption and objectives related to improving energy efficiency.

1.2.2.1 Environmental Impacts and Energy Consumption

A large part of all the new changes in the basic infrastructure of the energy industry seek to decrease carbon-based energy consumption [80]. Sustainable and green buildings can considerably lessen the ecological footprint of the constructed

Table 1.5 Challenges according to inadequate information

Description	References
During the construction process, buildings pose challenges for the disposal and recycling of waste	[76]
Craiglockhart Primary School consumes a significant amount of energy due to its outdated technology and inadequate insulation, resulting in thermal losses. Its high ceilings and single-glazed windows also contribute to its energy intensity. This design flaw results in inefficient energy consumption and wastage	[77]
Residential structures demand significant amounts of energy, primarily due to the use of single-glazed windows and external walls made of double hollow brick cavities in Algeria	[78]
Although suitable materials and designs can significantly reduce energy consumption, even the most optimal building design cannot attain complete energy efficiency	[79]
In the construction industry, sustainability faces several barriers, including building design, the scarcity and absence of sanctioned materials, and the documentation procedure. These obstacles make it challenging to achieve sustainable construction practices	[49]

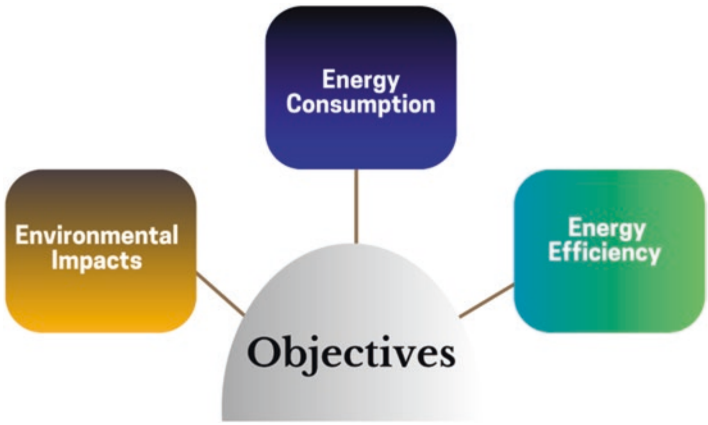

Fig. 1.2 Objectives of the sustainable buildings

environment. The construction and operation of buildings account for a substantial portion of energy use and greenhouse gas emissions. Green buildings are purposely designed and built to minimize the utilization of energy, water, and other natural resources. They are constructed in such a way as to reduce waste production and enhance indoor air quality [25]. Using insulating and energy-efficient equipment can reduce energy consumption and reduce the negative effects of carbon footprint. In addition, the use of renewable energy can reduce the reliance of sustainable buildings on fossil fuel-based energy and increase the building's energy security by combining different types of energy [32]. Reducing fossil energy consumption in buildings is not only very beneficial for the environment, but it also means reducing costs. Sustainable and green buildings can achieve lower operational costs over their lifetime due to reduced energy consumption, water usage, and maintenance costs. Sustainable building design can also promote sustainable development and community resilience by utilizing locally sourced materials, providing green space, and promoting public transportation [28]. In conclusion, sustainable and green buildings have a significant role in mitigating the environmental impact of the built environment while providing economic and social benefits to building occupants and communities. The primary purpose of Table 1.6 is to systematically evaluate and synthesize the scholarly literature that focuses on the research objectives of environmental impacts and energy consumption in the context of sustainable buildings.

Table 1.6 Environmental impacts and energy consumption

Energy consumption	References
In the UK, a simulation-based approach with passive-house planning tools is used to redesign and assess the performance of terraced housing units to reduce their energy consumption	[81]
In Malaysia, an environmentally friendly office building is assessed from the air quality perspective	[82]
Interest in passive design is revived through GB rating tools	[83]
The effectiveness of climate design strategies is validated	[84]
Sustainable buildings aim to achieve three goals: optimizing performance, minimizing costs, and enhancing quality	[56]
Older buildings often suffer from upper consumption and high costs	[52]
A concept for an environmentally sustainable building is created for construction	[85]
In India, environmentally friendly design practices for a novel business structure are being identified	[86]
To achieve zero-energy schools in Hong Kong, a PV energy supply is needed along with energy-conservation approaches and architectural design improvements	[87]
The Craiglockhart Primary facility consumes a significant amount of energy due to its outdated technology and lack of insulation, resulting in thermal losses. Additionally, its high ceilings and single-glazed windows contribute to its energy inefficiency. This design flaw results in inefficient energy consumption and wastage	[77]
Although suitable materials and designs can significantly reduce energy consumption, even the most optimal architectural plan cannot attain total energy efficiency	[79]
Encouragement is given for structures to fulfill the requirements of efficient energy set by a rating system	[88]
The daylighting in classrooms is evaluated using a method that depends on metrics derived from LEED standards to assess performance	[89]
Assessing the potential for improving the sustainability of educational buildings in a warm climate through integrating renewable energy systems in the United Arab Emirates	[90]
Renewable systems are integrated into passive building design	[91]
Determining real-world energy usage of residential buildings is achieved by comparing data from energy monitoring and computational energy simulation	[92]
A sustainable supply chain model for renewable energy is suggested to decrease energy usage in iron and steel companies	[93]

1.2.2.2 Energy Efficiency

Improving energy consumption has been one of the most basic needs of engineers in recent decades [94]. Improving efficiency in sustainable buildings is one of the best ways to correct the negative effects of fossil fuels. One of the main and fundamental reasons for increasing the efficiency of energy consumption is reducing the consumption of buildings, reducing the harmful effects of greenhouse gases, and reducing dependence on fossil fuels [16]. This goal will be achieved if we can use tools such as insulators, high-efficiency lights, and renewable energy sources [27]. By reducing energy consumption, we can also reduce operational costs and justify the use of sustainable energy from an economic point of view. Table 1.7 serves as a comprehensive analytical tool that critically examines the scholarly discourse on sustainable buildings, with a specific emphasis on the research objectives of energy efficiency.

1.3 Interests

Energy efficiency and reduced greenhouse gas emission through energy conservation are of significant interest, benefit, and motivation for sustainable buildings. Old buildings and traditional constructions have a great impact on energy consumption and cause the building to suffer from an economic crisis and damage the environment [62]. The goal of sustainable buildings is to consume less energy, reduce environmental impacts, and save more money for the owners of these houses in the long term [54].

Table 1.7 Energy efficiency

Energy efficiency	References
A smart energy management system is created to enhance the energy efficiency of campus facilities through the integration of artificial intelligence	[95]
Comparisons are made between energy model predictions and actual energy performance of three LEED-certified green buildings on a university campus to verify energy efficiency	[96]
Proposing the use of double skin facades (DSFs) as a passive technology for buildings to improve indoor thermal comfort and increase energy efficiency	[97]
A green residential building's energy efficiency is evaluated by proposing and examining a multigenerational system for residential purposes	[98]
Sustainability measures, including occupants' conduct, company guidelines, and advanced systems in eco-friendly structures, have been established in Malaysia to enhance energy efficiency	[99]
A framework is constructed to depict the energy consumption pattern of the Craiglockhart Elementary School and investigate various approaches to boost the building's effectiveness	[100]
Reviewed are the current government approaches and policies for enhancing the energy efficiency of buildings in Korea	[64]
Renewable energy systems are employed to achieve energy-efficient buildings in Shanghai	[101]

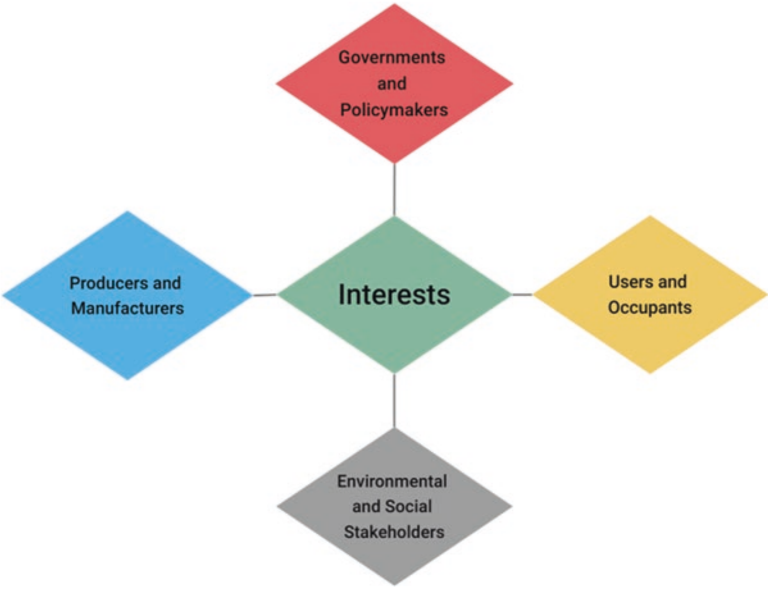

Fig. 1.3 Four groups that have interest in the sustainable building industry

The most important feature of sustainable houses is the use of insulating equipment such as insulated windows and doors, as well as the use of optimal heating and cooling systems and renewable energy sources, which improve energy efficiency. This feature reduces the amount of energy required for the building, and in this case, the cost of the building owner's bill is reduced. Various stakeholders' engagement and interaction is crucial for the successful promotion and implementation of sustainable buildings. As shown in Fig. 1.3, sustainable building process can benefit four different groups significantly. Government is the most influential entity to reduce conflicts and promote the successful delivery of sustainable building practices.

1.3.1 Governments and Policymakers

Governments and policymakers have an interest in promoting sustainable buildings for several reasons. First, sustainable buildings can help reduce the energy consumption and greenhouse gas emissions associated with the built environment. One of the most important priorities of governments and policymakers is the issue of global efforts regarding environmental changes [50]. Another important topic for governments and policymakers is to improve the quality of life and health for residents, which can be provided with sustainable homes. This can increase productivity and reduce absenteeism of the occupants, which can benefit both employers and employees. Third, sustainable buildings can help create jobs and stimulate economic growth by driving demand for new products, materials, and technologies

Table 1.8 Interests for governments and policymakers

Description	References
Meeting climate and environmental goals	[102]
Reducing energy consumption and greenhouse gas emissions	[103]
Stimulating economic growth through sustainable development	[104]
Enhancing public health and well-being	[105]
Meeting energy security and energy independence objectives	[106]
Supporting the development of new industries and job creation	[107]

[76]. This can support the development of local industries and supply chains and create new opportunities for innovation and entrepreneurship. The interest of governments and policymakers to promote sustainable buildings is driven by a range of economic, social, and environmental factors, all of which are linked to the goal of creating a more sustainable and resilient built environment [34]. The main objective of Table 1.8 is to provide a critical review of the scholarly literature concerning the interests of governments and policymakers in sustainable buildings.

1.3.2 Producers and Manufacturers

The motivations for building producers, such as developers and contractors, to promote sustainable buildings can include economic, social, and environmental benefits. Sustainable buildings can provide economic benefits through energy and water savings, reduced maintenance costs, and increased property values. Additionally, sustainable buildings can provide social benefits through improved indoor air quality, increased occupant health and productivity, and enhanced community livability. Finally, sustainable buildings can provide environmental benefits through reduced greenhouse gas emissions, minimized waste generation, and decreased use of natural resources. Furthermore, governments may incentivize sustainable building practices through regulations and policies that promote sustainable development goals. Table 1.9 reviews the scholarly discourse on the interest of producers and manufacturers in sustainable buildings.

1.3.3 Users and Occupants

Building users and occupants also have motivations for sustainable buildings. The users desire buildings that provide a healthy and comfortable environment to live, work, and play. Sustainable buildings can improve indoor air quality, provide

Table 1.9 Interests of producers and manufacturers

Description	References
Meeting regulatory requirements and building codes	[65]
Reducing operating costs and enhancing long-term profitability	[108]
Differentiating products and services from competitors	[109]
Enhancing brand reputation and goodwill	[110]
Attracting environmentally conscious customers and investors	[111]

Table 1.10 Interests for building users and occupants

Description	References
Reducing operating costs and utility bills	[112]
Enhancing comfort and well-being	[113]
Improving indoor air quality	[114]
Reducing exposure to harmful chemicals and materials	[115]
Meeting personal sustainability goals	[116]

natural daylight, and offer comfortable temperatures through efficient heating, ventilation, and air conditioning systems. In addition, building occupants are becoming more conscious of their environmental impact and want to reduce their carbon footprint. They seek to live and work in buildings with a low environmental impact, consume less energy and water, and generate less waste. Furthermore, occupants want to be associated with buildings that align with their values and ideals. Sustainable buildings are seen as a symbol of progress, innovation, and responsibility, and choosing to live or work in them can be a source of pride and prestige. Finally, occupants may also be motivated by financial incentives, such as lower energy bills or higher property values for sustainable buildings. As energy prices continue to rise, energy-efficient buildings can offer cost savings for occupants. Additionally, sustainable buildings may command a premium in the property market due to their lower operating costs and positive environmental image. The focus of Table 1.10 is to review scholarly papers that highlight the interests of sustainable buildings to building users and occupants.

1.3.4 Environmental and Social NGOs

The motivation for environmental and social NGOs in building projects is to ensure that the construction and operation of buildings positively impact the surrounding environment and the communities in which they are located. This includes reducing the environmental footprint of buildings, improving the health and well-being of occupants, and promoting social equity and community engagement. Environmentalists are concerned about the impact of construction projects on the natural environment, including air quality, energy consumption, and construction materials and waste management. Therefore, the communities that support the environment are looking for construction projects focused on reducing greenhouse gases, preserving natural resources, and reducing waste. On the other hand, local NGOs seek to ensure that construction projects have a positive impact on the people of the community and ensure that these buildings improve social equality and quality of life and facilitate social engagement and collaboration. Table 1.11 presents a comprehensive overview of scholarly papers that discuss the significance of sustainable buildings in the context of environmental and social stakeholders' interests.

1.4 Preferences and Suggestions

In order to address the challenges that have been identified in the development and evaluation of sustainable buildings, a series of preferences have been put forth. These preferences have been organized into separate parts, each targeting a different group of stakeholders. Figure 1.4 shows the stakeholders and game players of sustainable buildings. Implementing these suggestions will help mitigate the challenges

Table 1.11 Interests for environmental and social stakeholders

Description	References
Reducing greenhouse gas emissions and environmental impacts	[117]
Promoting sustainable resource use and waste reduction	[118]
Reducing the environmental footprint of the building sector	[119]
Enhancing social equity and promoting community well-being	[120]
Protecting natural ecosystems and biodiversity	[121]

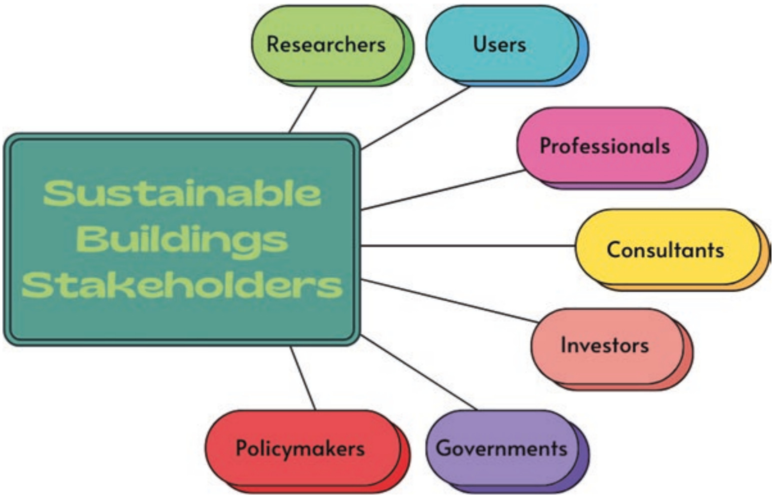

Fig. 1.4 The stakeholders of sustainable buildings

associated with the development and evaluation of sustainable buildings. By adopting sustainable practices, stakeholders can create buildings that benefit the environment and provide higher efficiency and lower energy consumption. Furthermore, government and policymakers can play a key role in promoting and incentivizing sustainable building practices by creating policies and regulations that prioritize sustainability.

1.4.1 Researchers' Perspective

Table 1.12 provides the sustainable buildings' priorities and suggestions from the perspective of researchers.

Table 1.12 Preferences from researchers' perspective

Researchers' perspective	References
Sufficient data collection is advised for prospective research and examination	[122]
Break down energy usage information, adjust energy models, and consider the air leakage and quality of building materials that affect their heat-retention capabilities	[123]
Examine occupants' actions in relation to energy consumption and environmental impact	[124]
Develop approaches by considering the ecological, societal, and financial ramifications and assessing sustainability across the corporate life cycle	[125]
Create design enhancements, such as enhancing post-processing capacity and selecting the most effective approaches for various energy-efficient design optimization issues	[126]
Comprehend the deficiencies in the present evaluation of the edifice	[127]
Perform a comparative analysis between energy storage systems using life cycle assessments in various settings	[128]
Consider parameters related to passive design strategies, such as indoor environmental quality and energy consumption	[129]
Explore the enhancement in energy efficiency by utilizing advanced heating and cooling systems across various building types	[130]
Compare professionals' perspectives by examining disparities in market-specific contexts in emerging and advanced economies to apply Green Building Technologies (GBTs)	[131]
Utilize CREST as a tool for evaluating sustainability in eco-friendly office buildings	[132]
Incorporate the benefits of location and weather patterns when designing environmentally friendly structures	[72]
Emulate the approach in other emerging economies	[133]
Analyze the correlation between interior and exterior systems	[134]
Enhance the construction regulations by prioritizing eco-friendly building practices, effective waste disposal, green architecture, sustainable growth, and an energy-saving mechanism	[74]
Scientists ought to incorporate climate information and geographic origins while constructing the building envelope to encompass a more comprehensive range of areas worldwide	[135]
Revisions are needed for the current certification protocols and energy regulations standards	[136]

1.4.2 Users' Perspective

Table 1.13 contains suggestions and preferences specifically for users.

1.4.3 Professionals Perspective

Table 1.14 offers insights into the sustainable buildings' priorities and suggestions, as viewed from the perspective of professionals.

Table 1.13 Preferences from users' perspective

Users' perspective	References
Utilize low GHG-emitting technologies with high GHG reduction efficiency to reduce their carbon footprint	[137]
Occupants play a significant role in managing energy demand at home	[36]
Raising environmental awareness among the public can enhance self-governance and corporate reputation	[138]
Increasing consciousness among building manufacturers and occupants about sustainable practices can promote sustainability goals	[139]
Project owners, managers, and LEED consultants should evaluate the economic feasibility of implementing sustainability goals to ensure cost-effectiveness	[122]
Facilitating knowledge sharing between stakeholders and technology developers can foster sustainable building practices	[140]
Occupants should understand the efficient functioning of facilities within their buildings	[141]

Table 1.14 Preferences from professionals' perspective

Professionals' perspective	References
Building scientists and mechanical engineers should consider residents' behavior during the design phase to maximize technology effectiveness and outcomes	[142]
Passive systems should be used to create sustainable structures	[135]
Those responsible for evaluating buildings must receive thorough training to possess a solid understanding of the assessment procedure to reflect actual reliable performance in the built environment	[143]
SEAM shouldn't have mandatory requirements for operations. However, in the continuous extensive implementation, professionals should eventually reach a consensus on the necessary criteria	[144]
Architects and sustainable design experts should collaborate during the building design phase to make decisions	[122]
Professional consultancy should be used to validate the discrepancies between the design objectives and the owner's needs	[145]

1.4.4 Consultants' Perspective

The focal point of Table 1.15 is to present the sustainable buildings' priorities and suggestions from the consultants' perspective.

1.4.5 Investors' Perspective

Through the lens of investors' perspective, Table 1.16 highlights the priorities and suggestions related to sustainable buildings.

1.4.6 Governments' Perspective

Table 1.17 provides an analysis of the sustainable buildings' priorities and suggestions from the perspective of governments.

Table 1.15 Preferences from consultants' perspective

Description	References
The expenses and advantages of incorporating sustainability objectives must be evaluated in a cost-efficient way by project proprietors, administrators, and LEED advisors	[146]
The exchange of information should be enhanced among technology developers and stakeholders	[147]
Entities should organize educational sessions, training programs, and workshops to promote continuous professional development	[148]
Greater awareness of construction techniques should be disseminated to address challenges such as economic feasibility and human health	[149]

Table 1.16 Preferences from investors' perspective

Investors' perspective	References
Decision-makers can utilize cost-effective investment strategies, prioritize primary energy demand, and consider overall costs based on their economic capacity, requirements, and preferences	[150]
The opportunities presented by the sustainable remediation movement from academia, government, and industry should be leveraged	[151]
Sustainable buildings should be constructed, and new techniques should be developed	[152]
Stakeholders can accumulate additional LEED credits in new or refurbished construction and enhancements	[153]
Funding should be allocated to sustainable building initiatives to guarantee good indoor air quality	[154]
Educating investors on the positive impacts and returns of investing in energy efficiency is important	[122]

Table 1.17 Preferences from the governments' perspective

Governments' perspective	References
Governments should establish policies that encourage the development of sustainable buildings	[155]
The rating system of upcoming LEED iterations and domestic energy regulations should be enhanced	[156]
The adoption of renewable energy sources for domestic consumption, such as wind and solar water heating, should be considered	[91]
Governments should raise awareness about the benefits of investing in energy and water-saving measures for sustainable buildings	[157]
The governance and oversight of sustainable buildings should be fortified	[158]
Governments can levy a carbon fee or provide rewards to promote policy implementation	[159]
It is important to establish a set of initial data for buildings that are in the process of obtaining green certification or for those that already exist	[160]
Collaborative actions are required to devise a sustainable energy strategy for all urban areas that tackles the difficulties of enforcing energy-saving building regulations	[161]

Table 1.18 Preferences from policymakers' perspective

Policymakers' perspective	References
Policymakers should establish effective policies informed by scientific institutions to promote sustainable building practices	[162]
Policies should be accompanied by defined procedures, standards, and guidelines. This is important to provide guidance for the planning, design, and construction phases	[139]
Policymakers should implement policies with the aim of reducing the carbon footprint of buildings	[163]
Policymakers need a higher level of knowledge in order to appraise and analyze the effects of policies regularly. This helps them to monitor progress toward achieving sustainable development goals	[164]
Policymakers should create policies with the aim of promoting the adoption of renewable energy sources in buildings to have a better environment and society	[158]
Policymakers should conduct investigations to identify variables that impact residential energy efficiency	[165]
Policymakers should establish a carbon trading market	[44]

1.4.7 Policymakers' Perspective

The policymakers' perspective on sustainable buildings' priorities and suggestions is outlined in Table 1.18.

1.5 Conclusions

Energy efficiency is a critical aspect of achieving sustainability and reducing carbon emissions. This paper contributes to the body of knowledge on this topic by conducting a systematic review of selected articles, highlighting obstacles, challenges, and preferences focused on achieving building sustainability through energy efficiency measures. Additionally, the paper provides an empirical analysis of the challenges and barriers involved in adopting sustainable building processes. By addressing these challenges, stakeholders can enhance energy efficiency in buildings, achieve sustainability, and contribute to global efforts to minimize adverse environmental impacts. The value of this paper lies in its ability to help various stakeholders understand these challenges and provide suggestions to researchers and other stakeholders to strategies and turn these challenges into opportunities for the construction industry. By overcoming these challenges, the industry can achieve sustainable building processes and contribute to global efforts to reduce carbon emissions and minimize adverse environmental impacts.

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Chapter 2
The Challenges and Solutions in Sustainable Buildings

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Abstract Energy is considered a fundamental issue in social and economic development in countries. In today's world, the optimal use of energy has received attention due to the increasing need for energy and environmental issues. Considering that modern buildings and infrastructures include a significant part of energy consumption and greenhouse gas production, they have been given special attention. Sustainable buildings play a significant role in reducing energy consumption globally. Also, the need to use renewable resources has increased under the consequences of global warming and the reduction of fossil fuels. As a result, the use of these resources to supply energy to buildings and the design and construction of sustainable buildings have been the focus of many countries to achieve environmental goals. As a result, to reduce the adverse environmental effects and save energy consumption, the composition of renewable resource technology and sustainable buildings is considered a suitable solution and will be investigated in this section. Figure 2.1 shows a graphical abstract of this chapter.

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Graphical Abstract

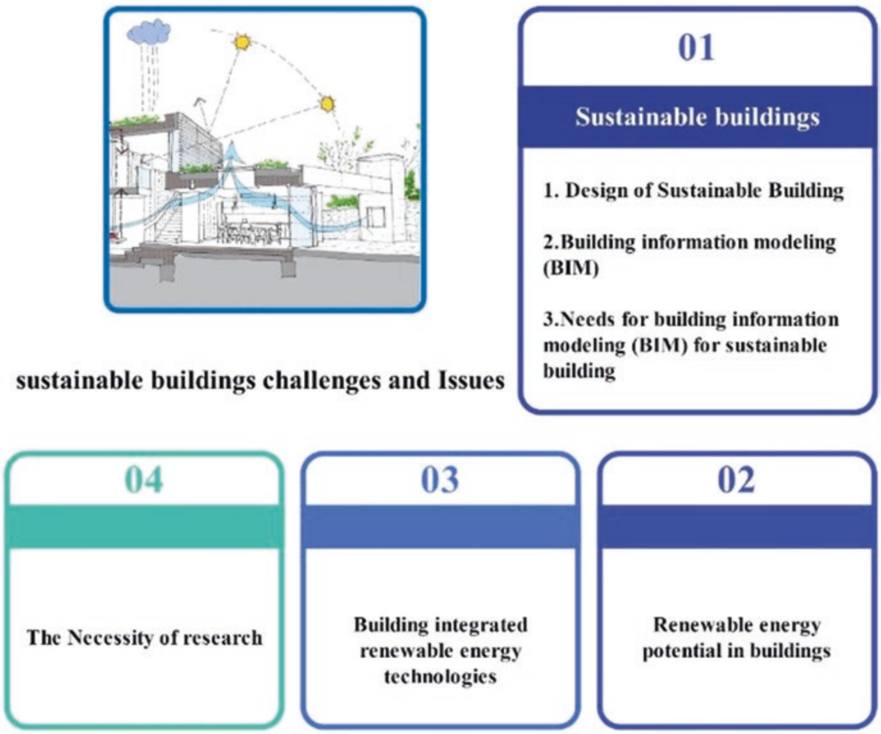

Fig. 2.1 A graphical abstract of the chapter

2.1 Introduction

With progressively genuine natural issues and vitality emergencies, economic advancement within the development segment has become a worldwide consensus. Building inhabitance and operations cause negative impacts on the environment. Private and commercial buildings account for about 40% of global vitality utilization. Agreeing to the US Vitality Data Organization (US EIA), in 2019, primary vitality utilization within the USA was around 2527 Mtoe (100.2 QBtu), and essential vitality utilization per capita was 7.69 toe (305 MBtu). Universally, people utilized approximately 14,501 Mtoe (575 QBtu) of vitality in 2015. In 2019, 62.7% of utility-scale power was created from fossil fuels such as standard gas (38.4%), coal (23.5%), and petroleum (0.5%). They are heightening development in vitality requests, driven by a 2% increment in carbon emanations related to vitality utilization in 2018. Renewables like wind, sun based, and geothermal accounted for 24% of the worldwide power era in 2016 and rose to 26.2% in 2018 [1]. The depletion of fossil fuels and the increasing awareness of environmental issues have prompted energy planners and policymakers to explore the possibilities of integrated resource planning. Consequently, energy-efficient combined heat and power (CHP) units have emerged as a solution for simultaneously providing heat and electricity [2]. Economic advancement objectives are 17 worldwide objectives created by the Joined together Countries Common to advance a viable future for all [3]. The objectives were set up in 2015, and their wide-scale sending is anticipated to be fulfilled by 2030 [4, 5]. Renewable energies created from sun oriented [6, 7], wind [8, 9], hydro [10], tidal [11], geothermal [12, 13], and biomass [14] offer assistance supply vitality requests and encourage the advancement of communities and security of the environment on a worldwide scale.

The amount of energy used by buildings is a matter of significant importance in Europe. Roughly 40% of primary energy and 36% of greenhouse emissions are believed to originate from buildings. The building sector is the top end-use sector in Europe, with a percentage exceeding 45% in certain Member States. The adoption of new objectives has occurred following the 2007 Climate and Energy package, which aimed at reducing buildings' primary energy consumption by 20% by 2020, increasing renewable energy production by 20%, and decreasing greenhouse gas emissions by 20% from 1990 levels. These new targets have been presented under the 2030 Climate & Energy framework. This package addresses the need for a 40% reduction in greenhouse gas emissions from 1990 levels, a 27% target for renewable energy adoption, and a 27% target for enhancing energy efficiency. The European Roadmap 2050 aims to diminish greenhouse gas emissions by a minimum of 80% by the year 2050, in contrast to the levels recorded in 1990 [15].

Most energy usage and emission concerns are connected to how buildings are run, such as their heating and cooling systems, lighting, electrical devices, and other building services. As awareness grows around buildings' environmental impact, individuals and global organizations have taken steps toward implementing rating systems that promote the construction of eco-friendly and sustainable structures. Over the past few years, several countries have introduced regulations that require energy and resource efficiency goals to be met and promote emission reduction in new construction projects or renovations. Different countries employ various rating systems to evaluate the ecological efficiency of constructions. Designers and architects focus more on reducing buildings' environmental impact and energy usage by enhancing their designs, increasing energy efficiency, and promoting conservation [16].

As the impacts of global warming loom large, an increasing number of stakeholders are shifting their attention from conventional energy sources to renewable ones to alleviate the burden of soaring energy expenses. The building sector's energy consumption is mainly dominated by heating, ventilation, and air-conditioning (HVAC) systems, accounting for a notable proportion of 40–60% worldwide. Developers and end-users have shown a growing interest in ventilation systems due to their pertinent roles, such as eliminating indoor air contaminants and dampness while preventing mold formation. Different ventilation methods, namely natural, mechanical, and hybrid, are categorized based on the various driving forces they utilize. The active system, also known as mechanical ventilation, is solely responsible for the proper functioning of many contemporary buildings. Their energy consumption is high, and their complex and bulky design occupies precious usable space [17].

There is a drive to incorporate established sustainable energy techniques into building design to facilitate power generation, temperature control, and water warming. The significance of energy usage within buildings is on the rise globally [18, 19].

2.2 Sustainable Buildings

The concept of sustainability can be shown in Fig. 2.2, which has economic, social, and environmental aspects. The notion of constructing environmentally friendly buildings, known as green buildings (GB), can be traced back to the 1800s or possibly an earlier period. Since 1851, passive mechanisms consisting of "ventilators on the roof and subterranean chambers for cooling air" have enhanced indoor air quality within London's Crystal Palace. Sustainable or high-performance buildings, recognized as GB, have played a crucial role in promoting worldwide sustainability. They have been linked with numerous landmarks such as the 1972 UN conference on the Human Environment, the 1973 OPEC oil embargo, the 1987 Brundtland Report, and various initiatives worldwide like the 1998 Green Building Challenge in Vancouver and the establishment of the World Green Building Council in San Francisco in 1999. The UK's 1990 Building Research Establishment Environmental Assessment Method was also developed with this objective in mind. GB construction is being adopted globally to reduce building energy usage, conserve resources,

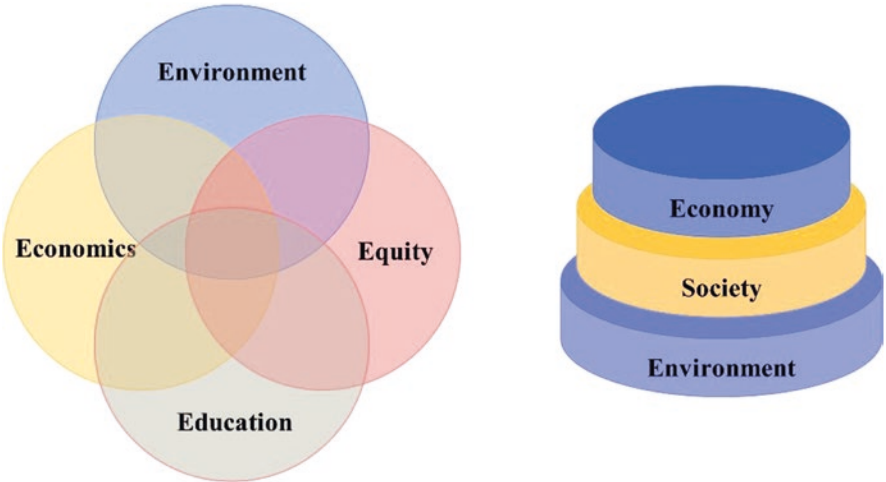

Fig. 2.2 Portrayal of the concept of sustainability

minimize water consumption, and support sustainable development objectives. This method reduces the negative impact of the constructed environment on the environment in terms of carbon emissions and ecological hazards. GB research has become increasingly popular and supported by industry and academia worldwide, mainly due to its advantages and prospects [20].

2.2.1 Design of Sustainable Building

Sustainable design and construction primarily emphasize reducing negative consequences on the environment, society, and the economy caused by buildings. The swift progression in various nations worldwide has produced a substantial amount of uncontrollable building debris, resulting in significant adverse effects on the surroundings, namely heightened contamination of air, water, and soil, contributing to ecological instability, health risks, and climate alteration. Furthermore, preliminary design and building methods have extensive effects on the economy and the environment over an extended period, leading to the inefficiency of energy and material resources [21, 22].

The optimization of building design, strategic selection of site location, and appropriate material choice constitute crucial facets of the Triple Bottom Line (TBL) framework and efficaciously aid in mitigating waste generation. When considering sustainable building practices, selecting sites that can minimize the effects of urban sprawl and prevent the destruction of natural habitats is imperative. Furthermore, these structures should be designed to have a minimal environmental impact, including energy conservation, utilization of appropriate materials that enhance durability, and optimization of performance. One potential strategy for reducing site disturbance during construction is leveraging natural hydrological features, such as stormwater flow, when selecting the site. By doing so, it may be possible to minimize the overall footprint of the building on the surrounding terrain. Moreover, choosing suitable materials that furnish thermal insulation, augment energy efficiency, and curtail contamination and energy dissipation is crucial. Implementing high-performance, low-emissivity lower-glazing is essential in attaining maximum energy efficiency in architectural constructions. The implementation of light bulbs that are energy-efficient and have integrated sensors could potentially lead to a reduction in the overall energy consumption observed in various building structures [23].

The paramount significance of energy conservation through implementing energy-efficient measures within buildings has pervaded global attention. Effective energy management in a building necessitates adherence to four primary principles, namely the implementation of passive building design with the goal of near-zero energy consumption before construction; the utilization of low-energy building materials during the construction phase; the incorporation of energy-efficient equipment to minimize operational energy demands; and lastly, integration of renewable energy technologies to cater to diverse power requirements [17].

The initial aspect pertains to the antecedent architectural blueprint utilized in the erection of solar passive edifices, which has gained extensive global traction as a viable means of achieving thermal regulation and augmenting buildings' luminosity. Another strategy involves the utilization of building materials with low embodied energy in the construction of structures. The third facet pertains to operational energy preservation using energy-efficient equipment within the confines of the edifice. Finally, the building must incorporate integrated renewable systems for hot water heating, solar photovoltaic electrification, and other related utilities [17].

In the European Union, beginning in the year 2020, newly constructed buildings shall incorporate all requisite measures necessary to achieve the condition of nearly zero energy building to conserve operational energy. This paper delineates the four principal facets of energy efficiency in achieving sustainable development in the global building industry. The initial considerations are linked to the efficacy of solar illumination, passive temperature management strategies, and the incorporation of rainwater harvesting systems into passive architectural structures, all of which must be tailored to the prevailing climatic conditions of the specific location. Passive heating designs have become integral to passive buildings in colder climates. The features under consideration encompass sunspace, a Trombe wall, an air handling unit integrated with air–air heat exchangers, and the requisite level of air tightness to accomplish the desired air exchange rate per hour. An academic writing style prompts precise and formal language, emphasizing clarity and objective statements devoid of colloquial terms. Passive cooling strategies for hot and arid climatic regions include water evaporation for wall and roof cooling, roof texture design, earth–water heat exchangers, passive downdraft space cooling, and solar refrigeration. Using low-energy building materials, including fly ash bricks, fiber-reinforced bricks, wood, and stabilized adobe blocks, is gaining significant popularity across various global regions, notably India, the Middle East, Europe, the USA, and the UK. This phenomenon reflects a growing awareness and preference for sustainable approaches in construction practices. Minimizing embodied energy in building construction is crucial in constructing a low-energy dwelling to facilitate sustainable habitat development. The third facet pertains to implementing operational energy conservation methods through using energy-efficient equipment, including but not limited to LED lighting, fans affixed with a five-star rating, and refrigeration and air-conditioning systems within the Indian context. This paper discusses incorporating integrated renewable systems, specifically solar water heaters for hot water usage and small wind turbines or solar photovoltaic systems for electricity generation on the rooftop of buildings. Such systems' economic and environmental implications are analyzed and utilized within said methods. An analysis of energy conservation strategies for structures reveals four overarching approaches that enable the reduction of energy consumption and, consequently, the mitigation of CO_2 emissions from such consumption. The following exposition encompasses a delineation of these factors [17]:

A) Incorporating solar energy utilization into building design and orientation to enhance comfort and efficiency.
B) Materials with a minimal energy footprint for building construction.
C) Utilization of energy-saving household devices to preserve the operational energy of the building.

It is developing sustainable energy technologies that can seamlessly incorporate into building structures. In this book, the focus is on the building of integrated renewable energy technologies.

2.2.2 Building Information Modeling (BIM)

BIM is a digitized technology that involves creating, organizing, managing, exchanging, and sharing building-related data in an interoperable and recyclable manner. BIM encompasses numerous crucial features that facilitate examining building design sustainability, making building performance analysis more convenient. Although BIM has made progress in enabling interoperability with EPS devices for assessing operational energy, most existing BIM software still needs interoperability with conventional LCA devices, which are the primary means of evaluating embodied energy. Assessment of embodied energy is commonly performed when the design has been finalized or developed to a certain degree, limiting the opportunity to explore various design options to lower the overall energy usage of the building. BIM technology promises to enhance productivity, efficiency, infrastructure value, quality, and sustainability while reducing lifecycle costs, lead times, and duplications, minimizing waste, and ultimately improving coordination between design disciplines [21].

2.2.3 Needs for Building Information Modeling (BIM) for Sustainable Building

The rising awareness about sustainability issues related to carbon emissions and reliance on nonrenewable energy sources has compelled the construction sector to embrace a green building approach [24]. Notably, projects significantly surpassing their budget and timeline are prevalent in the public and private sectors across multiple nations. Approximately 40% of global carbon emissions are attributed to building operations. Building projects worldwide have faced significant expenses and delays due to low workforce efficiency, which has raised concerns among professionals and scholars regarding the substandard results of the construction sector.

Therefore, increasing productivity plays a pivotal role in the construction process. BIM is a technological solution that can model sustainability measures, including thermal flow, energy utilization, lighting patterns, etc. During the building process, a comprehensive analysis of the entire life cycle is conducted, including both the embodied and operational energy stages, where alternative structural options are evaluated. Sharing information among designers would be highly beneficial for deciding on design alternatives to reduce energy consumption and greenhouse gas emissions in structures. Thus, there is a need for a proficient and cooperative building information system that can lead the examination process. One of the most significant impacts of BIM adoption in construction is its role in ensuring quality control. Construction professionals can regularly evaluate their projects, allowing them to identify any potential imperfections in the building process. Implementing BIM in the construction industry has the minimum impact on safety. Despite the potential of utilizing BIM functionalities to enhance security in construction, many industry stakeholders still need to implement safety measures through BIM [21].

2.3 Renewable Energy Potential in Buildings

Integrating renewable energy sources within building structures has been conceptualized to bolster energy security and mitigate dependencies on traditional utility supplies while reducing energy consumption's long-term environmental and financial consequences. The energy efficiency strategy of Malaysia encompasses environmentally sustainable solutions that not only effectively mitigate building energy expenditures but also furnish appropriate instruments to diminish carbon emissions. In addition, it is imperative to recognize that adopting optimal energy-efficient strategies in buildings currently accessible is insufficient. Such measures prove unable to eradicate the constant, ongoing need for energy to facilitate the daily operational processes of the formation. The objective of achieving energy efficiency in building operation and making it less dependent on external energy sources can be attained using incorporating renewable energy resources in the construction of the building, thereby resulting in a zero or diminished energy dependence. Renewable energy refers to energy sourced from natural processes that are not reliant on the consumption of finite resources. This energy category is characterized by the ability to be replenished over a relatively short time frame. Many renewable resources have become accessible, encompassing biomass, solar, hydropower, biofuel, wind, and geothermal. Renewable energy technologies that are most frequently utilized and can be conveniently incorporated into buildings comprise photovoltaic (PV) solar systems, solar water heaters (SWH), wind turbines, and hybrids. Additionally, the deployment of biomass as a viable energy source can be confined to select geographically isolated structures, contingent upon accessible organic matter derived from plant or animal residues [18].

2.4 Building Integrated Renewable Energy Technologies

Renewable energy has emerged as a potent remedy for the energy predicament in recent decades [25, 26], orchestrated to circumvent the unfavorable climate and environmental outcomes. As per IRENA's 21 research publications, 2019 manifested a remarkable upsurge in renewable energy's growth, as reflected in the augmented installed power capacity. These resources exhibit superior cost-effectiveness compared to the operational expenses and capital outlays associated with fossil and nuclear fuel-operated plants. The deployment of building integrated photovoltaic (BIPV) systems has been identified as a promising approach toward realizing net-zero energy buildings (NZEB) – crucial in achieving a substantial reduction in the utilization of fossil fuels, which are recognized contributors to global warming. Solar photovoltaic technology has increasingly emerged as the most cost-effective method for electricity generation in various regions worldwide, except Antarctica. Regrettably, the currently established legislative benchmarks to achieve a more significant proportion of renewable energy sources in the power mix fall short of expectations. This is partly due to the rapid pace of technological advances outpacing the corresponding regulatory framework. Notwithstanding, a widespread agreement exists concerning promoting renewable energy development and application, and nations are actively exploring their respective renewable energy potentials [27, 28], particularly in light of the well-established relationship between economic growth and energy consumption [29]. It is evident through examining energy demand data correlating with significant economic occurrences, as exemplified by the trends depicted in [30].

Renewable energy sources are harnessed from inexhaustible natural processes that are perpetually replenished. The sundry sustainable energy sources are procured directly from solar radiation or thermal energy generated from the earth's interior. This definition, as presented in reference [31], encompasses the production of electricity and heat through various renewable sources, such as solar, wind, ocean, hydropower, biomass, geothermal resources, biofuels, and hydrogen derived from renewable resources. The array of renewable energy technologies encompasses solar power, wind power, hydroelectricity, micro-hydro, biomass, and biofuels [32]. As per the Global Status Report of 2007, the employment of renewable energy sources accounted for around 18% of the total global energy consumption in 2006. The figure comprised 13% of conventional biomass, viz., wood burning. Hydropower emerged as the second largest renewable energy source, rendering a share of 3%, closely trailed by hot water/heating, which accounted for 1.3%. Modern technologies, encompassing geothermal, wind, solar, and oceanic energy sources, collectively accounted for a mere 0.8% of the overall energy consumption. Consequently, the technical capacity to utilize said sources is substantial, surpassing all other readily attainable alternatives [33]. Utilizing solar thermal collectors and photovoltaic systems has emerged as a promising solution for meeting a substantial portion of buildings' thermal and electrical energy requirements. In the upcoming years, alternative renewable energy sources, including wind turbines, biomass, and hydrogen generated exclusively from renewable energy sources, may be employed, reducing reliance on conventional energy sources. Renewable energy sources (RESs) and nuclear energy can be regarded as possible alternative energy sources to mitigate the effects of greenhouse gases. Among these two energy sources, it is worth noting that solely renewable energy sources (RESs) are both environmentally clean and compatible with the global ecosystem. Furthermore, RESs enjoy a relatively uniform global distribution, which affords convenient access for all individuals, irrespective of the levels of market trust and ownership undertakings involved. Moreover, RESs prove inexhaustible in nature, serving as a further testament to their unparalleled sustainability. Renewable energy technologies possess numerous advantages, including facilitating energy sustainability and security, augmenting employment opportunities, and extending longevity to energy systems. Despite the high cost of solar energy systems, it appears they remain consistent with European and international obligations within the context of renewable energy. The amiable environmental aspects of solar technology make it a highly favorable option for building and urban applications. This technology holds significant economic value for numerous countries as it presents a practical alternative to costly and foreign-sourced traditional energy sources such as crude oil, natural gas, coal, and nuclear fuels. Integrating solar energy systems into buildings represents a highly synergistic approach to fulfilling the diverse energy demands of heating, cooling, electricity, and lighting. The exteriors of residential buildings such as houses, commercial establishments including hotels, athletic centers, and other architectural structures can serve as auspicious areas for augmenting the utility of solar thermal collectors and photovoltaic panels. Structures can be intentionally planned within the framework of bioclimatic architecture to reduce their energy requirements and minimize their ecological footprint by utilizing advanced heat-insulating materials and specialized glass products (e.g., suberized cork or argon-embedded panes). Windows with advanced technological features, commonly called “smart windows,” have demonstrated efficacy in minimizing thermal losses during winter and reducing energy consumption for cooling purposes in summer. From this perspective, it is plausible that the potential for energy conservation in buildings, particularly in modern structures, may exceed 50% compared to conventional building energy consumption. This may ultimately evolve into a customary practice in constructed habitats. The deployment of appliances and dynamic solar-powered mechanisms is notably linked to the escalation of their expenses and their congruity with the edifice’s design and ecological backdrop. Solar energy systems are favored for aesthetic purposes to circumvent the adverse effects of diesel engines employed for thermal and electrical generation, such as their potentially deleterious environmental and social outcomes. The act of smoking and the presence of chimneys are phenomena subject to academic investigation. Applying the measures mentioned earlier assumes utmost significance, subject to their harmonious integration into the ecosystem’s pre-existing local and natural attributes, facilitated by prudent strategic planning and sound environmental analyses [18, 34].

2.5 The Necessity of Research

The importance of addressing environmental concerns on a global level is increasing, and the topic of urbanization is highly pertinent in this context. Dense urbanization can be held responsible for several environmental issues, such as urban heat islands, decreased energy resources, and emissions of greenhouse gases. Literature has provided evidence of a significant surge in global energy consumption over the past 40 years. According to the International Energy Agency, there has been a 93% increase in global energy consumption between 1971 and 2014 [35], with a considerable portion attributed to building usage. Buildings in European countries are held accountable for contributing to 36% of the overall production of greenhouse gas emissions. According to additional reports, a notable amount of energy is utilized by commercial establishments for heating, cooling, and illumination [36].

The increasing power demand, the threat of climate change, and the scarcity of energy resources make it imperative for energy-intensive industries to invest in precise energy monitoring methods to improve the efficiency and productivity of energy systems. The feasibility of determining the significant proportion of different sectors in the energy market is improving with the availability of energy usage information from residential, commercial, and industrial sectors [37]. A US Energy Information Administration prediction indicates that the disparity between energy production and consumption will exceed 2 billion GWH by 2030 [38]. With the increasing focus on global sustainability, managing and reducing energy usage and greenhouse gas emissions across the entire lifespan of buildings has become a swiftly expanding area of exploration in construction and engineering studies [39].

The availability of energy is vital for the progress and sustainability of various nations, acting as a lifeline supporting their economic and social development. With the swift expansion of infrastructure and economic prosperity, the escalating need for energy in the world remains a significant factor. The requirement for energy is impacted by the rise in population, individual earnings, and changes in demographics, such as the expansion of urban settlements and economic advancements. Energy consumption demonstrated a growth of 7.5% in 2012, and it is projected to increase within the spectrum of 6–8% during the future years. The need for energy is impacted by population expansion, income per person, and shifting demographics, particularly the rise of urban areas and economic advancement. In 2012, there was a 7.5% surge in energy usage, and predictions are that it will continue to increase by 6–8% in the following years. Therefore, it's crucial to utilize energy productively to conserve the existing energy resources and decrease the increasing energy demand. The building industry is addressing the difficulties above as a possible solution. The emission of greenhouse gases (GHGs) is heavily influenced by buildings and constructed areas [40].

As previously noted, buildings are responsible for most energy consumption, making it imperative to conduct sustainability evaluations in the building industry on a global scale to ensure sustainable development. The sustainable design aimed to decrease the exhaustion of significant resources like water, energy, and raw materials forestall ecological deterioration caused by facilities and infrastructure from inception to conclusion and construct secure, profitable, and high-performing environments that make sensible use of water and solar energy. As a result, the possibility of saving energy in buildings is substantial. Energy-saving techniques are formulated for both newly erected structures and buildings undergoing renovation. In addition to the usual methods for improving energy efficiency, successfully reducing building energy consumption requires implementing and integrating credible renewable energy technologies with the passive building approach [17].

2.6 Discussion and Conclusions

Constructing enduring edifices includes lessening adverse ecological effects while enhancing living standards. Applying a design approach that prioritizes the needs and preferences of users is necessary to attain these objectives. A novel and comprehensive strategy for constructing buildings is emerging, characterized by an integrated design approach that supersedes the reductionist approach relying on a minimal number of standards and a linear model. A comprehensive design strategy aims to enhance building performances in line with the goals of an integrated design. The structural arrangement in this approach seeks to improve the overall functionality of the entire building.

The fast-paced economic expansion of the world poses significant energy and environmental hurdles that need to be overcome to ensure sustainable progress both presently and in the future. Sustainable developments are the solution to maintaining equilibrium among economic progress, energy consumption, and environmental conditions. Developing energy efficiency in buildings is a significant industry that can contribute to mitigating the issues related to the exhaustion of energy sources and the degradation of the natural world. In general, there are two approaches to reducing energy consumption in buildings: implementing energy-efficient methods and incorporating renewable energy technologies as sources to fulfill the country's energy requirements. The most current energy usage in buildings and tactics for increasing energy efficiency in the construction industry are the primary topics addressed in this book [41].

Today's buildings consume substantial energy from the initial construction process to their operation and maintenance stages, leading to high energy intensity. Given the global energy crisis, creating practical approaches to energy conservation in buildings is vital. Numerous techniques can be implemented to decrease the utilization of traditional energy derived from fossil fuels to fulfill a structure's energy demands. By adapting to the specific site, the direction of the building, and the weather patterns of the area, it is effortlessly possible to incorporate an array of solar passive design elements into new constructions. Applying Trombe wall design principles as a solar passive heating retrofit in the honey storage facility has exhibited encouraging outcomes for winter warmth. Employing appropriate daylighting design can significantly decrease the need for artificial lighting during daylight hours, thus diminishing the amount of energy used by the building for lighting. As a result of incorporating solar passive attributes into the structure, the building's energy usage is decreased, ultimately leading to a decline in CO_2 emissions and promoting sustainable growth. Another crucial factor is utilizing building materials that are readily available locally and have low embodied energy to limit the significant energy consumption during the construction of structures, which results in reducing carbon dioxide emissions emitted by the building sector. The third component involves minimizing facilities' energy usage during operation by utilizing non-renewable sources. Therefore, the emphasis is on advancing renewable energy technology to satisfy the energy needs of buildings as a viable substitute. A structure that relies solely on renewable energy systems to meet its energy needs is called a zero-emission green building, indicating superior energy efficiency. The comparison between renewable and traditional energy systems is based on economic factors to determine the feasibility and adoption of these alternative technologies [17].

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Chapter 3
Introduction and Literature Review to Deployment of Photovoltaic Systems in Buildings

Oweis Gholitabar and Ali Ghasemi-Marzbali

Abstract Photovoltaic (PV) solar technology is one of the most promising developments in renewable energy. As the cost of solar panels continues to decrease, it is becoming more accessible and widely used in both urban and rural areas. Using solar energy to power our homes, businesses and communities can help reduce our dependence on fossil fuels and move toward a more sustainable future. This study examines modern technologies used in sustainable buildings, such as beeper systems and the mandatory implementation of photovoltaic systems in advanced countries. The methods of supplying electricity to buildings through photovoltaic systems are also discussed. Storage is a crucial topic in renewable energy and is discussed in the following sections. This study also critically examines the use of phase change materials (PCMs) as heat-absorbing materials in photovoltaic panels and their impact on heating and cooling in the interior of sustainable buildings.

3.1 Introduction

In recent years, there has been a significant increase in the adoption of renewable energy sources worldwide, driven by the need to combat climate change, reduce carbon emissions, and decrease reliance on traditional fossil fuels. Renewable energy is becoming increasingly recognized as a key pillar of a sustainable society, and its importance is only expected to grow in the coming years. Of course, there is infrastructure to reduce carbon emissions in buildings, by way of energy-efficient construction projects. For more than a decade, advanced global economies (European and American nations) have promoted the idea of zero-energy clean buildings. While the main focus of renewable energy system optimization is the

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combination of zero-energy clean buildings. The main priority of sustainable buildings is to reduce energy needs through design. Then, for the energy balance of a building, renewable energy can be designed in place or out of place of the building according to the given priority. Design factors such as the window-to-wall ratio, thermal insulation using materials like aerogel or vacuum insulation panel, and the use of thermal energy storage through phase change materials are just a few of the solutions available to address the energy needs of sustainable buildings. Additionally, various heating and cooling methods, such as Trombe walls, solar chimneys, green roofs and walls, cooling ceilings, and earth-to-air heat exchangers, are being explored to further reduce energy consumption.

While ongoing research into smart building projects and combined heat and energy systems is important for reducing energy needs, it is also crucial to optimize renewable energy systems. This involves finding the best models for energy storage to maximize resources and minimize costs, specific to a geographic location.

Optimizing hybrid renewable energy systems can have a significant impact on various targets, including Loss of Power Supply Probability (LPSP), Annual Cost of the System (ACS), Net Present Value (NPV), Levelized Cost of Energy (LCOE), carbon emissions, renewable energy reduction, Potential Energy Waste Probability (PEWP), Dump Energy Probability (DEP), and Loss of Load Probability (LLP). By considering these factors, renewable energy systems can be tailored to meet the energy needs of buildings while minimizing environmental impact and maximizing efficiency.

A significant part of battery modeling is the destruction caused by the battery; As in optimization models, this problem is not considered in batteries by researchers. Most optimization of hybrid renewable energy systems in the last 3 years has not considered battery destruction due to the extensive literature in battery modeling. A multipurpose optimization should be performed for an independent hybrid energy system, where the cost of energy and the propagation of the life cycle is minimized, as well as the destruction of the batteries. In methods of renewable energy management in power distribution in storage systems, at first the issue of insufficient photovoltaic power is discussed. Available power from PV is first used to respond to AC loads. If the battery charge state is higher than the minimum charge state, the power supply deficit is taken to the battery. If there is still a deficit of electricity, the energy storage system cannot provide electricity, and as long as the hydrogen level in the reservoir exceeds the minimum, the fuel cell will reduce the remaining power. If there is still a shortage of power and if the hydrogen level in the tank is no more, the fuel cell will not be able to provide energy. A fuel cell is a device that converts fuel (such as hydrogen, methanol, natural gas, gasoline, etc.) and oxidants (such as air and oxygen) into electricity, water, and heat. In other words, it is similar to a battery but does not require storage (charging), as opposed to a battery. The system will operate until the required fuel and air are supplied. Since photovoltaic power is greater than the demand for load, there is an excess power after the demand for load is met. And if the battery can't reach its maximum charge, this surplus power is used to charge the battery's energy storage system, and if there's still excess energy, it's because the battery can't be charged beyond the limit. Battery charging mode should not be lower than most because the battery can reach its maximum charge from excess power. The remaining surplus force is used to provide the proton exchange membrane electrolyze energy for hydrogen production in the hydrogen tank, where the hydrogen surface in the reservoir is less than the allowable surface, and there is also a surplus power, so the remaining amount is recorded as energy dissipation. In the case of batteries as energy storage systems, after the battery has consumed maximum power, the remaining balance is recorded as energy loss [1].

When designing sustainable and green buildings, it is important to consider factors such as durability, cost-effectiveness, resource conservation, inter- and intergenerational social justice, and diverse perspectives throughout the life of the building. To evaluate the performance of sustainable and modern buildings, this section explores the use of life cycle sustainability assessment (LCSA) to assess positive and negative impacts. Modern buildings are modeled as a covered area and a place, with building materials varying while keeping architectural plans constant. Additionally, the study shows that stability and optimization goals are evaluated annually to assess the impact of changes in the building's life. Results show that buildings made with ceilings, recycled metal frames, brick walls, insulated sheets, and green concrete used in the columns exhibit higher stability performance compared to other buildings studied.

From an energy management perspective, implementing cleaner production strategies (CPS) such as product modification (e.g., double-walled windows) and technological modification (e.g., solar photovoltaic panels and solar water heaters) has proven to be effective in improving sustainability in buildings. Analysis of buildings shows that the useful life of buildings and their components greatly impacts overall sustainability performance in residential buildings. Therefore, selecting durable materials with good thermal properties during the design phase is crucial for maintaining stability performance.

In the building sector, several research efforts have been made to address the environmental, social, and economic challenges, including the use of environmental life cycle assessment (ELCA), life cycle cost (LCC), and social life cycle assessment (SLCA) to assess sustainability based on indicators such as carbon footprint and energy consumption. To achieve maximum sustainability levels in cleaner buildings, it is crucial to integrate sustainable social, economic, and environmental goals. While LCSA is still in its early stages, it has the potential to assess the environmental, social, and economic aspects of sustainability in the building industry.

In designing renewable buildings, three systems must be considered: the wall system, base system, and roof system. Choosing suitable building materials for each component, including walls, ceilings, and foundations, is essential for optimizing sustainability. The use of alternative materials such as byproducts and recycled materials can also be considered in LCSA to further enhance sustainability in the construction of residential buildings.

Estimating the useful life of a building depends on the building material, damage mechanism, and the execution level of the work. Considering the combination of materials, architectural design, and specific weather conditions of the area, the useful life of buildings cannot be estimated accurately. Therefore, uncertainty always exists in predictions. However, efforts must be made to reduce uncertainty by considering reliable sources. Shelf life is predicted via probabilistic, cutting, and engineering methods.

Goals

- Evaluating the life cycle stability of residential buildings.
- Determining the sustainability rating of buildings made of various building materials.
- Determining the effect of service life on the stable performance of the relevant building.
- Determining the effect of maintenance on the stable performance of the building during its construction.
- Identification of important sustainability points (social, economic, and environmental) in the supply chain to develop performance improvement [2].

3.2 Modern Technologies in Photovoltaic Systems for Sustainable and Renewable Buildings

The main purpose of this section is to building-integrated photovoltaic (BIPV) systems, because their design is to reinforce electric and thermal power from demand side. To achieve an optimal balance between supply–demand cycles, it is important to design and implement strategies that take into account the technical aspects of building-integrated photovoltaic (BIPV) systems. Having a better understanding of these technical aspects is crucial to the success of this approach. Additionally, protocols have been developed for utilizing solar energy through airflow for heating/cooling, ventilation, and water circulation to further reduce energy consumption.

For buildings to become more sustainable, it is important to ensure that the useful life of nonstructural components matches the building's useful life, reducing the need for maintenance. Integrated Building Photovoltaic Systems (BIPVs) have been developed for both residential and commercial purposes to minimize energy requirements and greenhouse gas emissions [3]. The design of BIPV systems requires careful consideration of energy infrastructure, renewable energy sources, and energy efficiency regulations. This section focuses on the performance of roof and façade-based BIPV systems, as well as the parameters that affect heating and cooling loads in buildings. Various technologies exist to aid in the configuration of BIPV systems, prevent potential issues, and allow for design flexibility to adapt to local environmental conditions. It is also important to ensure compliance with building regulations and construction structures [4].

Solar energy received by the Earth every year amounts to approximately 1.8×10^{11} MW, which is around 10,000 times the global energy demand. Buildings in developed countries consume roughly 30–40% of the electricity generated annually, while those in developing countries consume approximately 15–25%. The increase in electricity consumption from primary energy sources results in a rise in CO_2 emissions, which has a severe impact on the environment. Reducing energy demand in buildings significantly decreases the required energy supply and thereby minimizes GHG emissions. Therefore, engineers and scientists are highly interested in achieving net-zero energy buildings (NZEBs) by focusing on increasing energy efficiency and setting minimum energy conservation criteria. NZEB is defined as a building that consumes no more energy per year than it can produce.

Solar energy technologies, such as heating/cooling systems, photovoltaic (PV) panels, and thermoelectric devices, offer promising solutions to meet the energy demands of our world. However, the suitability and feasibility of implementing solar power depend on factors such as the area, cost, location, national energy policies, and the size of the power supply system. PV systems, which generate electricity without mechanical movements, are considered the most environmentally friendly option. The cost of PV power plants has been decreasing rapidly, and their development and efficiency have been increasing, which ensures the secure generation of electricity worldwide. The last three decades have seen significant advancements in experimental and simulation techniques related to building-integrated photovoltaics (BIPV) technology, as urbanization has become increasingly prevalent in modern societies. Since the beginning of the century, more countries around the world have been interested in reducing and consuming fossil fuels and searching for more comprehensive solutions. Therefore, a complete understanding of the electrical properties of the PV panels used in the BIPV system is important for the removal of heat, which is done using PV panels. In addition, PV panels have the best performance among all types of PV modules, with respect to the view or ceiling at different tilt angles, allowing the investigation of innovative solutions to optimize solar radiation to generate thermal and electrical energy by PV cells.

3.2.1 Photovoltaic Integration in Building: Based on Air Cycle

Here's a possible rephrased version: The BIPV/T system is a technology that can absorb solar radiation and convert it into both electrical and thermal energy. When solar energy falls on the building cover, the crystal PV module can convert 15–20% of it into electrical energy, while the remaining 5–10% is either reflected or transformed into thermal energy, increasing the surface temperature of the PV modules. In large-scale applications, the peak temperature of a PV module can reach up to 60 °C, especially on hot summer days. To reduce the heat, air cooling is a cost-effective method that has been extensively researched. This technique involves creating an air gap between the PV panels and the building wall and using pre-heated air for cooling. This can be achieved by using the facade or inclined ceiling for forced air circulation. Typically, PV modules are installed on the roof or front view of BIPV systems. To adjust the temperature of the module, heat transfer by the fan is the most common method used. However, additional investment and higher consumption of electrical energy are caused. The consumption of electric energy in HVAC systems installed with solar-ventilated facades reduces by nearly 20% [5]. In an air-based BIPV system, airflow supplied for space heating is driven by a fan to prevent excess air from entering the air gap, which results in increased heat transfer to building spaces. The effect of fans on system performance can improve BIPV system efficiency to a power of approximately 9% [6].

3.2.2 Water Cycle Based on Integrated Building Photovoltaic Systems (BIPVs)

Water is a more efficient fluid than air for carrying heat generated from photovoltaic modules in BIPV systems due to its thermophysical properties [7]. By using a water-based cooling system, excess heat can be removed from PV panels, which leads to a significant increase in PV energy conversion efficiency when the circulating water temperature is below the PV cell temperature. As the water temperature increases, it can absorb undesired heat from the modules, and it can be used as a heat source for various heating and cooling applications related to buildings [7]. The use of hybrid solar systems in different building configurations has promising benefits for increasing the energy output per unit of installed collector surface. In addition to the conversion of solar energy into BIPV systems, reducing the transmission of radiation to buildings can help reduce the cooling/heating energy requirements of the building, and proper design and construction integration can save building materials. PV modules and hot water collectors can be installed vertically on the wall to act as a water heating system. Experimental investigations in different operating modes have shown that a natural circulation water system for forced circulation in a hybrid solar pre-heating system is better than using any other working fluid. The reported thermal efficiency was 8.56% at a zero reduction temperature of 38.9%, and the corresponding electrical efficiency increased by avoiding shadow effects [8]. In addition, a preferred thermal insulation performance was developed on the BIPV façade for winter and summer.

3.2.3 Passive and Active Effects of BIPV Systems

Total energy savings of air- and water-based BIPV systems depend mainly on various factors, such as optimizing the operation parameters and the precise design of equipment, type of insulation, and building materials. Cooling, heating, control system, and weather conditions significantly affect energy efficiency. Given the power consumption, minimizing demand is important to prevent the power plant's equipment from growing. A well-sized solar energy system for buildings should be determined through accurate simulations that take into account the building envelope and the selection and control of heating, ventilation, and air conditioning (HVAC) equipment. The system's size should also be designed to match the building's electricity consumption to ensure the stability of the national grid and minimize electricity costs.

3.2.4 BIPV Economic Considerations

The construction sector accounts for about 40% of the world's energy consumption. Therefore, a shift toward BIPV systems could lead to replacing traditional building materials with a mixture of PV modules, introducing innovative building materials with high thermal insulation and electric energy production. The widespread adoption of BIPV systems faces several challenges related to economic policies, including general acceptance, tariff implementation, and national economic support, as well as technical considerations such as energy conversion losses. Therefore, the BIPV economy can be classified based on these criteria. The economic topic in BIPV systems depends on the kinds of buildings that BIPV products are used on such as residential or nonresidential buildings with architectural features, technical-economic feasibility, economic support, annual maintenance and replacement costs, building loads and structures, etc. Thus, the basic drawback of BIPV systems is that it has a high cost. Therefore, an expensive technology BIPV system is currently only producing 0.05% of the energy used in the original environment by this promising technology [9].

3.2.5 Reviews

Discussions of heat generation related to the design and implementation of BIPV systems have major problems that require systematic reduction and development. Excessive heat of PV modules and heat transfer to the interior of the building can unwittingly increase the cooling load and increase the electricity consumption of air conditioning equipment. Our goal is to reduce the average energy consumption in buildings to levels that can be managed with passive technologies, still to meet the total demand for primary energy at 60 kWh/m^2. There is considerable weather. Existing urban areas, government economic policies, humidity and temperature, etc., affect the efficiency and installation of BIPV systems. Construction materials and building houses differ from country to country, but photovoltaic technology is almost similar and international.

One of the major shortcomings of BIPV systems is the lack of a monitoring system to ensure long-term performance. Monitoring is necessary to detect defects and determine any necessary system changes to maintain maximum performance over time. The integration of PV modules into building materials affects the thermo-physical characteristics, resulting in passive and active effects on indoor and wall temperature, cooling and heating, and overall thermal comfort. These factors have a significant impact on a building's electrical energy consumption and the design of the national electricity grid.

3.2.6 Overview

BIPV systems are an environmentally friendly solution that aligns with sustainable development goals by reducing carbon emissions and minimizing greenhouse gases. Energy savings in both air-based and water-based BIPV systems depend on several parameters, such as optimal operating parameters, correct equipment design, insulation types, and building materials. The price and performance of PV components are crucial factors affecting the development of the BIPV market. Additionally, recent advances in sustainable energy technologies and the increased aesthetic appeal of BIPV systems have generated strong interest in this field. Standardization and coding of BIPV systems can facilitate installation and reduce risks. In the construction sector, adequate knowledge about BIPV systems is crucial. The most promising aspect of BIPV systems is the prediction of the effect of electricity pricing variables through net metering policies. Such policies can encourage significant growth in renewable energy systems, especially in countries that exclude traditional fossil fuel-based power plants. Therefore, proper design based on current market tariffs is recommended to support further development of BIPV systems in new and existing buildings. Furthermore, studies on roof/facade PV installations need to be conducted in different economic scenarios to demonstrate the potential of combining PV systems with other building components, such as battery storage, which may affect the economic characteristics of the building's overall energy system. In the following section, we will discuss the issue of storage in solar systems after reviewing BIPV systems.

3.3 Investigation of Electrical and Photovoltaic Power Storage Technology for Supplying Sustainable Buildings

This section provides an overview of the development perspective, the scope of research, and the optimization of the design of hybrid photovoltaic-electric energy storage systems to provide electricity to sustainable buildings and can provide a clear guide for further research in the relevant fields. Solar energy is known as a worldwide replacement for fossil fuels due to its availability and environmental benefits. One of the most important solar photovoltaic applications is alternative energy supply methods for sustainable buildings. In most urban areas, this type of energy consumption is used. In order to compensate for the unexpected fluctuations in solar energy production, electric energy storage technologies have been introduced to meet building demand. The purpose of this section is to focus on the combined photovoltaic-electric energy storage models for generating and supplying electricity to buildings. The research output tested at the university briefly states: At first, the total installation capacity of photovoltaic electrical energy systems is investigated to demonstrate significant progress in the developing markets, in particular, the latest situation in the application, installation, and commissioning of solar energy as one of the most popular energy storage technologies in the developing markets and its use in sustainable and renewable buildings. The research progress in the field of photovoltaic electric energy storage technologies is classified by various types of mechanical, electrochemical, and electrical storage and then analyzed on the basis of technical, economic, and environmental performance. In addition, an extensive study on photovoltaic electrical energy hybrid storage systems in sustainable buildings is carried out using optimization criteria, which leads to its improvement in stable and far-away buildings in the future. In photovoltaic electrical energy, lithium-ion batteries, supercapacitors, and storage technologies offer a promising future in PV energy storage for building power supply. One of the issues discussed in the field of performance analysis, evaluation, and optimization of photovoltaic electrical energy storage systems in sustainable buildings is flexible control, network integration, and intelligent building. In recent years, fossil fuel shortages and their negative impacts on the environment have attracted global efforts to reduce energy consumption and explore alternative energy sources. Because construction sectors currently account for about 20–40% of total energy consumption in developed countries, using renewable energy as an alternative to fossil fuels in order to reduce the energy crisis and environmental pollution is of great importance. Solar and wind energy have increased significantly in recent years. Wind power (such as wind turbines) is usually installed on a large scale and widely used in various areas. For buildings with limited installation space and the need to control vibrations and adverse wind conditions in an urban environment, solar energy is better than the power source and its combination with the existing structure is easier.

However, since solar energy is usually intermittent and unpredictable, it is not consistently compatible with building demand. Technologies related to energy storage are essential for achieving sustainable and reliable power supply. The Integrated Energy Storage Unit can not only supply the required energy with the demand of the building, but it can also set the grid frequency for highly durable renewable energy systems. Therefore, it is important to investigate the integration of electrical energy-saving technologies (EES) with photovoltaic (PV) systems to provide effective power for sustainable buildings. Integrated solar energy and energy-saving technology have risen globally in recent years and have good economic and environmental gains.

3.3.1 Storage Technologies

Storage technologies can be classified into three main categories according to the working mechanism:

- Mechanical storage
- electrochemical
- Electric

Mechanical storage is one of the technologies that include hydroelectric energy storage (PHS), air energy storage (DES), and compressed air energy storage (CES). The technologies discussed in electrochemical storage include battery energy storage, electric energy storage, and hydrogen energy storage. Electric storage technology also refers to the energy storage of supercapacitors (SCS). These storage systems have been investigated from technical, economic, and environmental aspects. PHES (Water Energy Storage Pump) is the complete and most common (EES) and is used for large-scale energy systems, occupying up to 99% of the total capacity of energy storage. To further promote the penetration of renewable energy, PHES as an integrated storage technology draws great attention. To supply buildings with electricity, power generated by PV panels is used to pump water from a lower reservoir to a higher height in low-load hours, and stored potential energy can be released in this section and converted into high-quality electricity to meet the maximum electricity demand in buildings. A hybrid PV-wind system with a pump storage system is shown in Fig. 3.1.

As a wide energy storage technology, PHES has many advantages when combined with PV production systems:

1. High efficiency, about 75–85%
2. Flexible and prompt response
3. Convenient power support
4. Frequency support

3.3.2 Study Points on Optimization in Hybrid Systems Storage of Photovoltaic-Electric Power PV-EES

In addition to reducing the cost of electrical energy storage PV-(EES) systems, optimization studies are performed to consider additional goals from the three main parts of PV-EES systems: the source side (energy supply), demand side (energy

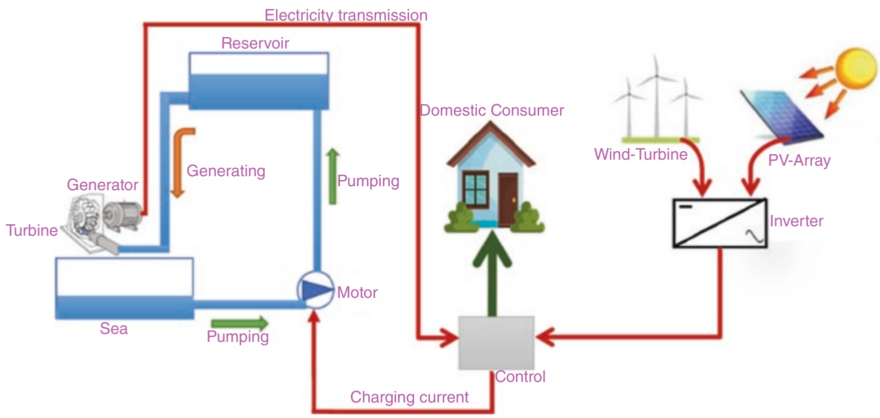

Fig. 3.1 A hybrid PV-wind system with a pump storage system

consumption), and the network side. On the source side, a significant amount of research is focused on system search and stability.

- PV-EES hybrid systems are promising technologies in the booming market and the penetration of renewable energy in building. This section reviews the recent growth of PV-EES hybrid systems for power supply of buildings in terms of universal application as well as the progress of research in system performance and design in optimization. The following research findings and gaps have been investigated to promote the use of PV-EES technologies in buildings.
- Storage technologies, lithium-ion batteries, and supercapacitors offer promising prospects in PV energy storage to provide electricity to integrated buildings, with applicable storage capacity, speed in response, relatively high efficiency, and reduced environmental impacts. However, our goal is to reduce the cost for more widespread applications in buildings. Further research should be done to improve and adjust these PV-EES-to-use technologies for cost management.
- Hybrid PV-EES technologies aimed at providing building electricity have special requirements in practical conditions such as geography, weather, storage scale, and building load. It is suggested that when considering technical, economic, and environmental possibilities, local conditions of source, demand side, and network side should be considered.
- To achieve clean, efficient, flexible, and smart buildings, control methods involving power distribution, PV panel, EES unit, building, and power grid must be further studied, and control algorithms must be created to address the implementation of these key components.
- Different decision-making techniques using different methods should be investigated for multimodal optimization to provide a suitable design for building power. Furthermore, to check the most appropriate method, one must use the chosen algorithm (such as NSGA-II, PSO) to achieve the appropriate solutions for PV-EES systems.

3.4 Technical and Economic Analysis of Integrating Solar Air Heating System in Residential Building Wall

Buildings are major consumers of energy, particularly in areas with varying climates where the need for heating and cooling is significant. To address this issue, renewable energy sources are being integrated into buildings to reduce energy consumption and greenhouse gas emissions while lowering economic costs. While the initial purchase and installation costs of renewable energy systems may be high, their operation and maintenance costs are negligible. This section will analyze the integration of renewable energy sources in the building sector using the SAHS solar air heating system, which heats building environments with solar energy. Technical performance, reduction of building energy consumption, economic efficiency, and reduction of greenhouse gas emissions will be evaluated, and the annual performance of the SAHS system will be analyzed in both warm and cold seasons.

Additionally, the proposed SAHS system will be compared to traditional heating systems, and its effectiveness in reducing building energy consumption using renewable energy will be assessed for various climate conditions and building orientations. The installation of SAHS on building walls helps reduce heat loss from the building and restore lost heat. In addition to economic benefits, using this system will also reduce annual CO_2 emissions based on weather conditions. Energy and climate change are interconnected because energy production primarily involves converting and burning fossil fuels, making it necessary to investigate energy production and use to combat climate change. Proper energy efficiency can significantly reduce greenhouse gas emissions since they are mainly released during energy production and use while also reducing energy imports and saving consumers' money. Energy efficiency has been identified as the fastest and most cost-effective approach to addressing economic and environmental challenges. As a result, the EU has set energy efficiency goals for 2030 and 2050 to reduce greenhouse gas emissions while promoting energy production from renewable sources and increasing building energy efficiency.

The EU targets up to 2030 include the following [10–14]:

- At least 40% reduction in greenhouse gas emissions (compared to 1990 levels).
- Increase the share of renewable energy in the final energy consumption (compulsory objective in the EU).
- A clear goal to improve energy development by at least 27%, compared with future energy consumption; this feature will be reviewed in 2020 with a 30% goal at the European Union level.
- And until 2050: The EU plans to reduce its emissions by 80–95% compared to 1990 levels. This share will be checked in 2020 with a 30% goal in the EU.

Renewable energy projects have emerged as viable and sustainable energy alternatives in many countries, thanks to various strategies developed to support them. The financial return on investment (ROI) is a crucial factor for users of these systems, given that their initial investment costs are typically higher than those of traditional fossil fuel-based systems. However, unlike conventional systems, which incur significant fuel costs, renewable energy systems have negligible operating and maintenance costs.

3.4.1 Application in the Building Section

This text describes how the construction sector is a significant contributor to energy consumption. In particular, building heating and hot water production accounts for almost 70% of the total energy consumption of the building. The text goes on to describe how the heating sector is responsible for 55% of the energy consumed in an apartment and 80% for single-family homes. The remaining energy is used for indoor ventilation, air conditioning, lighting, and other home appliances. Additionally, the amount of energy consumed per square meter will vary depending on the climate zone, with single-family homes consuming about 24% more energy per square meter than apartments in multi-family blocks [15–18].

Heating energy consumption in the building should compensate for the heat losses. Thermal losses are usually formed through the separator elements between the internal spaces and the outer environment, which is called the building cover. The heat supplied by heating systems must meet these thermal losses, which have a direct ratio. Annual thermal losses of buildings are expressed in kilowatt-hours per year or according to the residential area in kilowatt-hours per year.

This statement highlights that energy consumption and operating costs of renewable energy systems are dependent on the availability of incoming heat and sunlight. By reducing thermal losses in buildings, energy consumption costs for heating (whether through gas, liquid or solid fuel, or electricity) can be greatly decreased. Additionally, this reduction in energy consumption leads to a reduction in negative environmental effects associated with the production or use of fossil fuel energy, particularly greenhouse gas emissions [19].

Solar-air heating systems typically consist of two main components: a solar panel that is installed on the exterior wall of a building and an air distribution system that is installed inside the building. During the cold seasons, the solar panel heats the air, which is then circulated through the air distribution system. A heater in the system can be used to supply additional heat if needed before the air is introduced into the building. In warm seasons, the system is designed to prevent overheating by opening side vents or other paths to allow for natural ventilation. One additional advantage of installing a solar panel on the building facade is that it can help recover some of the heat lost through the building wall during cold seasons, and a solar ventilation system can recover up to half of the heat loss from the building wall.

3.4.2 Analysis of Economic and Environmental Effects

The objective of this section is to investigate whether residential solar air heating systems (SAHSs) can be considered a financially viable energy-saving option for homeowners without any government subsidies or financial assistance, based on the estimated costs. The SAHS system is expected to provide annual energy savings by harnessing solar energy to reduce thermal energy consumption and heat loss from the building. The calculation of annual cost savings for SAHS is contingent on several factors, such as the location's weather data (including air temperature, solar radiation, and wind speed), energy required for building heating, energy produced by the solar air heating system, fuel cost (natural gas), and the indoor air temperature of the building set at 21 °C. System performance determines the total future cost and Net Present Value (NPV).

$$\mathrm{NPV} = -I_0 + \sum_{i=1}^{n} \frac{CF_i}{\left(1+r\right)^i}$$

$-I_0$ = initial investment
CF_i = net cash costs.
$I = 1/n$ expected time.
n = 30 years old,
r = 5% discount value.
If NPV is 0, investing is best.

In addition to economic profitability, the environmental impact of the project is another important aspect that should be considered when analyzing the project. To reduce greenhouse gas emissions and dependence on fossil fuels, it is crucial to promote the use of renewable energy sources. By installing solar air heating systems (SAHSs) in residential buildings, the owners can enjoy several benefits, such as:

- Use efficient technology; no pollution, sound, operating costs, and maintenance.
- Energy invariance during the operating period; the heat absorbed by the panel enters the building directly.
- Do not depend on other distribution networks or other external systems because the energy is produced and consumed in the same place, and the building system is only used for its distribution.
- Using SAHS reduces the amount of CO_2 emissions generated from fossil fuels with heat generated from nonpolluting solar energy in the atmosphere.

3.5 Heating, Cooling, and Power Generation: With Thermal Energy Storage in the Building (PCM)

This section discusses the latest advancements in renewable energy systems for buildings, including heating and cooling, as well as power generation with thermal energy storage. The use of renewable energy for buildings is crucial in various countries and regions, as buildings account for around 40% of the total energy consumption and offer significant opportunities for energy conservation. In many buildings, there are now photovoltaic and heat pump systems, but the reference is unstable energy that is affected by the climate, and for high efficiency, the combination of thermal and electrical energy storage is essential. Electrical energy and chemical storage cause the development of hydrogen-powered batteries and energy. This can help overcome problems such as high cost, relatively low efficiency, and storage environment demand. Buildings are an important sector devoted to renewable energy and can use renewable energy sources in various ways, including energy supply. Factors such as heating, cooling, and electricity play a significant role in energy use in buildings, and renewable energy, including solar energy, heat pump, biomass, and wind energy, makes most buildings sustainable and renewable. Solar energy is produced by photovoltaic (PV) or solar panels, where the amount of energy produced in buildings is significantly affected by the extent of solar radiation that varies around the world. It is limited by the relative geographical position of the

Earth and the Sun and the various months. PV panels are usually made of two different layers of semiconductor material. When the light hits the cell, it can generate an electric current through the flow of electrons. Solar panels can also be suitable to produce heat in a different way by using the grass heat pumps. Heat pumps are mainly in two forms [20]:

1. Ground source heat pumps (GSHPs)
2. Air source heat pumps (ASHPs)

GSHPs heat the internal water of buildings and use the constant temperature of rocks, soils, and groundwater to provide thermal energy to indoor spaces.

In ASHP pumps, the ambient air heat source is also used. There are two types:

1. Air-to-water heat pumps, more suited to modern construction, are more suitable because low funds are better suited to upgrade heating systems when heat pumps are incompatible with traditional buildings. These heat pumps will transfer the heat from outside air to water to warm your room through radiators or floor heating. It can also keep the water stored in a hot water cylinder warm for your hot water, shower, and bath valves.
2. Air-to-air heat pumps, which transfer heat from outside air to your indoor air and increase the air temperature of each room. This hot air comes into your home through a series of fan coils or “blowers,” and air-to-air heat pumps are often known as air conditioning.

For thermal energy storage, phase change materials (PCMs) are more efficient. What are phase change materials? Phase change materials are materials that absorb and release thermal energy by phase change (known as latent heat). For example, when a solid material melts down into liquid, or when the material freezes and becomes solid, the heat it receives during the melting starts to release it. During the phase transition, many materials are able to absorb a significant amount of heat energy. This section also offers and reviews recent progress in PCM for its applications in buildings, both for heating and cooling.

3.5.1 Phase Change Materials (PCMs) in Heating, Building Cooling, and Electric Energy Storage

Solar thermal energy is a method of harnessing solar energy to generate heat. The Earth absorbs solar energy, and this energy can be transferred to space heating and cooling. Solar water heaters, which became popular in the late 1960s, are an important application of this technology. It is important to store this valuable energy when it is available for later use. Since the 1980s, passive systems that use phase change materials (PCMs) for thermal energy storage have been developed. Initially, PCM was placed in the lower parts of water tanks to store energy in heating systems. However, the low thermal conductivity of PCM limited the amount of energy that could be stored. Subsequent research focused on the use of composite materials to improve thermal conductivity, and PCM modules were added above the water tank to increase storage density and compensate for heat loss in the upper layer due to the latent heat of PCM. The use of a PCM storage unit can enable better management of water temperature fluctuations during the day and night. As a result, thermal stratified water tanks are commonly used for short-term energy storage.

Electrical energy can be stored using energy storage systems as batteries that have made significant progress, e.g., chemical storage that has also recently been developed. For storing electrical energy, there are underground energy storage systems or thermal energy storage of phase change materials (PCMs). It is a viable option to implement building within residential buildings. They can be used in lightweight structures, such as insulated wood, and also for various architectural devices such as glass, solar chimneys, solar ceilings, and building walls. There is currently much attention on integration (PCMs) with photovoltaic systems.

Energy consumption in the construction sector continues to increase, and thermal comfort in the living area can account for 40% of total energy consumption. Various solutions can be considered to reduce energy consumption, including improving building insulation. But one promising method to reduce energy consumption is thermal energy storage (TES), which is taken particularly from renewable energy sources such as geothermal energy or solar energy. TES technologies, sometimes called "heat batteries," can store heat or cold to be used later under different conditions, such as temperature, location, or power. TES can be used both for cooling and heating of buildings. This passage describes the three methods of thermal energy storage (TES): sensible heat, latent heat, and chemical thermos. Latent heat thermal energy storage (LHTS) is the most common method in the past two decades, as it allows for the storage of large quantities of heat with only small temperature changes and has high storage density. The phase change of a material, such as ice melting, is an example of latent heat storage. PCMs, or phase change materials, are widely used in TES, particularly in solid-to-liquid and solid-to-solid transitions. PCMs must have specific characteristics, such as a high heat transfer phase in volume units, high specific heat, good thermal conductivity before and after phase transfer, and low volume changes with low phase and vapor pressure. Various types of PCM, including minerals, salt hydrates, paraffin, and fatty acids, have been investigated in the past 20 years. In buildings, PCMs can be used in cooling modes, active and passive heating, and combined modes to increase thermal capacity and reduce peak heat load and room temperature fluctuations.

The system consisted of two parts of the wall, impregnated with different PCMs. The outer layer of the wallboard contained PCM with a higher melting point and was active during the warm season, while the inner layer containing PCM, characterized by a lower melting point, was active during the cold season. The results of their paper show that the necessary infrastructure to reduce the annual energy demand for AC in the new wall system and heating can be created [21]. Solar chimney is one of the optimum natural ventilation topics that reduce building energy consumption. Solar chimney is usually an open cavity that allows the movement of air with the help of solar radiation; therefore, it can also be connected to the roof, which is the most common wall chimney configuration and can be used to improve the thermal performance of solar chimney by integrating the PCM. PCMs can also be used to store electrical energy in buildings by combining with a solar collector system, photovoltaic systems, or thermoelectric installations. Overheating is one of the main problems of photovoltaic (PV) module performance reduction. In general, excessively high temperature leads to a significant decrease in the electrical efficiency of PV modules. Therefore, it is necessary to use cool roof systems using phase change materials (PCMs) as building insulation.

Applications in Buildings
Phase change materials (PCMs) are highly versatile and can be utilized in a multitude of ways for thermal regulation and storage in buildings with limited temperature ranges. By effectively storing solar energy, PCMs can aid in combating nighttime cold, as well as meeting heating demand by storing energy produced during the day and maintaining comfortable building temperatures. With their ability to store high-density heat or cold, PCMs offer a promising solution for thermal comfort in buildings.

PCMs can be incorporated into building materials to improve energy storage within walls or other components while maintaining a stable temperature range. The latent heat capacity of PCMs allows for the absorption of solar energy and artificial heating or cooling, which can reduce temperature fluctuations and improve thermal comfort in buildings. Micro- and macro-encapsulated PCMs can be embedded in building materials like concrete, gypsum wallboard, ceilings, and floors to achieve a relatively constant temperature range without significantly increasing the weight of building components. By adding additional amounts of PCM, either mixed with building materials or applied as a thin layer on building walls and roofs, peak temperatures can be reduced, and energy consumption minimized. Paraffin wax-based PCMs can also be used in building materials to absorb heat during the day and release it at night. During the charging process, the PCM boards on the wall reduce the surface temperature of the inner wall, but during the heat release process, the surface temperature of the PCM wall is higher than that of other walls. The temperature difference between day and night affects the reliability of PCM in reducing heat flux, with greater temperature differences indicating more reliable performance. PCM structural insulated panel walls are ideal for climates with large temperature fluctuations, such as hot days and cool nights. However, unlike insulating panels, the properties of PCM vary depending on the environment.

The direct exposure of the roof of the building to sunlight to increase the temperature can be seen in the buildings; these minimize heat transfer by limiting the heat flux into the building and can also keep the temperature inside the building constant, while providing the highest energy savings for electricity consumption.

The application in the building refers to the heating, cooling of the space, and domestic hot water supply. And one of the main applications of PCM is adding to building materials or building components to increase the thermal storage capacity of the structure. PCM applications can be divided into passive and active applications. By passive program, the PCM stores or releases heat only according to the temperature conditions of the part of the building to be heated or cooled. By active application, heat storage or release is actively influenced by additional equipment, such as fans or pumps that provide a heat transfer medium. Since building materials usually remain in buildings until they are out of use, the long-term stability of micro-encapsulated PCM and its incorporation into building materials is very important. Building materials with PCMs are among the most well-known passive applications of PCMs in buildings. Building materials are part of the building structure, and integrated PCMs increase the ability to store heat in them. If the temperature of the building rises above the phase change temperature, PCMs used in building materials are able to absorb heat. As a result, the interior of the building is cooled until the PCM is completely melted, and if the temperature of the building is lower than the phase change temperature, the PCM heats it. The advantage of using PCM is that it automatically controls temperature fluctuations in a building without consuming energy and without the need for additional equipment. Also, in the use of tiles, they can be installed in a normal false ceiling and absorb excess heat from the room and release it later. Underfloor heating and cooling ceilings with PCMs can be passive or active applications, as they are installed in the room to be heated or cooled. If the storage is elsewhere outside the room, the heat often needs to be moved by fans or pumps to heat or cool.

Floor Heating

Floor heating systems are a particular type of home space heating system in which hot water or hot air is produced somewhere and then flows through tubes on the building floor to heat the floor. The heat is then transferred to high space by free convection. Integrating PCM into floor heating systems can increase their capacity to store heat, allowing for the separation of production and heat demand in a building. Additionally, heat pumps can benefit from temperature stabilization on the heating side, for instance, if additional heat is supplied from a solar thermal collector or if the sun is shining directly onto the building.

Cooling Ceiling

Cooling ceilings are a special kind of cooling system in the building space. Normally, cold water can be produced somewhere and flow through roof cooling tubes to cool the space. Cooling ceilings, which usually have little capacity to store cold, with the integration of PCM, can store significant amounts of cold. This can be used at night to cool off the air outside and to cool space during the day. Phase change material or PCM is a promising option for thermal energy storage; due to its applications, it is also called heat and cold storage. Systematic PCM research began after the oil crisis, and in the late 1990s, research and development in PCM intensified significantly. Reviews of PCM products and their application fields show that today PCM is used in a wide range of commercial products, in many different applied fields, some in the early stages and others as standard. For example, we can refer to the application in buildings, cold chains, the human body, etc.

A fundamental issue regarding the commercialization of PCM technology is the significant expertise required. In the early 1990s, individuals interested in developing a commercial product with PCM often had to purchase PCM raw materials, and those who developed and produced PCM commercially had to develop end-to-end applications. However, this is no longer the case. Today, PCM is widely available with different types of encapsulations from many companies. Many application development companies focus on their expertise and use only existing commercial PCM. Additionally, for every customer, from PCM to its application, quality can now be checked and marked to ensure product quality. In this section, we provide an overview of the potential of PCM and its business applications. However, there is a great demand for research and development in many areas, from PCM development to system design, even in areas where commercial applications exist. Sometimes, not only technological challenges but also legal restrictions or noncompliance of regulations or planners may result in some impediments, especially in construction applications. For these reasons, continuous research and development, as well as awareness of the potential of PCM, are crucial despite legal and regulatory obstacles.

3.6 Conclusion

Sustainable development is a critical consideration when it comes to energy resources and their utilization. To promote sustainable development, renewable energy sources are often preferred over nonrenewable sources. The classification of renewable energy sources takes into account several factors, including the emission of greenhouse gases, availability of resources, land requirements, water consumption, social impacts, and the price of power generated. Renewable energy sources can provide good job opportunities in all special fields in the building sector and can help achieve 100% energy efficiency in buildings. It is recommended that more modern equipment, such as PCMs, be used in parts of solar panels. From an economic point of view, the competitive environment is better for the use of alternative energy sources, and they can also be used as a driving engine for development.

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Chapter 4
Introduction and Literature Review to Deployment of Photovoltaic Systems in Sustainable Buildings

Daniel Tudor Cotfas and Petru Adrian Cotfas

Abstract The concept of zero emission buildings imposed the photovoltaic panels' integration in buildings. This chapter presents photovoltaic cells and panels that are suitable for building integrated systems. Their advantages and disadvantages are discussed. Three building-integrated photovoltaic systems are discussed: roof photovoltaic system, cladding photovoltaic system, and semitransparent photovoltaic systems. The factors that have an important influence on power generation are also discussed. Some future developments are presented.

4.1 Introduction

The energy consumption by buildings at the global level accounts for around 40% of the total energy. The majority of buildings worldwide are not energy efficient, but rather pollution generators; in Europe, around 75% of buildings are in this situation. It is therefore compulsory to change the old concept. The nearly zero-energy building (NZEB) concept has been changed by the European commission to the new concept zero-emission building (ZEB) [1]. There are other countries and regions that have ambitious targets; for example, in California and Japan, all new buildings must be ZEB by 2030, Korea developed a plan with a roadmap to obtain ZEB, which was adopted in 2014 [2], Denmark adopted the roadmap for ZEB in 2013 with a secondary goal of increasing the renewable energy sector [3], China adopted more strategies for ZEB, and these are part of the general goal that the country becomes neutral carbon by 2060. Integrated building photovoltaic systems (BIPVs) are necessarily encompassed by this concept and promote sustainable development.

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Photovoltaic systems began to be integrated in buildings in the 1970s in the USA and Europe in 1982 [4] and after 2000 in the rest of the world. The Solar One was the first house (two bedroomed) that integrated hand-made thin-film photovoltaic panels and solar collectors on the roof. It was built in 1973 by the Institute of Energy Conversion at the University of Delaware to prove the application of solar energy conversion [5]. The first photovoltaic system integrated into a building in Europe was on a house near Munich (Fig. 4.1). The solution used by the Fraunhofer Institute for Solar Energy Systems was 60 m^2 of crystalline solar cells manufactured by AEG and Siemens with 5 kWp [6]. Commercial integrated building photovoltaic systems have been available since the 1990s. Therefore, photovoltaic systems started to be used in public buildings. The public library Pompeu Fabra, from Matarò, Spain, is one the first public building that has integrated a photovoltaic system.

Three types of photovoltaic cells are used: semitransparent monocrystalline and polycrystalline panels on the façade and amorphous and monocrystalline panels on the roof [8]. The power of the BIPV installed is 20 kWp, and the energy production is 20 MW per year. The historical buildings as Building of the Tourist Office in Alès (France) [9] have integrated photovoltaic systems with the goal of increasing their acceptance. On the façade, three PV systems are integrated on 100 m^2 and the installed power is 9.5 kWp [10].

Germany was the first country that launched the program "1000 Roofs Photovoltaic Programme" in the year 1991. This program was sustained by the federal and state governments between 1991 and 1995, and it had a real success. The total installed capacity was 4 MW_p [11], the program being followed by a more ambitious one, launched in January 1999.

The new program was called "100,000 Roofs Programme." Each PV system installed on the roof must be 3 kWp. The PV installed capacity increased by the end of 2003 to 300 MW [11, 12].

Fig. 4.1 First solar house in Munich. (Courtesy of Verena Herzog Loilb) [7]

The roofs covered with PV panels can pertain to houses (Fig. 4.2a) or/and their annexes (Fig. 4.2b), which have a lot of space and therefore the installed capacity can be higher.

Building-integrated photovoltaic systems are nowadays common worldwide. The 4 Times Square building is one of the first skyscrapers that integrates a photovoltaic system, finished in 1999. The thin-film PV panels are mounted on the

a)

b)

Fig. 4.2 Solar roofs covered by photovoltaic panels: (**a**) house and annex; (**b**) annex. (Photographer Cotfas Daniel Tudor)

south and west facades, from the 37th to 43rd levels. Malaysia Energy Centre was the first high-energy-efficient, net zero-energy building from Malaysia, which was constructed in 2007, using an integrated photovoltaic system [13]. The Pearl River Tower from Guangzhou City, China, which is part of the new zero-energy office buildings, was built in 2009. The photovoltaic systems were integrated alongside other types of renewable energy, such as wind and solar passive heating. They are used at the top of the tower and as a shading system on the facade, with double tasks, such as generating electrical power and reducing the electric energy consumed by the air conditioning [13]. The first ZEB building in India was inaugurated at the beginning of 2014, having a photovoltaic system peak power of 930 KW [13, 14]. The PV systems continue to prove their importance and to stir architects' interest in integrating them to the purpose of obtaining even energy-positive buildings, such as the office building from Lehigh Valley [14].

4.2 PV-Integrated Systems

There are three types of photovoltaic systems directly coupled, stand-alone, and grid connected [15]. The photovoltaic panels can be used by themselves or in hybrid systems, such as photovoltaic panels (PV) and solar collectors (PVT) [16], photovoltaic panels, solar collectors and phase charge materials, photovoltaic panels and thermoelectric generators (PV/TEG) [17], and photovoltaic panels, thermoelectric generators, and solar collectors (PV/TEG/SC) [18]. In this chapter, the photovoltaic systems using PV and PV/PCM are analyzed and discussed.

The building-integrated photovoltaic systems are only of stand-alone type and grid connected. BIPV stand-alone systems are generally used for houses or buildings that are isolated or placed so that the cost of bringing the grid is high. This type was the first BIPV system to be developed [19], including storage devices that generally consist of batteries. They are the main disadvantage of the BIPV system and increase the system price. The schematic diagram of the BIPV stand-alone system is presented in Fig. 4.3a.

The most used nowadays are the BIPV on-grid systems. The majority of the European Union countries, and not only, have created advantageous policies for the people who integrate or are willing to integrate photovoltaic systems in their buildings. They are currently regarded as prosumers, the generated energy is taken over by the electric grid, and the people can consume the necessary energy from the grid; additionally, at the end of the year, a comparison is made between the generated and consumed energy. In this way, the BIPV can avoid energy storage and the cost of the system is reduced. The schematic diagram of the BIPV on-grid system is presented in Fig. 4.3b.

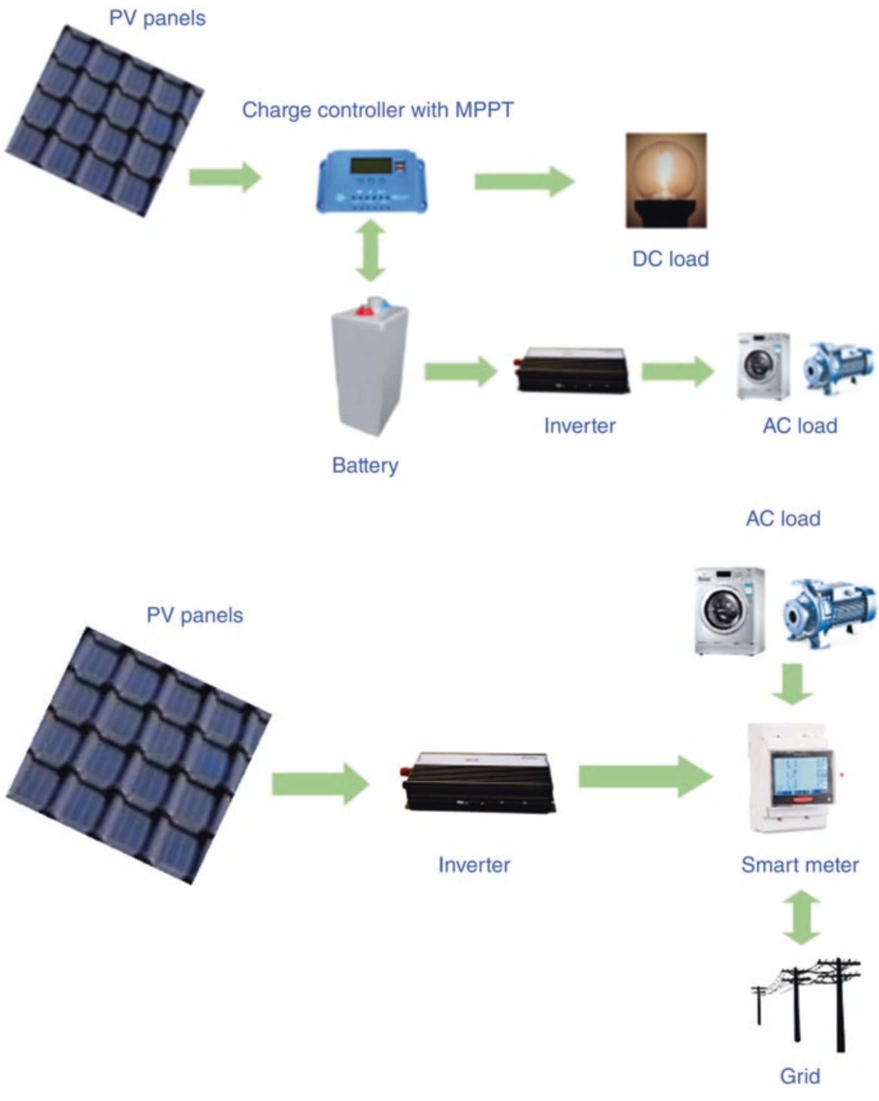


Fig. 4.3 Schematic diagram of the BIPV: (**a**) stand-alone system; (**b**) on-grid system

4.3 PV Systems for the Buildings

The photovoltaic systems can be deployed on the building simply with the goal of maximizing energy generation so that the building becomes energetically efficient or the PV system fulfills some requirements, such as being aesthetic, fitting into the existing design, or for a specifically designed building, but nevertheless maintain efficiency [20]. The possible integration option and the photovoltaic cells technologies are presented in Fig. 4.4.

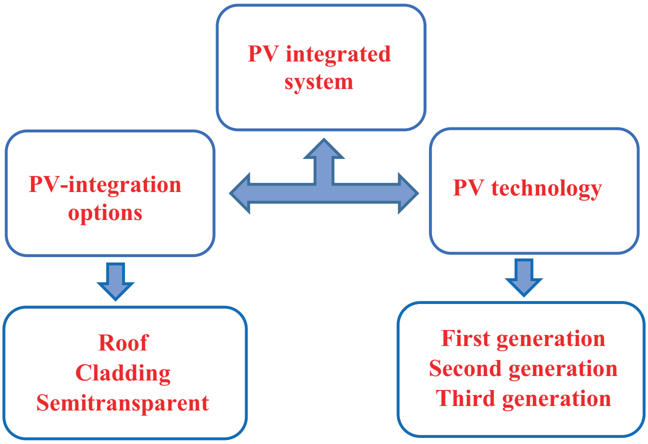


Fig. 4.4 BIPV system

Photovoltaic modules used in BIPV systems have photovoltaic cells manufactured using different technologies and materials. Nowadays, photovoltaic cells from three generations are used, the first one being monocrystalline – mSi and polycrystalline – pSi silicon cells and gallium arsenide – GaAs photovoltaic cells. From the second generation, amorphous silicon (aSi) is used, alongside the chalcogenide thin-film photovoltaic cells, such as copper indium gallium selenide – CIGS, cadmium telluride CdTe. Finally, from the third generation, organic solar cells, Perovskite solar cells, and Perovskite on Si tandem cells are used.

The monocrystalline and polycrystalline photovoltaic cells are still the most used for PV systems, as well as for BIPV systems. Crystalline silicon photovoltaic cells have more than 71% of the market, thin film photovoltaic cells around 19%, and the other solar cells the rest [21].

The advantages of the crystalline silicon photovoltaic cells are that the technology is mature, the cell is inexpensive, the efficiency is good, having increased in the last years due to the new technologies for the contacts, the entire front area becomes active if they are placed on the back of the photovoltaic cells, and they have the warranty, which is today of 30 years. The Maxeon photovoltaic panels, which use the technology with all contacts on the back, reach an efficiency of over 22%, have a very small degradation rate, of around 0.2% per year so that the warranty increases to 40 years, and a low-medium power temperature coefficient that is −0.29%/°C [22]. The disadvantage of the crystalline silicon photovoltaic cell is its strong dependence on irradiance and temperature.

GaAs photovoltaic cells have high efficiency, around 30%, with a lower dependence on irradiance and temperature, they are lightweight, but rather expensive, and the As is a toxic component [23]. These disadvantages lead to their small-scale use for the BIPV systems.

Thin-film photovoltaic panels, such as CGIS, CdTe, and amorphous silicon, have good efficiency, 19.5% for the first two and 12.3 for the last one [23, 24]. In comparison with crystalline photovoltaic cells, the temperature dependence is similar for CGIS and CdTe, but it is lower for amorphous silicon. The irradiance dependence is stronger for CGIS but lower for CdTe and amorphous silicon photovoltaic cells. They are very good candidates for the BIPV system because they are more aesthetically appealing than crystalline silicon photovoltaic cells due to their homogeneous black or brown appearance [20].

The representatives of the third generation are very seldom used for the BIPV, despite having good potential. There are few firms in the market that produce organic solar panels, with cell efficiency around 17% and panel efficiency around 8%, but the major concern is their stability. The aesthetic is an advantage, as well as the temperature and irradiation dependence, which is one of the lowest. However, there are some pilot buildings with BIPV systems based on organic solar panels [25, 26]. Perovskite and Perovskite on Si tandem cells are some of the promises for the future of the BIPV systems. Their efficiency is very good, around 20% [23], but they also have problems with their stability and are not on the commercial market. The temperature and irradiation dependence must be improved.

4.3.1 Roof Systems

The roofs of the houses and their annexes, the institutional, commercial, industrial buildings, and others, can be used to deploy photovoltaic systems, being in general, unused spaces. The roofs are flat, tilted flat, semi-spherical, or other tilted shapes. For the flat roofs, the deployment of the photovoltaic systems is straightforward, the constraints being few and easy to overcome. In the case of the tilted flat roof, there are more problems. The most important is the orientation of the roof and its tilt angle [28]. The best orientation for the roof buildings from the north hemisphere is toward south. The dependence of the yearly energy production in function of the azimuth angle for a photovoltaic system that is roof integrated was achieved using the tool Photovoltaic Geographical Information System, offered by the European Commission [27]. The BIPV system is 1 kWp, and the photovoltaic panels are from crystalline silicon. SARAH-2 solar radiation data set is used to calculate solar radiation. The obtained data for a BIPV system situated in Brasov are presented in Fig. 4.5. The yearly energy generated is calculated for two tilt angles of the photovoltaic panels: the yearly optimum angle for Brasov (it is given by the software) is 36° and the latitude angle for Brasov is around 45°. The azimuth angle was varied with a 15° step. The diminishing in yearly energy production of the BIPV system is only a little over 1% if the azimuth angle varies from 0 to 15. There is an important decrease if the roof is oriented toward east or west, around 22% if the photovoltaic panels are tilted at the optimum angle and over 25% if the tilted angle is 45 (Table 4.1).

The tilted angle of the photovoltaic panels influences the energy generated by the BIPV. For the constructed buildings, it is hard to adapt and unaesthetic to mount the photovoltaic panels at the optimum angle. In the case of the new buildings, the

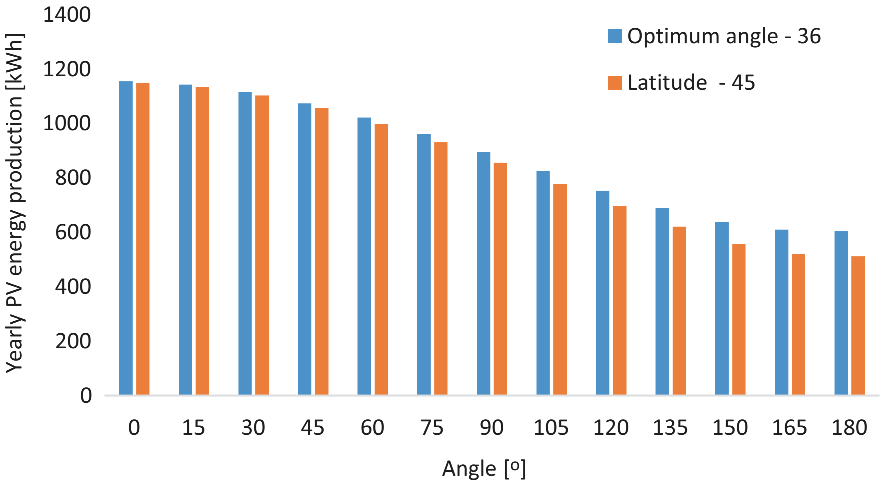


Fig. 4.5 Yearly energy production for a BIPV system integrated on the roof vs. azimuth angle

Table 4.1 Yearly energy production of the BIPV and the losses

Azimuth angle [°]	Energy production at 36° [kWh]	Energy production at 45° [kWh]	Losses at 36° [%]	Losses at 45° [%]
0	1155	1148		
15	1142	1134	1.13	1.22
30	1115	1103	3.46	3.92
45	1074	1056	7.01	8.01
60	1021	998	11.60	13.07
75	961	930	16.79	18.99
90	895	856	22.51	25.44
105	825	777	28.57	32.32
120	753	697	34.80	39.28
135	688	621	40.43	45.90
150	638	558	44.76	51.39
165	610	520	47.18	54.70
180	603	512	47.79	55.40

optimum angle can be calculated, considering all factors, and the roof can be built with the necessary tilt. Figure 4.6 shows an example for the calculation of the energy generated by a BIPV system of 1 kWp with crystalline silicon photovoltaic panels in function of the roof slope for three cases: yearly energy generated by the BIPV system, the maximum energy generated in a month, which is July for the tilted angle from 0° to 35°and August for the rest and the minimum energy generated in a month, which is December (the values of the maximum and minimum energy are multiplied by 5, to be visible in the plot).

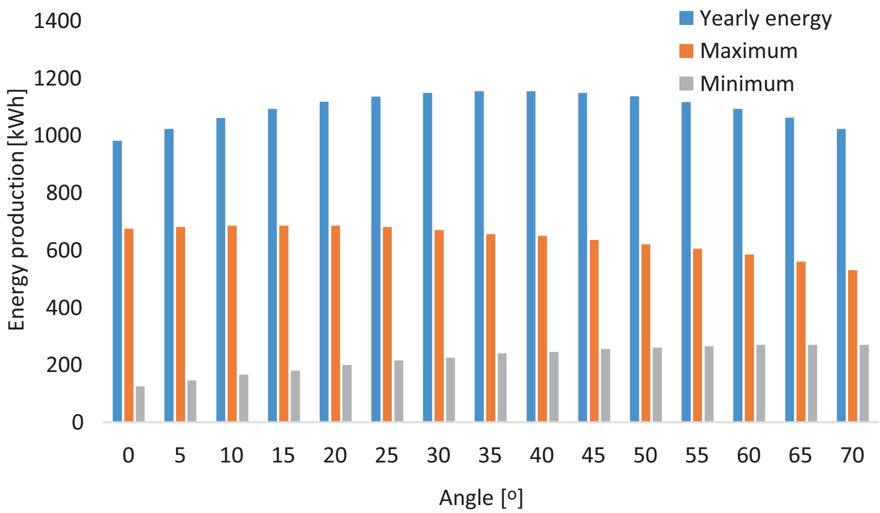


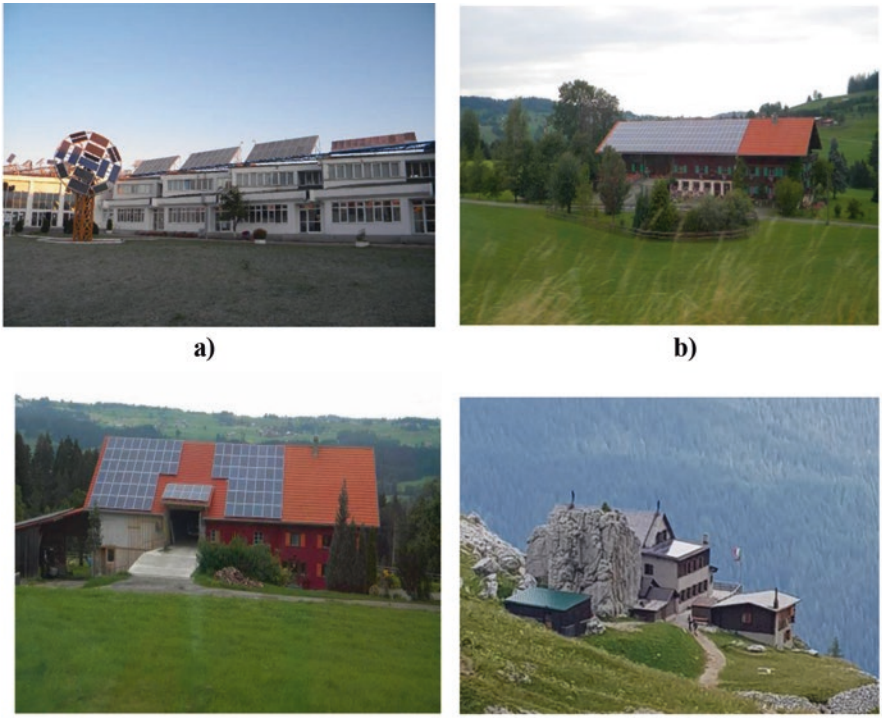
Fig. 4.6 Energy production for a BIPV system integrated on the roof vs. tilted angle

The slope variation is made with 5°, from 0° to 70°. The roof slope is very important, especially for the BIPV stand-alone systems. The energy production of this system must be maximized for the critical months, which are from October to March. The electric energy consumed is higher for these months, and the available solar radiation is lower. One way to maximize energy generation is to mount the photovoltaic panels at an optimum average angle for these months. This angle is around 55° for Brasov. The maximum yearly energy is obtained at 35°, which is near the optimum angle. If the photovoltaic panels are mounted at 55° in July, the decrease in energy production is by 7%, but for December the increase is around 12%.

The BIPV system on the roof is presented in Fig. 4.7. The PV system is deployed on the flat roof of the Transilvania University of Brasov building (Fig. 4.7a).

The slope of the monocrystalline silicon photovoltaic panels is 45°. It was chosen equal to the latitude. The installed capacity is 10 kWp, and the system is integrated into the national electric grid. The BIPV stand-alone system installed on the roof of a mountain cottage in the Dolomites mountains, Alleghe area, is illustrated in Fig. 4.7d. It uses polycrystalline photovoltaic panels. In flat roofs, the solar radiation that falls on the photovoltaic panels can be increased if white waterproof materials are used for insulation. There are two advantages: the increase in solar radiation on the photovoltaic panels by reflected one, which leads to an increase in energy generated by the photovoltaic panels by more than 10% [29], and the energy saved due to the reflection by the white surface and not using the air conditioning to cooling the rooms.

The efficiency of the photovoltaic panels used for BIPV systems varied in general from 8% to 25% [23]. This efficiency is calculated when the photovoltaic



a) b) c) d)

Fig. 4.7 (**a**) PV system deployed on the roof of Transilvania University of Brasov; (**b**) BIPV system on the residential building roof; (**c**) BIPV system on the roof of the annex of the residential house; (**d**) BIPV stand-alone system on the roof of mountain cottage in the Dolomites mountains, Alleghe area. (Photographer Cotfas Daniel Tudor)

panels are measured in Standard Test Conditions (STCs – AM1.5, irradiance 1000 W/m^2, and the working temperature of 25 °C), requirements which are met in very few cases in real work conditions. Consequently, the efficiency is lower than the calculated one. The rest of the solar radiation is converted into heat, which leads to an increase in the temperature of the photovoltaic panels. Other two factors that lead to an increase in temperature are the ambient temperature, which is strongly dependent on the climatic conditions of the location where the BIPV is installed, and the approaches to mounting the photovoltaic panels on the roof.

The temperature influences all parameters of the photovoltaic cells and panels. Table 4.2 shows the power temperature coefficients of the photovoltaic cells used for BIPV systems.

The crystalline silicon photovoltaic panels have the highest power temperature coefficient (Table 4.2), and they are the most used for the BIPV systems. Integration of the crystalline silicon photovoltaic panels in the roofs of the buildings require adequate approaches to reduce their work temperature.

Table 4.2 Power temperature coefficients and efficiency of the considered PV

PV	Power temperature coefficient [%/°C]	Efficiency [%] ± 0.03	References
Monocrystalline silicon	−0.47	24.4	[23, 30]
Polycrystalline silicon	−0.38	20.4	[23, 30]
Amorphous silicon	−0.18	12.3	[23, 30]
GaAs	−0.14	25.1	[23, 31]
CdTe	−0.25	19.5	[9, 23]
CGIS	−0.34	19.2	[9, 23]
Perovskite	−0.13	17.9	[23, 32]
Organic	−0.43	8.7	[9, 23]

The temperature of the photovoltaic panels can be reduced using different cooling methods. The most used for the BIPV system integrated on the roofs is natural cooling. The photovoltaic panels must be mounted on the roof, ensuring an air gap between them and the roof [8, 33]. Another new method is to use thermoelectric modules (TEMs) in two cases: TEM cools photovoltaic panels consuming energy – Peltier effect, and TEM cooling photovoltaic panels generating energy – Seebeck effect [17].

Roberts and Guariento give some values for power reduction of the BIPV system with crystalline silicon photovoltaic panels integrated into the roof in comparison with the PV free-standing system, with the same photovoltaic panels: for a large gap between PV and the roof, it is −1.8%; for a gap with good ventilation, it is −2.1%; for a gap with poor ventilation, −2.6%; without ventilation, −5.4% [8].

The easiest implementation of the photovoltaic panels is to use the roof slope as in Fig. 4.7b–d, but their aesthetic and acceptance nowadays by the large public becomes a huge problem.

One way to increase the acceptance of photovoltaic cells and panels is to change their color. There are many techniques to obtain different colors, such as using single and multilayer films, which produce through interference spectrally selective reflectance but the cost is high [34], colored coatings on internal surfaces [20], colored encapsulants – using interlayers, printed films, pigments, and semitransparent layers to give a red appearance for roof applications but efficiency reducing, dielectric nanoscatterers – the loss in efficiency is around 10% [35]. Røyset et al. analyzed 15 colored solar cells from five firms [34]. The efficiency and the photovoltaic cells suitable for roof integration are presented in Table 4.3.

The second way is to integrate in the roof, instead of the tiles, the photovoltaic panels with the proper color to match the roof tiles [37]. In this case, monochromatic photovoltaic panels as blue can be used (see Fig. 4.8).

Another way is to use direct photovoltaic tiles and shingles. On the roof of the Eindhoven University, these are tested to find the performance and the energy generation (Fig. 4.9).

Table 4.3 Efficiency of different colored photovoltaic cells

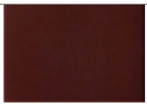
PV color	PV	Efficiency [%]	Methods	References
Tile red		16.4–17.2	The color-modulating layer is added on top of the antireflection layer	[34, 36]
Lavender		16.4–17.2		
Terracotta		16.7	The mineral coating is fixed at a high temperature onto the surface of the photovoltaic cell cover glass	[34]
Green moss		16.7		
Light gray		16.7		

Fig. 4.8 Aesthetic PV panels for the roof Jülich, Germany. (Photographer Cotfas Daniel Tudor)

There are different shapes for photovoltaic tiles, such as photovoltaic terracotta bent tile – using monocrystalline silicon photovoltaic cell with 17.2% efficiency and the maximum power generated is 3.92 W, measured at STC conditions, photovoltaic

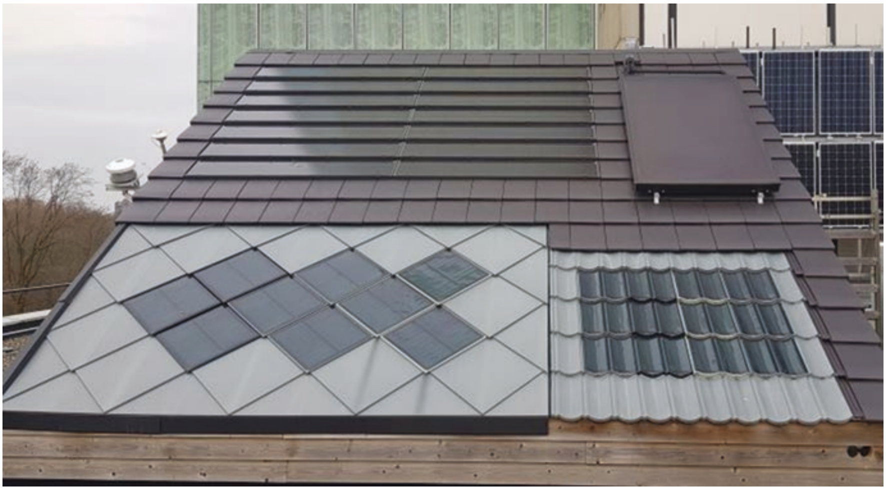


Fig. 4.9 Experimental photovoltaic panels with tiles – Eindhoven University. (Photographer Cotfas Daniel Tudor)

terracotta roof tile – using monocrystalline silicon photovoltaic cell with 15.3% efficiency and the maximum power generated is 7.84 W, measured at STC conditions [38], Autarq solar roof tile – it looks exactly like a normal tile and the weight is almost the same [39], and the thin-film photovoltaic cells on steel sheets (Fig. 4.9).

Using photovoltaic tiles and shingles has advantages and disadvantages. The main advantage is aesthetic. The photovoltaic terracotta bent and roof tile can keep the aspect of the roof. They can be used with very good results from the aesthetic point of view for historic houses or old houses [38]. The main disadvantage is the connection. Each tile has to have its own cabling, which means a lot of connections and some possible problems with the ingress of water and humidity and also the maintenance [9]. A problem that must be solved is the uniformity of the types and geometric shape of the tiles so that these do not depend only on the manufacturer. In the case of the new buildings, it can be solved more easily by adopting flat photovoltaic tiles.

4.3.2 Cladding Systems

BIPV cladding systems are a huge opportunity for energetically efficient buildings and for the old ones with a modest architectural image to become modern and aesthetic. Evolaa and Margani achieved a study about the renovation of old blocks from Italy built between the years 1950 and 1990, and the conclusions were that the energetic performance and the architectural image could be improved using the photovoltaic panels integrated as cladding systems [40]. The advantages of the BIPV cladding systems are their colors, the visual effect that can be made using different inclinations, isolation, and the green image of the building and owner. The orientation of the buildings and their shadows can be major disadvantages, as well as the high cost of the installations [41]. The main applications are for commercial and public buildings, but they can be used for houses as well.

One of the most successful applications for the BIPV cladding is the Copenhagen International School (Fig. 4.10). The façade is covered with 12000 photovoltaic panels, which is based on HJT or PERC monocrystalline photovoltaic cells. These cells have very good efficiency, for commercial ones, around 20–22%. The top of the PV panel glass is finished to ensure the desired reflectivity, and the bottom is covered by PVD coatings to obtain the butterfly wings effect – obtaining colors without pigments.

Each panel is tilted at a different angle to obtain a pleasant visual effect. There is a gap between 50 and 350 mm to ensure passive ventilation to cool the photovoltaic cells. The area covered by the photovoltaic panels is 6048 m^2 and the annual energy produced by the BIPV system supplies around half of the electric energy consumption [42].

The theoretical efficiency limit was calculated for photovoltaic panels of different colors. It is made under standard test conditions: irradiance 1000 W/m^2, 25 °C temperature, and AM1.5G spectrum. The efficiency of the photovoltaic panels will change if these conditions are changed, which in the real environment will evidently happen due to the ambient temperature, clouds, humidity, dust, and others [43]. Eighteen colored photovoltaic panels were considered, the lowest theoretical efficiency being obtained for yellow, 28.9%, and the highest for purple, 32.9%. Six neutral color photovoltaic panels are also considered (Munsell lightness values from 9.5 to 2), the lowest being for white 9.5, 241% and the highest for black 2, 33.4% [43]. The calculated efficiency, Ec, or experimental, Er, obtained for the photovoltaic cells and panels that are suitable for BIPV cladding systems are presented in Table 4.4.

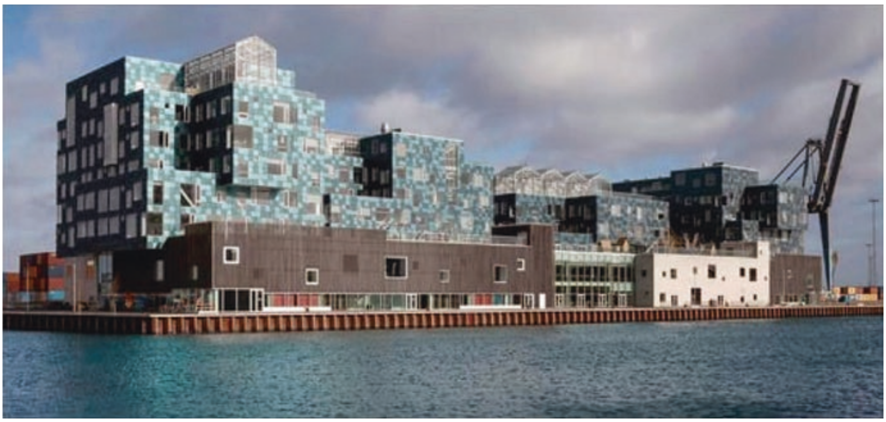
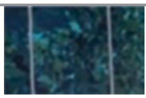
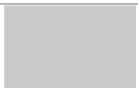


Fig. 4.10 BIPV cladding system of the Copenhagen International School. (Courtesy of SolarLab) [42]

Table 4.4 Efficiency of different colored photovoltaic cells for cladding systems

PV color	PV	Efficiency [%] Er	Efficiency [%] Ec	Methods	References
Tile red		16.8	–	The color-modulating layer is added on top of the antireflection layer	[34, 36, 43]
Lavender		16.8	–		
Kromatix green		–	32		
Terracotta		16.7	–	The mineral coating is fixed at a high temperature onto the surface of the photovoltaic cell cover glass	[34, 43]
Green moss		16.7	–		
Light gray		16.7	32.9		
White		11.4	24.1	Selective filter	[43, 44]
Black		14.5	33.4	The mineral coating is fixed at a high temperature onto the surface of the photovoltaic cell cover glass	[43, 44]
Yellow		–	28.9	–	[43]
Purple		–	32.9	–	
Neutral 8		–	28.4	–	

Three photovoltaic panels are tested on the roof of the Eindhoven University, black, neutral 8, and blue (Fig. 4.11).

The yearly energy production by a BIPV cladding system (vertical wall) in comparison with the one produced by a PV system at an optimum angle in function of the azimuth angle is presented in Fig. 4.12. It can be seen that the energy production

Fig. 4.11 Experimental colored photovoltaic panels – Eindhoven University. (Photographer Cotfas Daniel Tudor)

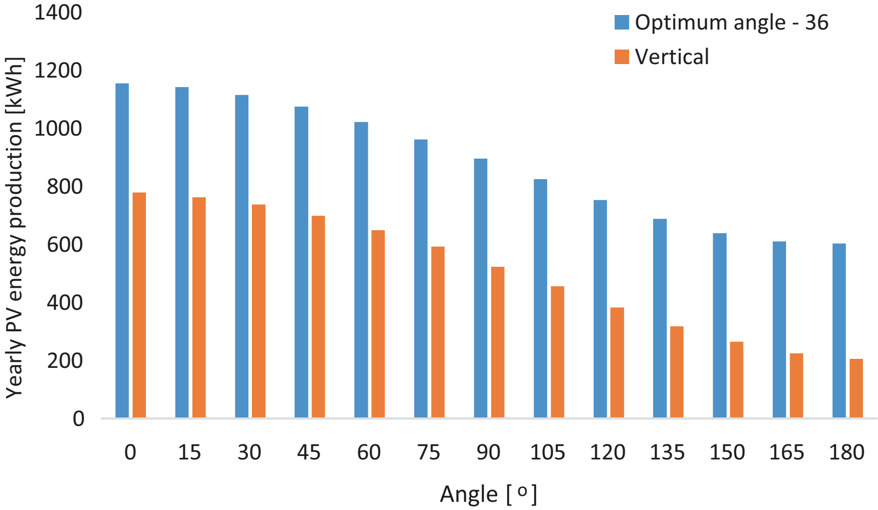


Fig. 4.12 Yearly energy production for a vertical BIPV cladding system vs. PV system tilted at an optimum angle for different values of the azimuth angle

by the BIBV cladding system loses around a third of the energy produced at an optimum angle. The losses increase with the increase of the azimuth angle, reaching even more than 100%.

The temperature is another factor that seriously influences the energy generated by the photovoltaic panels, as discussed in the roof system section. The cooling of the BIPV cladding system is very important. The photovoltaic panels tend to have different temperatures, increasing from the bottom to the top. The economic way to maintain a low temperature and quasi-uniform is to use passive cooling.

Different methods are used to cool the photovoltaic panels [8], such as using a gap for the natural air flow [45] see the passive cooling system for Copenhagen International School, forced air flow [46], and natural combing with forced air flow [47]. Another method is to use hybridization with the thermal collector PVT [48], thermoelectric generators, or phase change materials (PCMs) [49]. The PV/PCM system approach, presented in Fig. 4.13, uses two PCM materials with different phase transient temperatures and triangular aluminum cells.

The system can maintain the temperature of the photovoltaic panel under 30 °C at 560 W/m^2 irradiance [49]. The simulation was made for 3 days. In this case, the performance of the photovoltaic panels increases by more than 10%.

4.3.3 Semitransparent Systems

The semitransparent BIPV systems can be integrated into the façade of the buildings (Fig. 4.14) in the roof, as skylights [9] as in the community center Ludesch, in the balcony (Fig. 4.15) and in shading systems [51]. The main advantage of this type of BIPV system is that it is one of the most unobtrusive, and it can consequently be easily accepted from the aesthetic criterion. Different shapes and colors of the photovoltaic cells used for the panels lead to solving the aesthetic problem in a positive way. There are some disadvantages, such as the weight, which is higher than for commons ones, the limited space, the problems with the wires and connections, and the price. In general, the semitransparent BIPV systems are suitable for commercial and public buildings, but they can also be used with good performance for other buildings, such as houses, and small blocks, especially for shading and balconies.

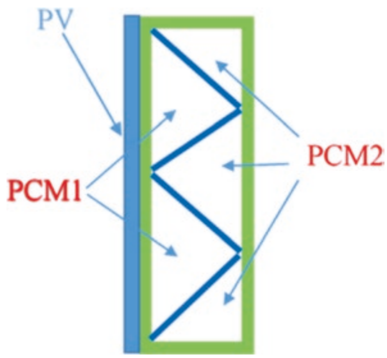


Fig. 4.13 PV/PCM approach to cooling the photovoltaic panels [49]

Fig. 4.14 Semitransparent façade – Parkhaus Gletscherbahn at Kaiser Franz Josefs Höhe. (Photographer Cotfas Petru Adrian)

Fig. 4.15 Experimental semitransparent balcony – Eindhoven University. (Photographer Cotfas Daniel Tudor)

Which is the best semitransparent photovoltaic panel type to be used for a façade? The mono or polycrystalline photovoltaic panels have an ascendant in comparison with other types. They have very good efficiency, the technology is mature, and it is used for all applications. Glass is also generally used for the bottom of the panel instead of the Tedlar to ensure light transmission. The space limitation is another favorable point in using them. The problem is that the mono or polycrystalline panels lose between 20% and 40% when they are used vertically [9]. Another type is thin-film photovoltaic panels with lower efficiency, but smaller dependence on irradiance and temperature than for mono or polycrystalline silicon photovoltaic panels. The area necessary to obtain the same electric energy using thin-film panels must be 30–100% higher than for the others. A strong advantage of thin-film panels is their flexibility.

The losses can be reduced if the temperature of the photovoltaic panels is dropped. The BIPV semitransparent system presented in Fig. 4.14 uses 400 photovoltaic panels of glass–glass of 22 mm produced by a2-solar, which generates 100 kW. Their cooling is made using a back naturally ventilated system. It is a single skin façade.

Another possibility is to use double-skin façade (Fig. 4.16) [51]. The photovoltaic cells have the double role of producing electric energy as well as reducing the thermal energy which enters the room. Preet et al. study this BIPV system experimentally in both ventilation modes, natural and forced, for different air cavities and air velocity [51], using CdTe thin-film photovoltaic cells. In the case of natural ventilation, the power generated by the panel varies from 10.3 W in the case of the 50 mm air cavity to 10.88 W for 250 mm, respectively. In the case of forced ventilation, 200 mm air cavity, the gain in power is 13.73% at 2 m/s air velocity in comparison with natural ventilation, and 28.38%, respectively, for 5 m/s air velocity. The power generated by the system at 2 m/s air velocity is 12.34 W and 13.93 W at 5 m/s, respectively.

The semitransparent thin-film photovoltaic panel is the best solution for the skylights, especially if these have curvature surfaces. The market of these photovoltaic panels has increased due to their growing applications.

BIPV semitransparent systems are suitable for balcony use and shading systems. They ensure a perfect aesthetic integration into the building and generate electric energy. The shading system can limit room overheating and create a pleasant environment inside by controlling the tilted and the light filtering by the glass of the photovoltaic panel [50].

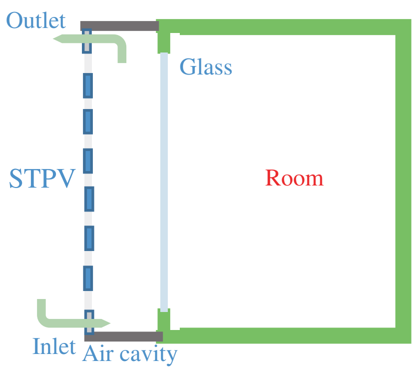


Fig. 4.16 Photovoltaic double-skin façade

4.4 Future of BIPV

The future of the BIPV system is dependent on the developments in the photovoltaic panel industry, but at the same time, it puts pressure on the industry to develop new types of photovoltaic panels better than previous ones in efficiency, in lifespan, and in terms of aesthetics.

Some development directions are briefly described below.

There are several firms that developed "artistic" photovoltaic panels to persuade architects and property owners to accept and integrate them in buildings. Such is the portrait of Michiel de Ruyter, achieved on the photovoltaic array (Fig. 4.17). This array is part of photovoltaic "artistic" arrays, which are tested to prove their performance.

Architects nowadays play a very important role in the evolution of the BIPV systems through their projects in which, alongside engineers, they find the optimum solution for integrating the photovoltaic panels. It is also important to find the optimum solution to tilt the panels so as to increase the generated power and to ensure the optimum cooling of the photovoltaic panels. A very illustrative example is the Sun Rock building from Taiwan. The entire façade (4000 m^2) is covered by photovoltaic panels, which can produce 10^6 kWh of electric energy per year [53].

The smart windows are very interesting for buildings' integration of photovoltaic cells. Their integration completes the function of the smart window, which is to block the sunlight in order to heat the rooms using electrochromic/thermochromic abilities through the electric energy produced [54]. The total area of the buildings' windows is huge, and their usage in energy production is another step to achieving the goal of producing green energy. Perovskite solar cells [55], organic solar cells, and dye-sensitized solar cells are potential candidates for smart windows. The

Fig. 4.17 Photovoltaic array – portrait of Michiel de Ruyter. (Courtesy of Kameleon Solar) [52]

properties of the perovskite solar cells offer the possibility to have different colors in the function of the necessary temperature for the crystallization of the light absorber layer [54]. There are three limitations for the actual smart windows that must be overpassed: small efficiency, stability, and long response time. There is some research on the topic. Xia et al. used the perovskite solar cell as a power source coupling with multiresponsive liquid crystal/polymer composites to modify the transparency. The efficiency obtained is higher than 16%, and the average visible transmittance is above 10% [56]. Another approach is to use ion gel as an electrochromic component and the perovskite solar cell, obtaining 76% transmissivity [57].

The energy crisis and the new energy trends impose the development of new thin film or ultra-thin photovoltaic cells and panels that must be suitable for integration in different buildings and structures. One technology that can be used is Roll-to-roll. Based on this, HyET Solar produces photovoltaic panels, Powerfoil, of different lengths, lightweight (around 0.7 kg/m^2), with an efficiency of around 12%, low-cost production, which are flexible and can be used for different shapes. Based on tandem amorphous/microcrystalline silicon, the BIPV system has a 1 MW installed capacity [58].

Saravanapavanantham et al. developed ultra-thin organic photovoltaic modules based on printing processes that offer scalable solutions. These will be very good for BIPV systems. The thickness of the photovoltaic cells is 50 μm, they are lightweight, 105 g/m^2, the specific power is 370 W/kg, and the efficiency is around 5% [59]. Their huge problem is the stability and, implicitly, the life span.

The future of the BIPV systems is promising if its market is analyzed. There are many reports to forecast the global photovoltaic market and, in particular, the BIPV system market. One of these forecasts is that the global market of the BIPV system will increase from 2020 to 2026 by almost 100% (Fig. 4.18). The roof applications

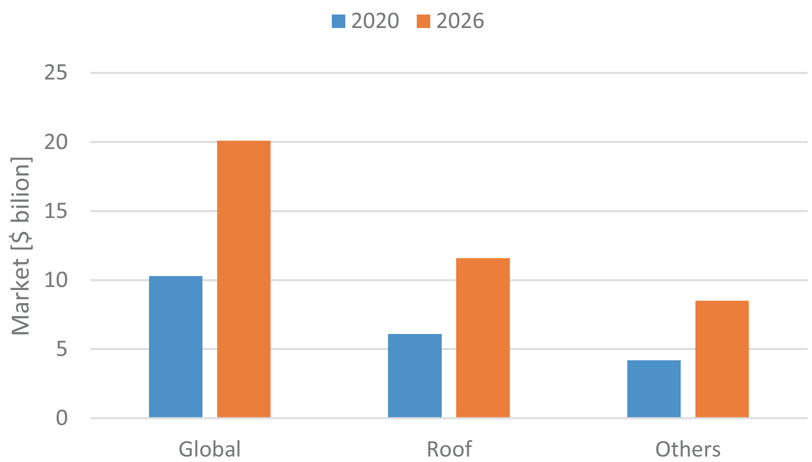


Fig. 4.18 Forecast of the BIPV system market from 2020 to 2026

have the best market, more than half of the global market. China will have a 4.1 billion market, which means 25% of the global market in 2026 [60]. The mono and polycrystalline silicon photovoltaic cells will cover more than 70% of the global market of 2026, while the thin-film photovoltaic cells will cover 20% until 2026.

4.5 Conclusions

The main conclusion is that even though there are barriers, such as space, shadows, optimal tilt, price, weight, and acceptance, the future of the BIPV systems means exponential growth boosted also by the energy crisis. The potential of the BIPV systems is very high, especially for industrial and commercial buildings that require very large spaces for implementation.

The new approaches allow a very good integration of the photovoltaic panels on the buildings' roofs and cladding, from both points of their performance and aesthetic. The new photovoltaic panels with homogeneous colors and a lot of variety of colors that can very well match the rest of the building were obtained with small losses in efficiency.

Thin film and ultra-thin photovoltaic panels allow for covering surfaces with different shapes and whose structures cannot sustain the weight of the mono or polycrystalline photovoltaic panels. The semitransparent and/or transparent photovoltaic cells have a huge impact on the roof canopy, facade, and windows. BIPV systems generate electric energy and make thermal energy economy using spaces that are unused. The future perspectives of the BIPV systems are very good, with all forecasts of their global market showing a consistent increase – for 2026, the rise representing 100%.

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Chapter 5
Building-Integrated Photovoltaic (BIPV) and Its Application, Design, and Policy and Strategies

Farzaneh Boronuosi, Sobhan Aghababaei, Sasan Azad, Mohammad Taghi Ameli, and Morteza Nazari-Heris

Abstract This chapter presents a system description of building-integrated photovoltaic (BIPV) and its application, design, and policy and strategies. The purpose of this study is to review the deployment of photovoltaic systems in sustainable buildings. PV technology is prominent, and BIPV systems are crucial for power generation. BIPV generates electricity and covers structures, saving material and energy costs and improving architectural appeal. BIPV generates clean electricity on-site and reduces building energy consumption through daylight usage and cooling load reduction, contributing to net-zero energy buildings. However, its adoption is limited by higher system costs compared to typical roof-mounted systems. BIPV systems serve as the outer layer of a structure and generate on-site electricity or grid export, resulting in material and electricity cost savings and enhanced architectural appeal while reducing pollution. The BIPV market is expected to grow from $17.7B in 2022 to $83.3B by 2030, with a CAGR of 21.4% from 2022 to 2030. A graphical abstract for PV system deployment in sustainable buildings is shown in Fig. 5.1.

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Graphical Abstract

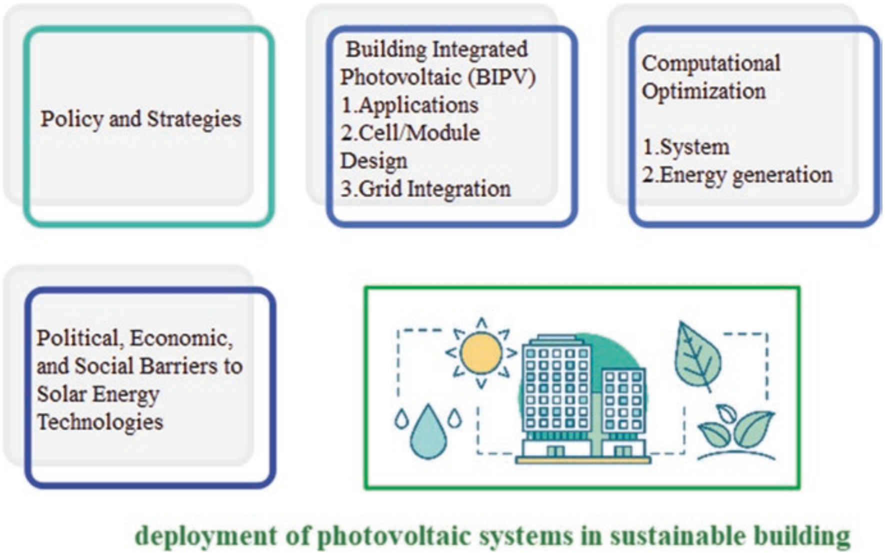

Fig. 5.1 Graphical abstract

5.1 Introduction

Solar energy is currently the most abundant, inexhaustible, and clean renewable resource [1]. The amount of energy that the sun radiates onto the earth in a day surpasses the energy consumed by humans in a day by up to 10,000 times [2]. The difficulty lies in obtaining this energy that is presently accessible without incurring high expenses. One of the most encouraging sustainable energy options is using photovoltaic technology. The use of photovoltaics (PV) is a sophisticated approach to generating electricity directly from sunlight without any worry about damaging the environment or running out of energy supply [2]. Building-integrated photovoltaics (BIPVs) are a type of photovoltaic technology seamlessly integrated into building structures, commonly used in roof and facade construction to replace traditional building materials. According to [1], BIPV systems are either incorporated as a functional element of the building's structure or are seamlessly integrated into the overall design of the building. Compared to nonintegrated systems, using BIPVs is highly advantageous as it eliminates the requirement for land allocation and facilitation of the PV system [3]. BIPVs have been recognized as a crucial component among the four key elements necessary for the future success of PV. The implementation of photovoltaic modules that generate electricity on location can lead to a reduction in overall building material costs and result in significant cost savings for mounting. This is particularly true for building-integrated photovoltaics, as they do not require additional assembly components such as brackets and rails. The BIPV mechanism converts sunlight into electricity and is eco-friendly with zero emissions. The worldwide demand for BIPV products has increased due to their numerous benefits [2]. The use of photovoltaic technology can facilitate the utilization of solar energy, which is a highly sophisticated and praiseworthy technological advancement. Four key factors require careful consideration when considering the potential uses of photovoltaic technology in the future. These factors include efficiency improvement, expense reduction, implementation of BIPV technology, and storage systems [3]. The BIPV innovation converts buildings into energy generators instead of energy users [4]. Integrating construction technology and BIPV technology is crucial for improved performance in this development. The photovoltaic modules are utilized as a structural component of the building's exterior, serving as its roof, facade, or skylight [4]. BIPV tech integrated into building envelop offers aesthetical, economical, and tech solutions. Product properties are cell efficiency, voltage, current, power, and fill factor. Critical factors for successful BIPV projects include proper module orientation, the distance between buildings, avoiding shadows, and architectural considerations. Accurate positioning can be achieved through anisotropic models and optimization techniques [5]. Replacing BIPV facilities in structures is important as their efficiency improves through research and development. BIPV is sustainable and creates zero-emission buildings, making its future promising [5]. Adopting and applying eco-friendly construction techniques are now considered pivotal in building practices. This is because they are believed to foster the creation of healthy, secure, cozy, and environmentally conscious structures. Green construction or sustainable building, as described by the Environmental Protection Agency in the United States, encompasses the utilization of environmentally conscious and efficient techniques during every stage of a building's life cycle and the building itself [6]. Due to differences in economic development, geographical setting, availability of resources, and various other factors, there is no universally agreed-upon definition of green buildings in literature. Based on the findings of Khan et al. Green building (GB) has undergone a challenging development since 2019, resulting in the implementation of eco-friendly structures. Green buildings substantially contribute to infrastructure development in nations and areas, emphasizing sustainable building management across a building's life cycle, from its design and construction phases to its operation and maintenance. Green building assessment instruments are a series of tools utilized to evaluate the efficiency of eco-friendly constructions. Buildings that demonstrate sustainable construction and provide a high quality of life are green constructions. The ultimate aim is to reduce the adverse effects of resource depletion, climate change, and building-generated emissions [7]. According to the Notebook Planning Commission (2018), structures utilize energy, water, and raw materials while producing waste and possibly hazardous atmospheric emissions during all stages, including construction, use, upkeep, alteration, and removal. As a result of these observations, guidelines, designations, and evaluation schemes were developed to promote sustainable, environmentally friendly building designs that minimize negative environmental impacts. The inception of the Environmental Assessment Method (BREEAM) by the Building

Research Establishment (BRE) played a pivotal role in the promotion of eco-friendly architecture during the 1990s in the United Kingdom [4]. Following this, alternative rating systems for environmentally friendly construction, such as LEED and Green Star, were introduced. BREEAM is presently acknowledged as the most effective classification system. Moreover, these evaluative techniques consider multiple factors when appraising environmentally sustainable structures. The criteria often emphasized in green rating systems involve features related to the quality of the interior environment, energy efficiency, and materials [6]. The past 10 years have witnessed a significant increase in green building and sustainable construction movements. Consequently, it has led to a comprehensive scrutinization of building materials and techniques globally. Furthermore, investments in infrastructure can result in negative social and environmental outcomes by intensifying susceptibility to natural disasters and creating an unmanageable debt load. Despite this, research carried out by Thacker and colleagues suggests otherwise. It is suggested in 2019 that governments and politicians develop durable plans for the sustainability of national infrastructure systems, along with adaptable tactics, to showcase their commitment [8]. In the same manner, in Sharma's (2020) study, the focus was on infrastructure's fundamental role in communities. This is achieved by ensuring the provision of essential amenities that include water, energy, telecommunications, waste management, and transportation [9]. Hence, for sustainability and eco-friendly construction to be prioritized, the choice and usage of materials that are environmentally friendly and possess desired characteristics should be emphasized over using traditional building materials. De Gracia and A.L. can be expressed as De Gracia and an individual with the initials A.L. According to Pisello (2018), structures are responsible for more than a third of worldwide final energy consumption and are notable generators of carbon dioxide (2) discharges. Approximately 50% of total energy usage in buildings is attributed to space heating, cooling, and hot water generation. The large usage of fossil fuels for space and water heating and the rising need for cooling in countries with high-carbon grid systems make these areas prime targets for reducing energy consumption, enhancing energy stability, and decreasing carbon dioxide emissions. By developing energy-efficient heating and cooling systems that produce little to no carbon footprint, significant reductions can be made in CO_2 emissions by 2050. These technologies, including solar thermal, CHP, heat pumps, and thermal energy storage, are commercially available. Although these technologies have immense potential, there are several hindrances to their widespread implementation, such as higher upfront expenses, market uncertainties related to novel technologies, insufficient knowledge, and ambiguity regarding technical, regulatory, and policy aspects [10]. The need to meet energy efficiency standards in new and old buildings has led to extensive research and designing techniques to reduce CO_2 emissions while enhancing indoor comfort and functionality [10].

In rural regions, alternative energy sources existed, including wind farms, solar facilities, biomass installations, and similar options. In city settings, solar energy systems, including solar thermal and photovoltaic technology, are commonly used in buildings. During the early years, according to Carmen (2021), the investigation of solar energy applications in construction was predominantly focused on technical aspects. The primary concern was to enhance the installation's energy efficiency and economic affordability. Establishing energy models was a challenge, exclusively concentrating on renewable energy systems. To effectively battle climate change, enhance energy performance in cities worldwide, and accomplish greater city resilience, it is imperative to have initiatives that concentrate on encouraging the adoption of renewable energies and energy storage mechanisms at an urban level. M.H. found that terms such as "sustainable communities," "energy autonomy," and "energy self-sufficiency" are used to address sustainable development encompassing environmental, social, economic, technical, and political challenges [11]. According to Shubbak's (2019) study, the current focus on research in the field of photovoltaic (PV) and Balance of System Technologies (BoS) involve the advancement of material constituents, production methodologies, and utilization options, making it an important area of investigation in today's world. The members of the BoS are pivotal in establishing links, safeguarding against chemical damage, and securely affixing cells onto panels. Additionally, they play a crucial role in electronically managing the cells' yield levels for electricity usage, storing them in batteries, or transmitting them to the utility grid. Furthermore, the system integrates the functionalities of testing and monitoring, along with the utilization of portable solar-powered devices [12]. PV systems, whether centralized utility-scale or distributed, consist of two components: solar cells and BoS, made up of PV panels, electronics, and energy storage. Several European Union nations, including Sweden, Denmark, Austria, Germany, and Switzerland, have implemented a new method of solar planning that demonstrates the ability to effectively utilize solar energy without compromising a site's cultural heritage and architectural value. The discovery has led to the increasing popularity of solar energy as one of Malaysia's most viable alternative sources. The preservation of the environment in Malaysia's energy industry has been made possible through the development of solar energy, which has proven to possess green potential. The first part of this chapter describes the Building Integrated Photovoltaic (BIPV) System description consisting of building applications, cell/module design, grid integration studies, and policy and strategies. Computational optimization will be mentioned in the second part; finally, the main conclusions are presented [13].

5.2 Building Integrated Photovoltaic (BIPV)

PV technology is proliferating compared to other renewable energies, which is why much research has been done on the subject. Among these studies, building-integrated photovoltaic (BIPV) systems play an important role in power generation. Kongual et al. [14] examined various energy efficiency options for buildings in China as part of the 11th Five-Year Plan period. In this connection, they explained the funding of his BIPV project and its application procedures. In [4], a critical appraisal of the exploration into the prospective capabilities of constructing-integrated power storehouses was conducted, focusing on the advancements in China. In [15], BIPV systems are also considered building-integrated energy storage systems divided into three: the BIPV system with solar cells, grid-connected, and the BIPV system with PV Trombe wall. For grid-connected BIPV systems, the grid has been viewed as an infinite-cycle battery with enormous capacity. Quesada et al. [16] examined the pertinent research and advancements about opaque solar facades within the initial decade of the twenty-first century. The classification of opaque solar building envelopes has been divided by scholars into two distinct subcategories: active solar facades and passive solar facades. The incorporation of building-integrated photovoltaic (BIPV) and BIPV with thermal (BIPV/T) systems into a functioning solar façade was delineated. Moreover, the present study material has been categorized into "theoretical and experimental research," "development," "feasibility," and "illustrative instances of the application." It has been determined that both Building Integrated Photovoltaic (BIPV) and Building Integrated Photovoltaic/Thermal (BIPV/T) technologies are financially feasible systems. The cooling effect of the air flowing behind the PV panels allows them to generate large amounts of energy more efficiently. In [16], the authors reviewed transparent and translucent solar façades using the same paper texture. Therefore, translucent BIPV and BIPV/T systems were described and checked as active façade systems. Jere et al. [17] reviewed current BIPV techniques in their work. Since BIPV applications generally follow the development of PV cells, they first provided information on current PV technologies and their classification. The authors reviewed BIPV products on the market, which they classified into four subgroups: films, tiles, modules, and solar glazing products. They concluded that new PV technology would lead to more efficient and cheaper BIPV, resulting in a faster payback period. In [18], a comprehensive analysis of key developments in various BIPV/T systems is provided. Developed in the early 1990s, the BIPV/T system has been of increasing interest since 2000 because of its potential to contribute to the design of net-zero energy buildings by increasing the use of solar energy. A wealth of articles report experimental and numerical studies related to BIPV/T system design and the impact of BIPV/T systems on building performance. BIPV/T systems under investigation are air-based, water-based, concentrating, and systems incorporating phase change working media such as BIPV/T and heat pipe or heat pump evaporators [18]. In [19], photovoltaic power generation integrated with buildings with thermal energy recovery offers excellent potential for integrating buildings without energy consumption, although this technology has been widely used. The advantage is safer than the traditional PV systems of BIPVT. In [20], a BIPV/T framework, the stream of a liquid that's often discussed in a canal underneath PV boards gives way to the recuperation of a significant portion of sun-oriented radiation as warm vitality. Hence, warmth can be delivered through BIPV/T frameworks to supply building requests. Conversely, the board is cooled by recuperated warm from the photovoltaic board, consequently expanding its power-era productivity. Shi and Chew [21] surveyed the plan for renewable vitality frameworks. A portion of their pondering clarified BIPV and BIPVT frameworks and gave cases from the things conducted so far. In [22], pathways and inquiries about openings for the BIPV frameworks of the long run were explored, and PV advancement and its effect on BIPVs, unused materials and arrangements for BIPVs, and their long-term strength were talked about in detail by giving cases from the writing. It was said that retrofitting and moderately simple establishment of BIPVs is exceptionally critical since of the tremendous volume of existing buildings. It was also expressed that governmental endowments are of incredible significance to induce the consideration of the industry, particularly sun-powered cell coating items that display extraordinary openings since they give sun-oriented shading, sunshine transmission, and power generation. Another imperative advancement is PCM innovation. In [23], stage alter materials are utilized for warm capacity and detached electronic temperature control. All of the examined PV–PCM frameworks have the control to the temperature increment of PV utilizing PCM. If the organic cell effectiveness increases, utilizing a PCM to preserve a natural cell at an ideal generation temperature may be suitable. There's a certain potential for the PCM due to the elevated temperature of the PV. In [24], cases of BIPV/T frameworks within the writing were given as part of an outline of photovoltaic/thermal (PV/T) frameworks. In [25], propels, approaches, and arrangements related to BIPV applications in Sun-powered Decathlon Europe houses were displayed. As discussed in [26], a little parcel of the photovoltaic industry constitutes BIPV. However, it is developing relentlessly. The need for approved forecast simulations required to form conscious financial choices avoids the broad utilization of BIPV. The venture, which can take a long time to compare the performance of BIPV boards to the estimation of photovoltaic reenactment devices, has been embraced by the National Organized of Benchmarks and Innovation (NIST). Input parameters that portray the electrical execution of BIPV boards uncovered to different meteorological conditions are required for the existing reenactment models. Within the same ponder, the creators have clarified how to create exploratory tests by giving the essential parameters. Reference [27] pertains to the thermal analysis of double-layer facades utilizing Building-Integrated Photovoltaic (BIPV) panels. Within the literature, scholarly inquiry has categorized studies as theoretical or experimental. Specifically, these studies have been subdivided into two distinct systems, natural and mechanical ventilation, which have been empirically evaluated concerning external influences. The investigation of mechanically ventilated facades was deemed significant by the researchers owing to the adaptable nature of the system [27].

5.3 System Description

A schematic of the BIPV system is shown in Fig. 5.2. As you can see from the figure, the photovoltaic system is integrated into the facade of the building. Outside air enters the system from the bottom and exits from the top. Absorb heat from PV modules, reduce temperature,and improve efficiency and service life. In some applications, systems use fans and air ducts to draw heated air into rooms to reduce heating loads in winter. Such systems are called BIPVT systems and benefit from electrical and thermally solar energy. Figure 5.3 shows a schematic of the BIPVT

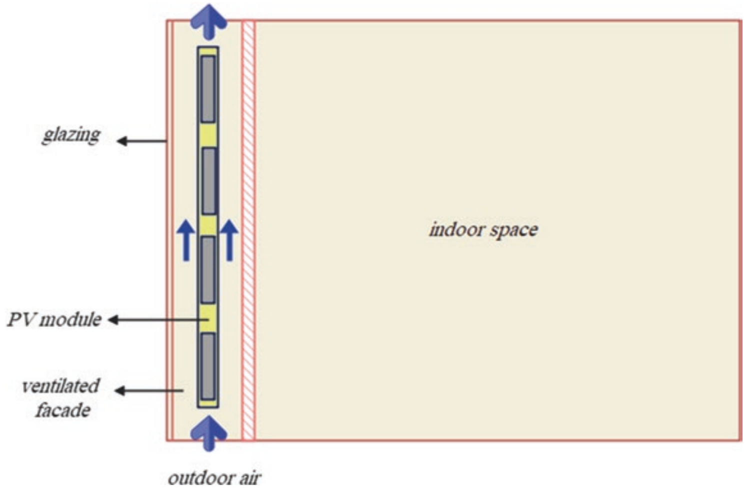

Fig. 5.2 Schematic of a BIPV system

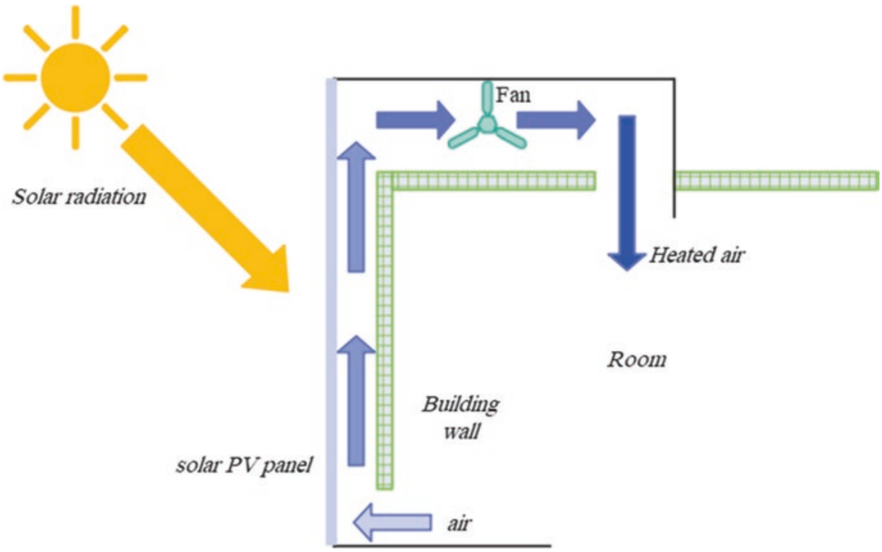

Fig. 5.3 Schematic of a BIPVT system

system [16]. BIPV systems can be categorized by solar cell type, application type, or market name. Photovoltaic technologies fall into two subcategories, silicon-based and non-silicon-based, while roof and façade integration is only two application types. In contrast, the classification described in [17] was used for marketed products. BIPV products are classified into four categories: foils, tiles, modules, and solar glazing, depending on the manufacturer's description or the material BIPV products replace.

5.3.1 Building Applications

Building application refers to an experiment conducted in a building or an investigation conducted in a laboratory. Various analyzes of prototypes or systems were performed. In general, module efficiency is lower at higher temperatures. Much research has been done to solve this fundamental problem. According to these studies, efficiency is improved by absorbing heat from the backside of the PV [28]. Research has been done to achieve this. Use air or liquid to create forced convection, open alternate inputs between hot and cold regions of the PV, supply fresh air, change the PV air gap, and optimize the air gap. This way, the modules' annual production and service life can be extended. Otherwise, shade, ambient temperature, building orientation, and tilt significantly impact achieving higher performance and efficiency in building applications. In the section, some of the applications of sustainable buildings are mentioned [28]. Yang and colleagues [28] investigated the performance of a BIPV system's installation subject to experimental investigation. To achieve optimal effectiveness, the photovoltaic panels were positioned with sufficient space between them and the wall to facilitate ventilation. Based on the findings, the roof was identified as the site with the most power. The system was estimated to produce 6878 kWh of energy annually at a cost of HK$3 per kilowatt-hour, which varies based on location and installation method. The cost of energy produced by the BIPV system varies between HK$1.5 to HK$3 per kilowatt-hour, with factors such as installation technique and location influencing the final price. Corbin and Zhai [29] studied a new type of BIPVT that includes thermal absorbance components, a tank for storing heat, and a pumping system that circulates water to the absorbance components. Two distinct computational fluid dynamics models were formulated. The initial design comprised a BIPV system that adhered closely to the ceiling surface. Conversely, the alternative method consisted of a tube-fin absorber that was liquid-cooled and situated in the cavity to scrutinize the benefits of active heat retrieval. The findings indicated that the second BIPVT exhibited an increased electrical efficiency of 5.3% compared to a naturally ventilated system. The system's thermal efficiency was determined to be 19%, while its total efficiency was measured at 34.9%.

The PVT system in [30] is experimentally created as an unglazed, single-pass, open loop. To ensure that the fluid in the system experiences the least possible friction loss and that a channel is formed for a mass flow rate ranging from 0.02 to 0.1 kg/s, a power input in the range of 4–85 W is necessary. Upon analysis of the experimental findings, it can be noted that a rise in mass flow rate yields an upsurge in thermal and electrical efficiency. During midday, the range for thermal efficiency is from 28% to 55%, while the content for electrical efficiency is from 10.6% to 12.2%. In their research, Yang and Athienitis [31] explored the efficiency of two BIPVTs that utilize inlet air. The setup used for the experiment includes 45 inclined and two heat-treated glass components. According to the findings, it was demonstrated that two inlet panels had 5% greater thermal efficiency than a single semi-transparent panel that exhibited a 7.6% higher thermal efficiency, as per an alternate report. Furthermore, opting for a primary, cost-effective design for both inlet panels is recommended.

5.3.2 Cell/Module Design

The advancement of BIPV technology has brought to light the need for the enhancement of modules and the importance of boosting efficiency. Research on this matter involves examining diverse models or assemblies comprising varied components for novel structures. Research concerning the aesthetic design of semi-transparent photovoltaic modules indicates that they exhibit superior efficiency when contrasted with conventional modules. The latest variety of white modules shows potential for achieving greater energy efficiency and operating at lower temperatures. In addition, a novel module design has been developed that utilizes a sandwich configuration consisting of a top layer of thin film, a middle layer of polyurethane, and an organic color plate on the reverse side. The new structure's material traits displayed improved operational effectiveness. Applying dye-sensitized solar cell technology represents a substantial advancement for building integrated photovoltaics. In the past 20 years, numerous endeavors have focused on thin-film technologies to significantly diminish the expense of producing each watt of power. The principal constituents of these slender-film methods are CdTe, CIGS, and amorphous Si. However, current manufacturing and materials obstacles could improve the growth of these technologies in the photovoltaic market. These hurdles primarily stem from the high processing temperatures (exceeding 500 degrees Celsius) required and environmental concerns surrounding the use of Cd and Te. As a result of the significant progress in the development of thin-film technologies, a new photovoltaic device known as dye-sensitized solar cells (DSCs) [32] has surfaced, offering the possibility of low-cost manufacturing and diverse applications such as the production of lightweight or flexible commodities. Advanced laboratory DSCs, called Grätzel solar cells, have achieved a 13% energy conversion efficiency on small-sized devices [33].

5.3.3 Grid Integration Studies

Research on grid integration generally emphasizes enhancing the efficacy of the PV system using modifications to its configuration. Energy distribution systems are designed to minimize losses and improve the effectiveness of acquiring energy by being structured in this manner. Choosing DC operations that align with the recommended power output for residential PV storage systems can enhance the overall system's efficiency. Energy loss occurs in the power grid due to electronic accessories, transformers, and lengthy distribution cables. To prevent the unnecessary integration of the grid, it is wise to back up grid resources with a BIPV system. Phase change materials (PCMs), employed for heat storage and passive temperature regulation in electronics, can draw in significant energy in latent heat. In Ref. [34], Bakos et al. evaluated a BIPV system's viability with a computerized RET tool. The first BIPV system had a 2.25 kW capacity—system: 3 inverters (850 W each). Energy production is estimated at 4000 kWh with system cost. PCM's use was studied in BIPV to control temperature rise [35]. The model investigated various parameters, including temperature, insolation, geometry, and PCM. It was the only validated PV. Chel et al. [36] simplified the model developed for BIPV system sizing and cost assessment in the study. They tested their method on a 2.32-kWp PV system case study. The system had two subarrays: 32 modules at 35 Wp each and 16 modules at 75 Wp each. BIPV electricity costs US$0.46 per unit.

5.4 Policy and Strategies

The following discourse on Building-Integrated Photovoltaic (BIPV) technology encompasses discussing future courses of action to implement and promote its progress and the obstructions that impede its advancement. Essentially, there is a need to enhance the developer's willingness alongside incentivization strategies for investors. Moreover, the communication between all relevant stakeholders must be amplified concerning advancements in Building Integrated Photovoltaics (BIPV). In Ref. [37], a life cycle model was used on US amorphous silicon PV shingles in various locations. A 2-kWp PV system with 6% efficiency and a 20-year lifespan was chosen. Data on generation, payback, efficiency, and pollution avoided were calculated for each area. Efficiencies ranged from 3.62% to 5.09%, with payback periods varying from 3.39 to 5.52. BIPV systems are most effective in reducing air pollution in cities using coal and natural gas, not in towns with high insolation and displaced conventional electricity. In [38], the need for enough talented workforce for PV/BIPV establishment and support was tended to. It was expressed that this circumstance may result in ineffectively introduced frameworks and negatively affect the industry. The PVTRIN venture, upheld by the European Commission, tending to this fact, was clarified in detail. These potential dangers were thoroughly examined throughout the design, construction, installation, commissioning, and operation processes. In every stage, there is an enumeration of impediments and remedies [39]. BIPV is restricted by its limited market and exorbitant expenses for all involved parties. The proliferation of technology necessitates the careful development and implementation of practical solutions across all relevant parties.

5.5 Political, Economic, and Social Barriers to Solar Energy Technologies

Boudet (2019) presented a comprehensive examination of the multidimensional significance of energy, encompassing its economic, social, and political ramifications and potential impact on public health and the natural environment. The preceding statement implies that the arrival of novel technological advancements typically incites a potent public response. The comprehension of these public reactions assumes utmost significance as the determinants that govern such reactions, mainly through public endorsement, can wield considerable influence over the adoption and deployment of innovative technologies [40]. This discourse delineates a range of technological advancements that are pivotal to the energy field. These include extensive energy infrastructure projects comprising wind, solar, fossil fuels, and utility-scale marine renewables, alongside smaller-scale ventures such as electric vehicles, solar rooftops, and brilliant meters. Such advancements in energy technology have earned recognition as a "Center of Excellence" technology. Consequently, the strategy delineates a comprehensive array of patterns that would aid policymakers, technologists, and the public to effectively exchange information and ease the progression towardmore sustainable energy systems [40]. Energy is a fundamental element in facilitating economic expansion and advancement. The escalating energy demand from burgeoning population growth and expanding economic development underscores the imperative for integrating renewable energy sources. Durganjali and colleagues. The study conducted in 2020 revealed a notable escalation in the undertakings necessary for the advancement of solar technology. Photovoltaic systems exhibit exceptional levels of energy conversion efficiency and require a significant capital investment. Moreover, many photovoltaic cells are required to harness adequate solar energy effectively. The effectiveness of PV modules is significantly impaired by overheating; thus, more solar panels are required for optimal performance [41]. A study by M.S. Rahman et al. (2017) discussed energy use. Fossil fuels are used in various sectors of production. Minerals such as tin, bauxite, and iron are consumed in Malaysia as they are used as raw materials in various manufacturing processes [42]. Therefore, we analyze different elements of fragmented energy consumption to identify those that have the most significant impact on Malaysia's economic growth [42]. M. Irfan et al. research (2019) highlights the dual impact of their work on both a nation's economic progress and the well-being of its people. Solar energy initiatives demand substantial investments and display short scope for cost reduction through scale. It will be a considerable period before payback is administered. Numerous economic obstacles emerge; for instance, launching a new solar energy project can be challenging due to the considerable upfront investment required, a lack of understanding of market demand, inadequate support from the government, and the reluctance of financial institutions to fund significant projects. Numerous societal hurdles exist, including the necessity to enhance comprehension of solar power, particularly in rural regions, and a need for more endorsement and engagement from the public. New solar energy projects face a significant hurdle as people persist in dependence on traditional power sources [39]. In 2019, Sinha discovered that photovoltaic technology may be easier to access if there is greater awareness among the general public. The growth of photovoltaic systems, notably in developing nations, must be improved by a significant hindrance. Local customers view their need to understand solar power technology as an impediment to considering it a feasible alternative. Furthermore, the construction of extensive solar power facilities necessitates a significant expanse of land. Therefore, the scarcity of land is an issue [43].

5.6 Computational Optimization

The energy used to heat, cool, and light buildings accounts for up to 40% of CO_2 emissions in developed countries [13]. The construction industry is the most promising sector in terms of its potential to effectively and economically reduce CO_2 emissions. Numerous regulatory and certification enticements exist to augment the sustainability of buildings. The aforementioned comprises a range of regulations governing the construction of buildings, including the nationally established building codes, the European Union's Building Energy Performance Directive (EPBD), the Building Research Establishment Environmental Assessment Method (BREEAM), and Leadership in Energy and Environmental Design (LEED) ratings, as well as regional planning guidelines. Computer simulations can quantify the energy consumption of building designs that are proposed. The process encompasses the utilization of heat, sunlight, and airflow modeling techniques to inform decision-making on building design, materials selection, control mechanisms, and system implementation [44]. However, designing sustainable buildings takes work. All buildings are unique, no prototypes. Designs should achieve high levels of performance at the lowest possible cost. Many physical processes lead to conflicting goals. The scope for designing possible solutions is vast. These challenges have made the application of computational design optimization techniques advantageous [44].

The analysis of the best possible outcomes and strategies for achieving them is the focus of optimization theory, as stated by Beightler et al. The subsequent explanation provides a comprehensive mathematical depiction of the optimization quandary [45].

$$\begin{aligned} &\min F\left(x_1, x_2, \ldots, x_n\right) \\ &G\left(x_1, x_2, \ldots, x_n\right) \geq 0 \\ &x_i \in S_i \end{aligned} \tag{5.1}$$

Several objective functions F exist and are conventionally expected to be reduced. Several functional limitations labeled as G are conventionally required to have a value of no less than zero. The importance of each design variable xi is limited to specific values Si, which can be discrete or defined by boundary values. The interchangeability of objectives and constraints relies on how the problem is framed. It should be noted that the above explanation does not mandate the presence of continuous functions or the existence of differentials. Numerous varied techniques exist for utilizing computers to enhance engineering designs. Below are succinct particulars of several prevalent optimization algorithms employed in sustainable building optimization. These are all heuristic approaches, meaning there is no guarantee of reaching the best solution. Still, they provide an effective method with a strong chance of finding the optimal solution or coming nearby. Sources are attributed to the original publication that introduced them or a contemporary examination of their application. "Direct search" involves comparing trial solutions with the current best solution found, then utilizing the previous results to determine the next trial strategy. Extensive discourse is presented in Ref. [46]. Nelder and Mead [47] propose that when the objective function and constraints are linear, the optimal solution must be at an extreme point. Nonlinear programming refers to various expansions that enable nonlinear restrictions and objectives. The approach ofthe interior point method involves moving within a feasible area described by barrier functions.

5.6.1 System

The energy consumption of a given building can be considerably impacted by the Heating, Ventilation, and Air Conditioning (HVAC) systems that cater to specific areas within the structure. To function effectively, they necessitate particular configurations and regulations.

1. Design: Wright et al. [48] optimized HVAC systems using a Genetic Algorithm. Goals: affordable energy and comfortable temperatures. It is modeled one space, heating/cooling with coils, fan, and heat exchanger, hourly for three design days. The zone and HVAC system were simulated using different models. There were 11 HVAC design variables and 189 control variables. Design coil and fan performance limitations and system capacity were constrained. Violations resulted in infeasibility and were included as a third objective. Results were shown for three thermal weights on three design days. This study expanded on Wright and Farmani's [49] work by incorporating three fabric properties.
2. Control: Newer studies validate HVAC systems with building models and measurements, valid for control optimization but less generalizable than simulation methods. Lee and Cheng [50] minimized chiller energy consumption with a hybrid algorithm using Particle Swarm Optimization and Hooke-Jeeves. Čongradac and Kulić [51] used a Genetic Algorithm and a neural network metamodel trained on measured data for a similar problem.
3. Lighting: Buildings' artificial lighting can use energy and affect cooling and overheating. Previous studies covered daylight and glare concerns. Studies on energy use simulate daylight for less artificial lighting. Using external sensor

data, Coley and Crabb used a Genetic Algorithm to predict daylight levels. This approach may have been replaced by programs that simulate lighting levels directly. Cassol et al. optimized artificial lighting design in their work [52]and optimized lighting energy use and level through Generalized Extremal Optimization and radiosity simulation by varying light location and power. The optimization was intensive yet robust and flexible.

5.6.2 Energy Generation

Although reducing the energy needs of buildings is beneficial, renewable energy sources are required to meet unavoidable demands to attain extremely low or zero carbon emissions. Various regulatory and evaluation arrangements mandate that the method of power generation must have a direct link to the structure it is intended to power. The ensuing parts delineate optimization usage instances in three energy generation domains integrated into buildings.

1. Combined Heat and Power: CHP systems harness the unused heat generated during electricity production to warm buildings, including space heating and hot water supply. Different designs come in various sizes, from small-scale ones that cater to one home to more extensive district heat networks that provide heat to entire cities. CCHP is a system that utilizes absorption chillers to generate chilled water for cooling by employing available heat. Ooka and Komamura [53] developed a two-stage optimization process for reducing carbon emissions and energy usage in CCHP systems. The first stage dealt with equipment capacities, and the second with hourly output coefficients. A multi-island Genetic Algorithm was used, and demand data were for a peak day. Solutions were validated against brute-force search, a unique approach in this field.
2. Solar technologies: Solar technologies utilize solar radiation to either heat water or generate electricity via photovoltaic (PV) cells. Most frequently, these technologies are integrated into buildings, particularly on rooftops, where the structure provides support at a high and unobstructed level. Solar thermal systems typically generate heat at a low level, which is primarily sought after for providing hot water to constructions. Photovoltaic cells can generate electricity for building use and transfer surplus power to the grid during off-peak periods, reducing the requirement for centralized infrastructure and the associated energy losses from transmitting power over long distances. Analytical approaches have been applied to address different issues concerning building-integrated solar technologies. By strategically modifying the placement and specifications of the two major components, namely PD panels and vision glazing, Charron and Athienitis [54] were able to optimize the productivity of a dual-skin facade mechanism.
3. Ground energy and storage systems: Ground temperatures stay consistent year-round, creating a helpful temperature variance (warmer than air in winter, cooler

in summer). Heat pumps provide heating through underground pipes and can also use excess energy. The heat extracted in summer can be stored in the ground or other systems to reduce peak demand—examples of optimization for these technologies. Khalajzadeh et al.'s research used a meta-model [55] to design a vertical ground heat exchanger and achieve the highest possible heat transfer efficiency by manipulating pipe diameters, flow velocities, and temperatures.

5.7 Conclusion

The chapter comprehensively assesses various conceivable perspectives, thoroughly investigating the obstacles, difficulties, and contrasts affecting each feasible route toward flexibility. Incorporating solar energy technologies such as solar thermal and photovoltaic (PV) in buildings confers momentous environmental rewards, thereby enhancing the sustainability of human practices in the long run. Numerous countries have explored and adopted eco-friendly renewable alternatives to tackle escalating energy demands while simultaneously curbing the adverse environmental consequences and other associated issues attributed to fossil fuels. The utilization of renewable energy sources carries paramount resourcefulness in mitigating pollution, particularly in mitigating the emission of greenhouse gases. The objective above is attained through mitigating atmospheric emissions, predominantly by substituting conventional fuel and fossil-derived energy sources. Renewable energy presents the potential to serve asalternative a viable energy source for urban residents, contributing significantly toward environmental sustainability, overall health and well-being, political stability, economic development, and sociocultural advancement. The utilization of solar photovoltaics (PV) exhibits exceptional potential in curtailing energy emissions, thereby serving as a valuable aid in mitigating climate change. The anticipated progression of enhanced efficiency and lower cost of photovoltaic power generation systems suggests a possible noteworthy contribution to the energy landscape in the forthcoming years. The optimal solar energy resource potential implementation entails involvement, cooperative efforts, and integration among various entities such as the government, the private sector, non-governmental organizations, and the local community. Moreover, the utilization of the STEEP framework may be executed and deliberated upon in a prospective investigation of solar photovoltaic technology in any given nation. Solar photovoltaic (PV) energy is anticipated to impact the global sustainable energy system's development significantly. The trend toward sustainable building design shows evident expansion, particularly on multi-objective optimization. This is partially attributed to the expanding computing capability, which now makes it possible to tackle previously tricky problems. This trend will probably persist as optimization endeavors venture into sectors that exceed our proficiencies. Form optimization requires sophisticated models and extensive analysis to thoroughly explore the expansive realm of design options. The improvement of various aspects of building design in a comprehensive manner will expand, encompassing a multitude of intricate factors or merging divergent disciplines in building design.

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Chapter 6
Integration of Small-Scale Wind Turbines in Sustainable and Energy Efficient Buildings

O. Apata, P. N. Bokoro, and G. Sharma

Abstract The integration of renewable energy resources in buildings is one way of achieving energy efficient and sustainable buildings (zero-energy buildings (ZEBs) or low-energy buildings), reducing fossil energy consumption, and cutting down carbon emissions in urban areas. Buildings are an integral component in the development of any city, and they provide a unique opportunity to contribute toward the achievement of the seventh sustainable development goal (SDG) of the United Nations, which is aimed at ensuring access to affordable, reliable, sustainable, and modern energy for all. To buttress the importance of buildings to urbanization, the United Nations Environment Program launched the Sustainable Buildings and Climate Initiative to promote and support sustainable building practices that encourage energy efficiency and the reduction of greenhouse gas (GHG) emission. Though photovoltaic systems have become increasingly popular with sustainable buildings, small-scale wind turbines can be integrated into such buildings to increase energy efficiency and cut carbon emissions. This chapter therefore investigates the different types of wind turbines available, the practical integration of such wind turbines in sustainable buildings, and the different factors affecting the performance of such small-scale wind turbines in sustainable buildings.

6.1 Introduction

Over the last decade, there has been a rapid growth in population which has ultimately led to a corresponding increase in urbanization. Statistics from the world bank show that more than 56% of the world's population is concentrated in cities, with the trend expected to continue and the urban population doubling its current size by 2050 [1]. The increase in urbanization brings with it some challenges such

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as increased demand for affordable housing and viable infrastructure. The rapid urbanization of cities and its contribution to climate change have raised critical questions about the possibility of how the built environment needs to evolve sustainably, reducing carbon emissions. As the world continues to face an unprecedented environmental crisis, there has been a growing interest in sustainable and energy-efficient buildings. In this context, renewable energy sources such as wind, solar, and geothermal power have gained significant attention as potential alternatives to traditional fossil fuels. Among these renewable sources, wind energy is particularly promising, and small-scale wind turbines are emerging as a viable option for powering homes and buildings [2].

There is a direct relationship between urbanization and buildings since buildings are a key component in the fabric of any society. The building sector is a very important area that can provide opportunities toward achieving the sustainable development goals as well as limiting environmental impact. The exponential growth of the building sector has also prompted an increased demand for energy usage. According to the 2021 report of the International Energy Agency (IEA), the buildings and building construction sectors combined were responsible for over 30% of the global final energy usage and contributing about 27% to total energy sector emissions [3]. To address the issues of sustainability and GHG emissions from buildings and the built environment, the United Nations through its climate action plan, otherwise known as the Paris Agreement [4] and the Sustainable Buildings and Climate Initiative (SBCI) [5], has proposed several strategies to promote and support sustainable building practices that focus on energy efficiency and reducing GHG emissions. These initiatives and strategies demonstrate the importance of ZEB in contributing toward the achievement of the sustainable development goals (SDGs) of the United Nations. To encourage the development of sustainable buildings and the decarbonization of the building sector, the use of more renewable and energy-efficient technology in buildings is being promoted while energy codes and minimum performance standards for buildings have increased in both stringency and scope [3].

A sustainable building can be referred to as an energy-efficient and environmentally responsible building. Such a building is required to produce significantly less carbon dioxide emission in comparison to a regular energy equivalent building. Such buildings have a better indoor air quality and low environmental impact. It is important to point out that sustainable buildings can either be a zero-energy building or low-energy building [6].

Zero-energy buildings, also known as net zero-energy buildings, are an innovative approach to sustainable architecture and design that aim to reduce or eliminate the net energy consumption of a building over a period. This implies that the energy produced is equal to the energy used by the building. These buildings use a combination of energy-efficient design, passive solar heating and cooling, on-site renewable energy generation, and energy storage technologies to achieve their goal of zero net energy use [7]. The concept of zero-energy buildings has gained increasing attention in recent years as the world faces the challenge of reducing greenhouse gas emissions and mitigating the impacts of climate change. With buildings accounting for a significant portion of global energy consumption and carbon emissions, zero-energy buildings have the potential to play a crucial role in achieving a sustainable future. As the benefits of zero-energy buildings become increasingly clear, it is likely that they will become a more common approach to sustainable design and construction in the years to come.

Low-energy buildings, also known as energy-efficient buildings, are designed to consume less energy than traditional buildings while still providing a comfortable and healthy indoor environment for occupants [8]. The primary goal of low-energy buildings is to reduce energy consumption and greenhouse gas emissions, while also improving energy security and reducing reliance on nonrenewable energy sources. Low-energy buildings typically feature a combination of energy-efficient building materials, passive design strategies such as orientation and shading, high-performance insulation, efficient heating and cooling systems, and renewable energy technologies. These features work together to reduce the amount of energy needed to maintain a comfortable indoor environment, resulting in lower energy bills and a smaller carbon footprint [9]. As energy costs continue to rise and concerns about climate change increase, the demand for low-energy buildings is growing. Many countries have implemented building codes and standards that require new buildings to meet minimum energy efficiency requirements, and many existing buildings are being retrofitted to improve energy performance. Low-energy buildings offer a promising solution for reducing energy consumption and greenhouse gas emissions, while also improving the comfort and health of occupants. As technology and design strategies continue to advance, it is likely that low-energy buildings will become even more common in the future, paving the way toward a more sustainable built environment.

The idea of sustainable and energy-efficient buildings can be implemented by applying innovative technologies and measures based on renewable energy solutions. The choice of renewable energy technology is based on the availability of the energy source. The major renewable energy technologies commonly adopted for sustainable buildings, as seen in Fig. 6.1, are as follows:

- Wind turbines.

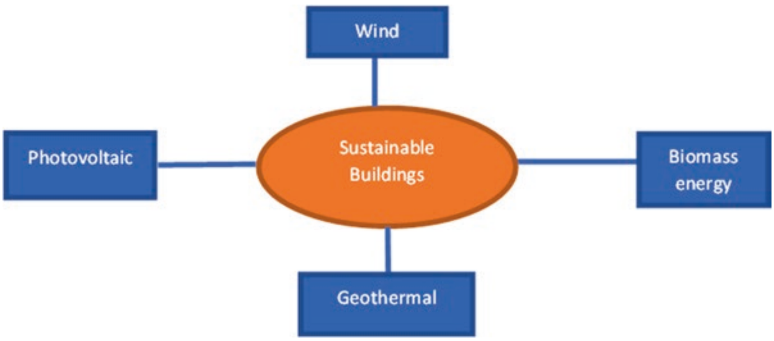

Fig. 6.1 Schematic representation of major renewable energy technologies adopted for building

- Photovoltaic (PV).
- Biomass energy.
- Geothermal.

Though PV is one of the most used renewable energy technologies in achieving sustainable buildings, this chapter will focus on the integration of wind turbine systems in sustainable and energy-efficient buildings. This technology will be discussed in subsequent sections of this chapter.

Wind energy is a clean and renewable source of energy that has numerous benefits over traditional fossil fuels. One of the most significant advantages of wind energy is that it produces zero emissions, which means that it does not contribute to air pollution or global warming [10]. Unlike fossil fuels, which are finite resources, wind energy is abundant and inexhaustible, meaning that it can provide a reliable source of energy for generations to come. Another advantage of wind energy is its cost-effectiveness. While the initial investment in wind turbine technology can be high, the ongoing maintenance costs are relatively low, making it a cost-effective source of energy over the long term. In addition, wind energy can help reduce dependence on foreign oil, as it is a domestic source of energy that can be generated locally.

Wind turbines have been used for centuries to harness the power of the wind, but only recently have they become a realistic option for generating electricity on a small scale. Advances in technology have made it possible to produce turbines that are smaller, quieter, and more efficient than ever before, making them ideal for use in residential and commercial settings. Small-scale wind turbines are designed to generate electricity on a smaller scale than traditional, large-scale turbines. They are typically used to power homes, businesses, and other small buildings and can be installed on rooftops or on free-standing towers. Small-scale wind turbines have several advantages over larger turbines, including lower costs, easier installation, and greater flexibility in terms of location. Small-scale wind turbines can supplement energy supply and reduce dependency on the grid, making buildings more resilient to power outages and reducing greenhouse gas emissions.

The integration of small-scale wind turbines in sustainable and energy-efficient buildings is an exciting area of research and development and an emerging trend in the field of renewable energy. This approach involves incorporating wind turbines into the design of buildings to supplement energy supply and reduce reliance on the grid. Small-scale wind turbines have the potential to provide a source of clean and renewable energy, while also reducing greenhouse gas emissions and improving energy security. Integrating small-scale wind turbines in buildings can reduce energy costs by supplementing energy supply from the grid. This can help reduce electricity bills for building owners and occupants. In some cases, excess energy generated by small-scale wind turbines can be sold back to the grid, providing an additional source of revenue.

However, the integration of small-scale wind turbines in buildings presents various challenges that require careful planning and coordination between architects, engineers, and energy professionals. Also, the integration of small-scale wind turbines into buildings requires careful consideration of factors such as wind speed and direction, noise, vibration levels, and building codes and regulations [11].

The rest of this chapter discusses the different types of wind turbines that can be integrated into buildings, the practical integration of such wind turbines in sustainable buildings, the status and future of small-scale wind turbines for sustainable buildings, the technical and economic aspects of integrating wind turbines into buildings to improve energy efficiency, and the issues affecting the integration of small-scale wind turbines in sustainable buildings.

6.2 Wind Energy

The wind industry has continued to experience significant growth and expansion. The importance of wind energy in decarbonization and sustainable energy solutions is illustrated in Fig. 6.2, which shows an upward trend in wind power installations globally from 488 GW in 2016 to 906 GW at the end of 2022, as indicated in the 2023 report of the Global Wind Energy Council [12]. Despite the growth in global wind power installations, it is important to note that investing in a wind system is dependent on the availability of wind resources. The National Renewable Energy Laboratory (NREL) has produced wind resource maps that are based not just on wind speed but on wind power density [13]. Since the combined effects of wind speed frequency distribution, the cube of wind speed, and dependence of the wind power on air density are all incorporated in wind power density, it is a better indicator of the availability of wind resource in any given location. Wind maps usually give a rough estimation of wind speeds and might differ from the actual wind speed by a range of ±10 % − 15%, and this deviation can be further compounded up to ±20% [14].

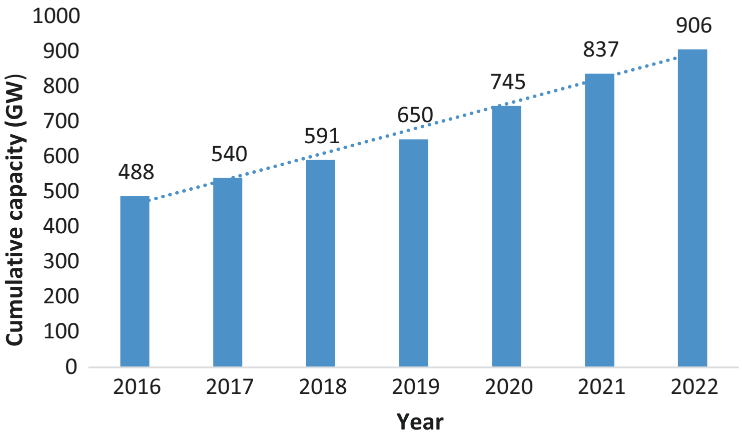

Fig. 6.2 Global cumulative installed wind power capacity, 2016 to 2021

Table 6.1 Wind power classification

Wind power class	Resource potential	Wind speed at 50 m (m/s)
1	Poor	<5.6
2	Marginal	5.6–6.4
3	Fair	6.5–7.0
4	Good	7.0–7.5
5	Excellent	7.5–8.0
6	Outstanding	8.0–8.8
7	Superb	>8.8

Wind resource can be classified according to the electricity-producing potential over an annual basis, as shown in Table 6.1. The choice of level of classification is solely for the purpose of convenience and not an indication of any meteorological or physical boundary.

It is not economically feasible to invest in wind technologies in areas with lower wind resources. From Table 6.1, it can be observed that a class 3 wind resource site is a good site to consider small wind turbines (100 kW or less) or large, low wind speed turbine opportunities. Class 4 wind resources and above provide an opportunity to deploy large utility scale wind turbines. However, this chapter will focus on small wind turbine applications.

6.3 Wind Turbine Technologies

Wind turbine technologies are based on the operational principle of conversion of kinetic energy of a wind resource into mechanical work. Wind turbines are primarily classified as either vertical or horizontal-axis wind turbines. These technologies vary in complexity, cost, and efficiency of wind power extraction. They also come in varying sizes and can be regarded as large wind turbines (rated above 100 kW), small wind turbines (rated between 10 and 100 kW), and micro wind turbines (rated below 10 kW). The large turbines are usually grouped together to create wind farms or wind power plants for wholesale bulk electricity production, while the smaller wind turbines are suitable for residential or industrial electricity generation.

Wind turbines can also be grid connected or off-grid connected depending on the application. The different sub-units that make up a wind turbine system are shown in [15]. Wind turbines are usually built with either two or three blades that rotate with the corresponding wind speed. The turbine blades work more efficiently when turned into the wind. It is important to note that though strong winds are desirable for wind power, too much of wind can also damage the turbine after it attains maximum speed if there are no appropriate controls in place. Though wind quality is a significant factor in the generation of electricity by wind turbines, other components of the wind turbine, such as the hub height and rotor diameter, as well as the management of operation and maintenance of the wind turbine, all play a significant role in the extraction of maximum electrical energy from wind by the wind turbine. The vertical and horizontal wind turbine technologies will be discussed further in the following subsections.

6.3.1 Vertical-Axis Wind Turbines (VAWTs)

Vertical-axis wind turbines (VAWTs) usually have their blades attached to the top and bottom of a vertical rotor. The axis of rotation of the rotor of the VAWT is perpendicular to the ground and wind direction. A unique feature of this wind turbine type is its ability to operate in low wind situations and better capability for handling turbulence. They are therefore better suited for use in urban environments and cities where wind flow is less predictable. The VAWT is a preferred choice for buildings and rooftop installations and on-ground installations that would ordinarily prevent installing taller horizontal turbine structures.

The VAWT blades are always oriented into oncoming wind by design, meaning they are omnidirectional. The simplified tailfin or yawning ensures that the turbine blades are always oriented in the right direction. The simplified vertical blade design of the VAWT means it has a relatively cut-in wind speed, which allows it to function when surrounded by infrastructure or buildings irrespective of wind direction. These wind turbines can also be installed close to the point of use such that they reduce load on any existing grid infrastructure, thereby reducing environmental concerns and promoting sustainability.

Since the VAWTs are shorter in height than traditional horizontal wind turbines, they have a lower visual and environmental impact around buildings. The closeness of the VAWT to the ground means there is a lesser need for structural support making it easier to carry out maintenance functions on the wind turbine and its components parts. Initially, VAWTs were designed for crop irrigation and pumping water in remote areas with low speed from different directions; however, these turbines are now efficient solutions for use in urban areas and built-up areas with unstable wind supply [16]. Figure 6.3 shows that the VAWTs can be further categorized into two designs, namely the Savonius and Darrieus VAWTs.

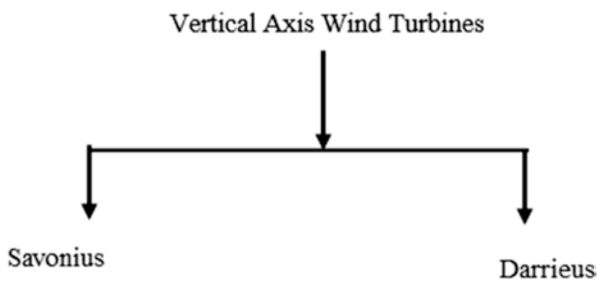

Fig. 6.3 Classification of VAWTs

6.3.1.1 Savonius Wind Turbines

The Savonius wind turbine is named after its inventor S.J. Savonius who developed a patent for its design in the 1920s [17]. The Savonius is a simple wind turbine design operational on the principle of "differential drag" so that the turbine blades cannot rotate faster than the wind speed. The rotor of this VAWT uses offset semi-cylindrical aerofoils and half cups or cylinders that are usually designed to face opposite directions in such a way that they form a S-shape design and attached to the vertical shaft. This S-shape design ensures that the turbine blades are unidirectional.

As shown in Fig. 6.4, the Savonius wind turbine has four blade configurations for rotational performances. These turbines work by creating a differential drag force between the concave and convex parts of the rotor blades during rotation around the vertical shaft.

A unique characteristic of the Savonius wind turbine is its self-starting ability and being able to generate torque because of the drag force of its geometry. The main advantage of the Savonius turbine is its simple rotor design, low tip-speed ratio, and low cut-in wind speed. This enables it to rotate easily and extract energy from any nondirectional wind. This makes the Savonius wind turbines well suited for urban locations with low and turbulent wind speeds. However, since this wind turbine is based on the principle of differential drag, it has a much lower efficiency when compared to the Darrieus wind turbine since it can only extract about 25 to 30% of available wind power.

6.3.1.2 Darrieus Wind Turbines

The Darrieus wind turbine is named after its inventor, G.J.M Darrieus who invented the turbine in 1931 [18]. The blades of this turbine can be straight, curved, or helical and mounted onto a vertical shaft. The curved configuration is commonly referred to as a D-type blade while the straight blade configuration is commonly called the H-type blade. These configurations are illustrated and discussed in [19]. The operation of the Darrieus wind turbine is based on the principle of lift force. This means

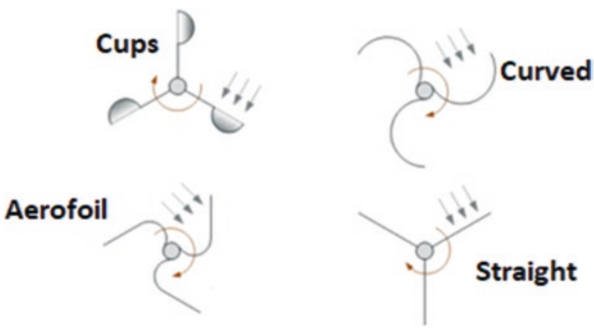

Fig. 6.4 Blade configurations of the Savonius wind turbine

that the turbine can produce maximum driving torque when the turbine blades move across wind faster than the speed of the wind. This principle makes it possible for the Darrieus wind turbine to extract more usable energy from wind per unit of swept area when compared to the Savonius turbine.

Unlike the Savonius wind turbine that is self-starting, the Darrieus wind turbine requires an external mechanism to start it initially. This means that wind can only exert a driving force upon the turbine rotor after it begins to rotate. The turbine blades of the Darrieus wind turbine are optimized to ensure that bending stress is minimized on the turbine blades ensuring that the force on the blades will be exclusively a result of tension. Just like the Savonius wind turbine, the Darrieus wind turbine is also a very good fit for urban areas with weak or unstable wind speeds.

6.3.2 Horizontal-Axis Wind Turbines (HAWTs)

The horizontal-axis wind turbines are the traditional design of wind turbines and the most used. They have a semblance to the historical windmills. The HAWTs utilize airfoils fitted to a rotor and can be designed with two or three blades. The most used blade configuration today is the three-blade configuration though the two-bladed configuration remains popular. The blades of the HAWT can be positioned either downwind or upwind [20], as illustrated in Fig. 6.5. The upwind HAWTs deliver more power and operate more smoothly when compared to the downwind HAWTs. However, the major setback of the upwind HAWT is the complexity associated with its yaw control system in keeping the turbine blades facing the wind. The downwind turbines do not need any mechanical orientation system for the blades since they face the wind direction. However, the major setback of this is the increase in turbine fatigue because of frequent oscillations caused by fluctuations in wind speed. The upwind design of the HAWT is the most used since it delivers more power than the downwind configuration.

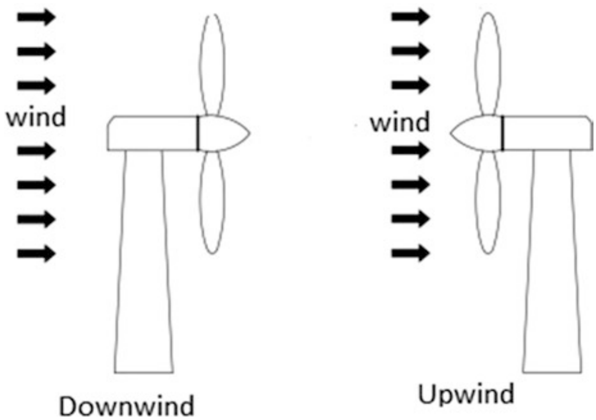

Fig. 6.5 Horizontal-axis wind turbine configurations

The principle of operation of the HAWT is based on aerodynamic lift. There is a flow of air around the upper and lower portions of the turbine blade when exposed to winds. This flow is more visible over the top of the blade due to the curvature of the blades and produces a low-pressure area on the top side. The differential in pressure between both sides of the blade creates a force in the direction of the top of the blade. This force acts perpendicular to the wind acting on the turbine blade. Since this force is usually stronger than the force of the wind against the turbine blade, it allows the turbine blades to turn.

The HAWTs are not suitable for use in urban area or roof top applications in residential buildings because of the frequent and dramatic change in wind directions in such areas, making it difficult for the HAWTs to align with changes quickly and properly in wind speed. Therefore, the HAWT is more suited for onshore or offshore commercial applications.

6.4 Integrating Wind Turbines in Buildings

As seen from the previous sections in this chapter, the VAWTs are more suitable for generating energy in urban and suburban areas due to their ability to operate in low wind situations and their better capability for handling turbulence. The VAWT is a preferred choice for buildings and rooftop installations and on-ground installations that would ordinarily prevent installing taller horizontal turbine structures. Such wind turbines can also be included in building designs and integrated into buildings from an economic, structural, and architectural perspective and can be mounted among buildings not just on the rooftops [21]. Though the VAWT is the preferred choice for wind applications in urban and suburban areas, the HAWTs are deployed for such applications in some instances.

The integration of small-scale wind turbines in either residential or commercial buildings presents an excellent opportunity for reducing the carbon footprint in such buildings, making them energy sustainable and efficient. As a result of the shape of buildings, these wind turbines exploit the concentration of wind power and are classified into three categories, namely building-mounted wind turbines (BMWTs), building-integrated wind turbines (BIWTs), and building-augmented wind turbines (BAWTs).

6.4.1 Building-Mounted Wind Turbines (BMWTs)

The BMWTs are usually installed at greater altitudes to access higher-quality winds. This class of small-scale roof-mounted wind turbines can either have a horizontal-axis or vertical-axis rotor type. These wind turbines have the capability to operate close to buildings and can exploit any augmentation that this might cause to the local wind. Typically, the BMWT with a horizontal-axis rotor is mounted on a mast and securely fixed onto the roof of the building, as illustrated in [22]. In this case, the building functions as a tower for the turbine such that the turbine is strategically installed in a desirable wind flow. BMWTs are usually connected to the structure of the building. It is therefore important that the structure of the building must be able to support the turbine with respect to any vibrations and noise. These turbines can also be mounted on the walls of buildings.

As a result of the separation of airflow, there is usually the formation of turbulence, which makes the vertical-axis wind turbine more appropriate for use. To mitigate the consequences of wind turbulence along the edges of the building, a curved roof can be used or by placing the wind turbines on shafts or poles so that they can reach the undisturbed air.

6.4.2 Building-Integrated Wind Turbines (BIWTs)

These are wind turbines that can be integrated into building designs, making the turbines an integral component of the building. Such turbines are integrated into the building design from different perspectives ranging from an electrical or energy point of view to the actual construction or architectural point of view.

The structural integration of BIWTs usually requires an additional support structure for the wind turbine. To reduce or eliminate challenges such as vibration and noise transmission, it is important to carry out proper test measurements and properly position the turbines. Usually, the small vertical-axis wind turbines produce lesser noise in such applications. The specific rated power curve of the wind turbine in combination with the turbine size is a significant factor in deciding the required structural support system for the wind turbine. Pole-mounted HAWTs are integrated into the building, facing the direction of wind, and are therefore able to fully maximize energy yield.

The HAWTs can maximize energy yield due to the possibility of installing large rotors, taking advantage of the large section undisturbed airflow. The integration of wind turbines in a building structure can be done by installing such wind turbines between two adjacent buildings, on the rooftop and inside a hole within the building. The distance of separation between the buildings is a key variable in the integration of the wind turbines between the buildings. Since BIWTs require structural strengthening, they are not directly applied to existing structures without modifying the structures of such buildings [23].

6.4.3 Building-Augmented Wind Turbines (BAWTs)

BAWTs are applicable to buildings that have been purposely designed to profile and strengthen the flow of wind through the installed wind turbine. This can be achieved by incorporating a special roof construction onto the building, which acts as a flow concentrator or by creating ailerons that are integrated into the building envelope. The building acts as a support structure for the wind turbine and is usually included as a part of the building design. There is usually a need to carry out a wind flow assessment using a wind tunnel test [24].

The building design is usually based on the principle of aerodynamic building form. These buildings are augmented to create a channeling effect that improves the velocity of wind around the building. Integrating BAWTs into a new building requires such a building to be specifically designed to augment wind flow through the turbines. The decision on the turbine location or turbine type is dependent on the designer. The application of BAWTs to building designs can either be in the vertical-axis rotor type or the horizontal-axis rotor type. As shown in [22], vertical-axis wind turbines are stacked in double helical columns where the wind speed is assumed to be highest.

6.5 The Economics of Integrating Small-Scale Wind Turbines in Sustainable Buildings

Integrating wind turbines into buildings to achieve more sustainable and energy-efficient buildings can involve a range of costs, both upfront and ongoing. This section explores the different costs associated with integrating wind turbines into buildings. However, these costs may be offset by the potential economic benefits, including cost savings on energy bills, increased property values, and government incentives and support programs. Building owners and operators should carefully evaluate the costs and benefits of integrating wind turbines into their buildings before taking a decision.

One of the primary costs associated with integrating wind turbines into buildings is the upfront cost of purchasing and installing the turbines. Wind turbines can be expensive, particularly if they are large and powerful enough to generate significant amounts of electricity. The cost of installation can also be significant, particularly if the building requires structural modifications to support the weight and vibrations of the turbines. The cost of integrating wind turbines into buildings can vary widely depending on the size and type of turbines, the complexity of the installation, and the availability of skilled labor in the area.

Another cost associated with integrating wind turbines into buildings is ongoing maintenance and repair costs. Wind turbines require regular maintenance and repairs to ensure they are functioning properly and efficiently. This can include tasks like cleaning the blades, lubricating the bearings, and inspecting the electrical components. In addition, if a turbine experiences a major failure, the cost of repairing or replacing it can be significant. The maintenance and repair costs associated with wind turbines can vary depending on the size and complexity of the turbines and the availability of skilled labor in the area.

The effectiveness of wind turbines is highly dependent on the wind resources available at the building site. Buildings located in areas with low wind resources may not be able to generate enough electricity to make the investment in wind turbines economically viable. Wind studies may be needed to determine the wind resources available at the site, and these studies can add to the overall cost of integrating wind turbines into buildings.

In addition, wind turbines can be noisy and can generate vibrations that may impact the comfort and safety of occupants. Additional costs may be incurred to mitigate these impacts, such as designing the building to accommodate the turbines or using specialized soundproofing materials. There are also costs associated with integrating wind turbines into the existing electrical infrastructure of the building. The turbines must be connected to the electrical grid, which can involve additional costs for electrical equipment and wiring. In addition, if the building is not designed to accommodate the extra electrical load generated by the turbines, upgrades may be needed to the building's electrical system to avoid overloading the system.

Despite these costs, integrating wind turbines into buildings can offer economic benefits, including the potential to generate renewable energy and reduce reliance on grid electricity. This can result in cost savings on energy bills over the long term. In addition, buildings that incorporate renewable energy technologies like wind turbines can increase in value, making them more attractive to investors, tenants, and homeowners.

Moreover, many governments around the world offer incentives and support programs for renewable energy projects, including wind turbines. These programs can provide financial assistance, tax credits, or other incentives that can help offset the cost of integrating wind turbines into buildings. In some cases, these incentives can make the cost of integrating wind turbines into buildings comparable or even lower than the cost of traditional energy sources.

6.6 Technical Considerations of Small-Scale Wind Turbines for Sustainable Buildings

The integration of wind turbines into buildings poses some technical challenges, but with the development of new technologies and techniques, it is becoming increasingly feasible. This section explores some technical aspects of integrating wind turbines into buildings, including the structural considerations, wind turbine design, and the electrical systems required.

The structural integration of small-scale wind turbines in a building is a major challenge. Local laws and regulations play a huge factor in the structural integration of such wind turbines in buildings. There is usually a need for a structural engineer to sign off or approve the tower and proposed integration design, which must fulfill all safety requirements and the appropriate building codes referenced. The possibility of turbulence is a critical factor that may limit the choice of turbine selected to operate in such a setting as well as cause unwanted noise or structural vibrations. An environmental impact assessment is therefore an important priority in the execution of such a project. Integrating wind turbines into buildings requires careful consideration of the building's structural integrity. The additional weight and vibrations generated by the wind turbine can have an impact on the building's stability and safety. The building must be able to support the weight of the wind turbine and its associated equipment, which can be significant. The location of the wind turbine on the building is also an important consideration. The wind turbine should be placed in a location where it can capture the maximum amount of wind, while also minimizing the impact on the building's aesthetics and functionality.

The design of wind turbines for integration into buildings is also critical to ensure that they can operate efficiently and effectively in their new environment. There are several factors that need to be considered when designing wind turbines for building integration, including rotor diameter, blade pitch, and the orientation of the turbine.

Rotor diameter is an important factor to consider when designing wind turbines for building integration. In general, smaller turbines are more suitable for rooftop applications. This is because smaller turbines can take advantage of the higher wind speeds available on rooftops, while larger turbines can capture more wind energy from the larger surface area available on the building facade. Blade pitch is another important factor to consider when designing wind turbines for building integration. The blade pitch refers to the angle of the blade relative to the plane of rotation, and it plays a crucial role in determining the efficiency of the turbine. Blades with a high pitch angle generate more torque and are more suitable for low wind speeds, while blades with a lower pitch angle are better suited for high wind speeds.

Integrating wind turbines into buildings requires a significant amount of electrical infrastructure to connect the wind turbine to the building's electrical grid. The electrical system must be designed to ensure that the wind turbine's output is properly integrated into the building's electrical system and that any excess electricity generated by the wind turbine is properly stored or exported. The electrical system must also be designed to ensure that the wind turbine operates safely and efficiently. This includes the installation of a control system that monitors the wind turbine's output and adjusts the rotor speed and blade pitch to optimize the wind turbine's performance. The control system must also ensure that the wind turbine operates within safe limits and that any faults are detected and addressed promptly. The electrical system must also be designed to ensure that the energy generated by the wind turbines is properly balanced with the energy consumption of the building. This requires careful monitoring and control of the power output of the turbines, as well as the energy consumption of the building. The electrical integration of wind turbines into buildings can also present challenges related to grid stability and power quality. For example, fluctuations in wind speed can cause fluctuations in the power output of the turbines, which can impact the stability of the grid. Additionally, the use of power electronics to convert the DC power generated by the turbines into AC power can introduce harmonic distortion into the grid, which can impact the quality of the power supplied to the building and other nearby consumers. To address these challenges, advanced control and monitoring systems can be used to regulate the power output of the turbines and maintain grid stability. Additionally, the use of advanced power electronics such as active filters can help mitigate harmonic distortion and maintain power quality.

Regular maintenance is required to ensure that the wind turbine operates safely and efficiently. This includes the inspection and maintenance of the wind turbine's structural components, such as the blades and rotor shaft, as well as the electrical components, such as the control system and the generator. Maintenance is particularly important for VAWTs, as they have more moving parts than HAWTs, and are therefore more prone to wear and tear. Regular maintenance can help extend the lifespan of the wind turbine and ensure that it operates at its maximum efficiency.

6.7 Current Status and Future of Small-Scale Wind Turbines for Sustainable Buildings

The technology of small-scale wind turbines has improved significantly in recent years, making them a more viable option for integration into buildings. Advances in materials, design, and manufacturing have led to smaller, lighter, and more efficient wind turbines that are better suited to urban and suburban environments. They are particularly attractive for their ability to generate electricity in urban and suburban areas, where solar panels may not be as effective due to shading or limited roof space. Small-scale wind turbines have been used for decades in remote locations, such as off-grid cabins and farms. However, they have only recently started to gain traction as a viable source of renewable energy for urban and suburban buildings. This is due in part to advancements in technology that have made small wind turbines more efficient and cost-effective.

Presently, the number of wind turbines integrated in either residential or commercial buildings globally is a small fraction compared to the potential this renewable energy sector has. However, in some places, such as the United Kingdom and some parts of Europe, there has been a rapid increase in the number of buildings being designed or retrofitted to be sustainable by integrating wind turbines. One area of innovation in small-scale wind turbine technology is vertical-axis wind turbines (VAWTs). Unlike traditional horizontal-axis wind turbines (HAWTs), VAWTs are designed to capture wind from any direction, making them better suited to urban and suburban environments where wind direction is variable. VAWTs are also typically quieter and less visually obtrusive than HAWTs, making them a more attractive option for integration into buildings.

In the short term, the integration of wind turbines in buildings faces uncertainty; however, in the long run, there are expectations that the push for reduction in carbon footprint and economic factors which have led to increased fuel cost will lead to a wider scale integration of wind turbines in both residential and commercial buildings in areas with suitable wind resources.

Building design is a factor that cannot be ignored in the integration of wind turbines into buildings. It can therefore be safely said that the future of wind turbines for sustainable buildings is tied to the future of architecture. Innovative architectural designs will play a key role in how wind turbines are integrated into buildings and the type of wind turbines that can be used in such projects. The green tower concept is an emerging concept conceptualized by William McDonough [25]. This concept is commonly referred to as the Tower of Tomorrow. The impact of wind is reduced because of the aerodynamic shape of the building. The curved form of the building reduces the need for a lot of materials for construction while structural stability is increased and maximizes enclosed space. Buildings based on this design take advantage of natural ventilation and daylight.

One area of development is in the design of smaller and more efficient turbines. Researchers are exploring new materials and designs for blades and rotors, as well as new control systems that can optimize the performance of small wind turbines in varying wind conditions. Another area of development is in the integration of small wind turbines with other renewable energy sources, such as solar panels and energy storage systems. By combining different sources of renewable energy, buildings can become more self-sufficient and less reliant on the grid.

For small wind turbines to become more widely adopted, there will need to be increased support from governments and regulatory bodies. This could include incentives for the installation of small wind turbines, streamlined permitting processes, and the development of standards and regulations to ensure the safe and effective operation of small wind turbines.

6.8 Issues Affecting the Integration of Small-Scale Wind Turbines in Sustainable Buildings

The integration of wind turbine technologies into an existing building or designing new buildings with the planned integration of these wind turbines comes with some challenges. This section examines some of these issues affecting the integration of small-scale wind turbines into sustainable buildings.

Regulatory challenges can also impact the integration of small-scale wind turbines in sustainable buildings. In many cases, there may be zoning restrictions or other regulations that limit the installation of wind turbines in certain areas. Additionally, building codes and regulations may not adequately address the installation of small-scale wind turbines, leading to confusion and uncertainty for homeowners and businesses. Regulatory changes can also facilitate the integration of small-scale wind turbines in sustainable buildings. For example, zoning regulations could be modified to allow for the installation of wind turbines in more areas and building codes could be updated to provide clearer guidance on the installation of this technology.

The building on which the wind turbine is to be integrated can itself be a challenge since there is a possibility that the building can be an obstruction in the direction of wind flow, thereby creating a totally different environment for harvesting the available wind energy. There is a general conception that the higher a turbine is on a building, the better it is because more wind energy would be captured. However, the building can cause a disruption in wind flow since the behavior of wind in the environment is not necessarily directly comparable to a wind field in a wide-open terrain. It is therefore important to have a proper assessment of wind speeds as well as the wind direction. While small-scale wind turbines can generate electricity from relatively low wind speeds, they still require consistent wind flow to be effective.

The financial component of integrating small-scale wind turbines in buildings cannot be overlooked. These costs cover both the investment and maintenance costs associated with such a project. The investment cost includes not only the cost of installing such wind turbines but also costs such as feasibility studies and activities related to system design. The feasibility study for such a project should cover analysis and prediction of wind conditions on and around a building for both existing and new buildings, respectively, to determine location and feasibility. While the cost of the turbines themselves has decreased in recent years, the cost of installation and maintenance can still be high.

Reliability and safety are a primary issue of concern to be addressed in integrating wind turbines into buildings. The means of suspending such wind turbines is a very important thing to consider. There might be a need for implementing more sophisticated means of suspending the wind turbines such as bridging or suspension roads. Bridging can be used as a form of protective screening. The turbine suspension must be able to support the turbine weight, and the building must be able to support both. It is important to design a “fail to safe” suspension wherever possible due to the proximity of people to these turbines [26].

Another challenge is the visual impact of small-scale wind turbines. While some people may see them as a positive addition to a building or neighborhood, others may view them as an eyesore. This can create conflict and opposition to the installation of small-scale wind turbines, particularly in residential areas.

In addition to these challenges, there are also technical issues that can affect the integration of small-scale wind turbines in sustainable buildings. For example, the turbines may generate noise and vibrations that can be disruptive to occupants of the building. Additionally, the turbines may not be compatible with existing electrical systems, requiring additional investments in infrastructure to ensure proper integration.

Despite these challenges, there are several strategies that can be employed to facilitate the integration of small-scale wind turbines in sustainable buildings. One approach is to increase public awareness and education about the benefits of this technology. This can help build support for the installation of small-scale wind turbines and encourage homeowners and businesses to invest in this technology. Another approach is to incentivize the installation of small-scale wind turbines through tax credits, rebates, and other financial incentives. This can help offset the upfront cost of installation and encourage more widespread adoption of this technology.

Finally, technical innovations can help address some of the challenges associated with small-scale wind turbines. For example, advancements in blade design and material science can improve efficiency and reduce the noise generated by these turbines. Additionally, new control systems and grid integration technologies can help ensure that small-scale wind turbines are compatible with existing electrical systems and can be effectively integrated into the grid.

6.9 Conclusions

This chapter has introduced the integration of small-scale wind turbines into sustainable buildings. There are different possibilities of integrating wind turbines into buildings to meet energy demands if such buildings are designed to be energy efficient and there are available good wind resources. The different ways of integrating wind turbines into buildings have been outlined. The possible challenges that may arise from this have also been discussed in detail. It is important to state that the development of this important renewable energy sector will be dependent on the contributions of several key actors such as developers and investors, architects and engineers, industry groups and manufacturers, and policymakers and planners. In conclusion, the integration of small-scale wind turbines in sustainable and energy-efficient buildings presents a promising solution for achieving a more sustainable future. This technology can help reduce reliance on nonrenewable sources of energy and decrease greenhouse gas emissions. However, the integration of small-scale wind turbines in buildings is not a one-size-fits-all solution and requires careful consideration of factors such as wind resources, building orientation, and local zoning regulations. The integration of small-scale wind turbines in sustainable and energy-efficient buildings can play a crucial role in achieving a more sustainable future. Although the technology is not yet widely adopted, its potential benefits make it a promising solution for reducing reliance on nonrenewable sources of energy and decreasing greenhouse gas emissions. Further research and development are required to overcome the challenges associated with small-scale wind turbines and promote their wider adoption.

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Chapter 7
Operation Optimization of Sustainable Buildings

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Abstract Following the restructuring of the electricity industry, various innovative concepts have emerged, such as intelligent parking lots, renewable energy sources, and sustainable buildings. This chapter presents a novel model that incorporates a thermal model, a fuel cell co-generation system, and a battery to minimize the operation costs of a sustainable building. The primary objective is to prioritize device performance and optimize other sustainable building equipment operations in order to minimize the day-ahead operation cost of sustainable building. The proposed model leverages a mixed-integer nonlinear programming (MINLP) approach, optimized using the General Algebraic Modeling System (GAMS) platform. Two various scenarios have been utilized to show the effectiveness of the proposed method. It's worth noting that the proposed sustainable building model is based in Australia, and all input data relates to the summer season.

7.1 Introduction

7.1.1 Problem Definition

During the last few years, the energy industry has experienced a significant change from conventional networks to smart and sustainable systems [1]. The most important reasons for this metamorphosis have been greenhouse gas emission and global

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warming [2]. During this movement, the presence of renewable sources, including wind [3], solar, and electric vehicles [4], has increased in the smart structure of energy networks. In addition, demand-side management programs have been occupied in providing the required energy of smart networks [5]. One of the most important elements in this sustainability revolution is the role of sustainable buildings [6]. The main idea of sustainable buildings is to minimize energy consumption [7] and maximize energy efficiency [8], which will help us reduce greenhouse gas emission and address the global warming problem. It is an important issue that buildings consume almost 40% of the world's energy and produce a huge amount of greenhouse gas emissions [9]. Therefore, it is essential to investigate more about energy optimization in building operations to ensure a sustainable energy future.

7.1.2 Literature Review

In a recent publication [10], a novel approach for managing energy in a sustainable building was presented, aiming to minimize operational costs and mitigate high peak demands. The system comprises a photovoltaic system, battery, robust controller, smart devices, and smart communication network. Another experimental design for home grid systems was presented in [11], utilizing the artificial bee colony algorithm to minimize operation costs and optimize sustainable building efficiency. Additionally, a stochastic energy management approach was introduced in [12], aiming to reduce sustainable building costs and incorporating plug-in electric vehicles, photovoltaic systems, and batteries. In [13], a new energy management system for sustainable buildings was proposed, utilizing a voltage control methodology to reduce power consumption, improve energy efficiency, and reduce peak demand. In [14], a day-ahead electrical load forecasting method for sustainable building management was presented that does not rely on historical or statistical databases. The proposed model aims to increase flexibility between power production and consumption. A tutorial on intelligent controller development was discussed in [15], utilizing Game Theory algorithms to move significant energy loads from high- to low-demand times and decrease electricity expenses. In [16], the operation of sustainable building devices was optimized using mixed integer programming techniques, and solar panels were used to balance power production and consumption.

A ZigBee networking-based sustainable building control system was introduced in [17], aiming to reduce energy consumption by controlling unnecessary demand and device operation times. Computer simulations were used to test the system's performance. In [18], a robust approach was developed to manage the output uncertainty of embedded photovoltaic systems within sustainable buildings. In [19], a wireless communication architecture to smooth power peak demands, decrease CO2 emissions, and optimize the performance of existing sustainable building devices was proposed. In a recent paper [20], a novel approach for optimizing the electricity costs of sustainable buildings by scheduling thermal and electrical devices is presented. The proposed method considers various factors such as social random factor, comfort level, resident's consumption behavior and seasonal probability. An overview of the modules of the energy management system is reviewed in [21], along with the operation of devices and utilization of renewable energy sources such as biomass, wind, and solar to reduce sustainable building bills and increase energy efficiency. In [22], a basic framework is proposed for a standalone intelligent home in Sydney that minimizes associated expenses by integrating a photovoltaic panel to fulfill electricity consumption during high-demand periods. The author minimizes sustainable building operation costs and increases occupants' comfort level with the use of MATLAB/Simulink in [23].

A system is proposed in [24] that produces real-time solutions to avoid high peak demand and reduce sustainable building operation costs, which is equipped with a battery, photovoltaic system, and smart devices. In [25], the consumption power of the demand side management is estimated, and the costs of the sustainable building are reduced using the Particle Swarm Optimization tool in MATLAB software. The proposed tool simulates the operation of devices within the sustainable building as a hybrid renewable energy system. In [26], the authors introduce the concept of a modern home and an internet infrastructure for smart living spaces using a Service Oriented Approach. A framework for scheduling residential energy consumption is proposed in [27], which aims to minimize the waiting time for device operation within the sustainable building and reduce costs by taking into account real-time pricing tariffs. A MINLP approach is introduced in [28] to optimize the operational expenses of a sustainable building, while simultaneously enhancing comfort and thermal comfort levels. The optimization is performed using GAMS software. A model for optimizing sustainable building management is introduced in [29], with the goal of minimizing expenses and decreasing peak energy demands to improve the performance of sustainable buildings.

In [30], the authors suggest that global optimization (multiple sustainable buildings) is superior to local optimization (single sustainable building) and propose a generic management approach that can be applied to most domestic technologies. An algorithm for scheduling thermostatically controlled devices within the sustainable building is introduced in [31] with the aim of reducing costs and improving comfort levels. In a recent investigation [32], a mathematical model utilizing MILP is employed to optimize the operation of a sustainable building, aiming to reduce costs while enhancing thermal comfort. The model considers dynamic electrical constraints and a thermal model that incorporates the utilization of heat-pump technology. In a study detailed in [33], an optimization approach is employed to optimize the operation of an embedded battery system in a sustainable building, with the objective of reducing operational costs and minimizing energy losses. The proposed method is found to outperform the particle swarm optimization method.

Two online stochastic combinatorial optimization algorithms are presented in [34] to schedule device consumption in response to uncertainty in electricity market prices, with the aim of reducing sustainable building costs and maintaining comfort levels. The proposed model is compared to reactive control strategies. An intelligent management system is presented in [35] to optimize the operation of high-power consumption devices within the sustainable building, using a demand response analysis tool. In reference [36], a novel approach is suggested for managing the sustainable building devices operation in the presence of demand response events and resource management time constraints. The performance of the in-home energy management application is evaluated and optimized to minimize sustainable building costs and carbon emissions. In reference [37], the results of this method are compared with those obtained from an optimization-based residential energy management application. In [38], a game theory model is proposed to optimize cost-effective strategies for sustainable building, where the users are considered as players and the efficient management of sustainable building operations devices and loads in the presence of different pricing tariffs are the strategies of the game.

7.1.3 Contributions

Each of the studies conducted on sustainable building planning has explored significant aspects of the field. However, there remains a pressing need for more comprehensive studies, particularly in the context of the energy optimization of sustainable buildings with the presence of diverse energy sources and equipment. This chapter presents a novel approach to sustainable building scheduling through mixed integer optimization. The model incorporates a thermal model, a fuel cell co-generation system, and a battery to minimize the cost of sustainable building operation. It correctly models the energy sources and accounts for functional limitations. The primary objective of the proposed model is to prioritize device performance and optimize other sustainable building equipment operations to minimize the day-ahead operation cost of the building. The effectiveness of the proposed method is demonstrated through two scenarios. It is noteworthy that the proposed model is based in Australia and uses input data related to the summer season. This chapter makes a valuable contribution to the field of sustainable building planning through the development of an innovative approach that effectively optimizes energy systems to minimize operation costs.

7.1.4 Arrangement of the Chapter

Section 7.2 provides an in-depth explanation of the mathematical model proposed, including thermal, fuel cell, and battery storage mathematical formulation. The third section provides the input data used in the chapter and simulation, and the results obtained are described in Sect. 7.4. The final section, Sect. 7.5, presents the overall conclusion of this study.

7.2 Problem Formulation

The operational expenses of the sustainable building may be stated as follows:

$$\min \text{Operation cost} = \sum_{t-1}^{T} \begin{pmatrix} \rho_{\text{grid},t} \times P_{\text{grid},t} \\ +\rho_{\text{gas},t} \times (u_{CHP,t} \times G_{FC,t} + u_{aux,t} \times G_{aux,t} \\ +S_{CHP} \left| u_{CHP,t} - u_{CHP,t-1} \right| \end{pmatrix} \tag{7.1}$$

The components of Eq. (7.1) can be described as follows: the first component represents the cost and quantity of power exchanged among the electricity market and the sustainable building; the next component represents the expense of the utilized gas and produced power by the co-generation fuel cell technology; and the third component is included to avoid unnecessary on–off switching of the fuel cell co-generation machine. In this expression, $\rho_{\text{grid},\,t}$ and $P_{\text{grid},\,t}$ represent the cost and quantity of power traded to the electricity market, while $\rho_{\text{gas},\,t}$ represents the cost of gas and the states of the fuel cell co-generation machine and auxiliary boiler are denoted by $u_{\text{CHP},\,t}$ and $u_{\text{aux},\,t}$, respectively. $G_{\text{FC},\,t}$ and $G_{\text{aux},\,t}$ represent the overall power utilized by the fuel cell co-generation technology and the auxiliary boiler, respectively, at the same time. Lastly, S_{CHP} is the cost incurred per operation cycle of the fuel cell co-generation machine.

7.2.1 Thermal Constraints of the Sustainable Building

The exchanged thermal power between the inside and outside environment, and between the floor and inside or outside environment, can be shown as follows simultaneously [39]:

$$\phi_{ao,t} = \left(T_{\text{indoor},t} - T_{\text{outdoor},t}\right) / R_{ao} \tag{7.2}$$

$$\phi_{fa,t} = \left(T_{\text{floor},t} - T_{\text{indoor},t}\right) / R_{fa} \tag{7.3}$$

$$\phi_{\text{fg},t} = \left(T_{\text{floor},t} - T_{\text{ground},t}\right) / R_{\text{fg}} \quad \left(T_{\text{floor},t} - T_{\text{outdoor},t}\right) / R_{\text{fg}} \tag{7.4}$$

$T_{\text{indoor},\,t}$and $T_{\text{outdoor},\,t}$ represent the temperature of the inside and outside, while $T_{\text{floor},\,t}$ and $T_{\text{ground},\,t}$ represent the temperature of the floor and the ground, respectively. R_{ao} denotes the resistance of the area between the inside and outside, while R_{fa} and R_{fg} represent the resistance of the area between the floor and inside and between the floor and outside, respectively. The thermal energy transfer between the inside and outside is denoted by ϕ_{ao}, while ϕ_{fa} represents the thermal energy transfer between the floor and inside. Additionally, ϕ_{fg} indicates the transferred thermal energy between the floor and the ground. The absorbed thermal power by the floor can be mathematically expressed as follows [40]:

$$\phi_{HCS,t} = ((u_{HCS,t} \times \eta_{\mathrm{H},t}) - (1 - u_{HCS,t} \times \eta_{c,t}) \times P_{HCS,t} \tag{7.5}$$

u_{HCS} denotes the mode of operation, which can be either heating or cooling and takes a value of 1 if the system is in heating mode and 0 otherwise. η_{H} and η_{c} are the coefficients of heating and cooling, respectively, while P_{HCS} represents the power consumed by the heat pumps. The power consumption of the heat pumps and the coefficients of the heating and cooling system are subject to certain limitations. These constraints are modeled as follows [41]:

$$0 \le P_{HCS,t} \le P_{HCS,\max} \tag{7.6}$$

$$\eta_{\mathrm{H,min}} \le \eta_{\mathrm{H}} \le \eta_{\mathrm{H,max}} \tag{7.7}$$

$$\eta_{C,\min} \le \eta_{C} \le \eta_{C,\max} \tag{7.8}$$

$\eta_{\mathrm{H,\ min}}$ and $\eta_{\mathrm{H,\ max}}$ represent the lower and upper limits of the heating coefficient, while $\eta_{\mathrm{C,\ min}}$ and $\eta_{\mathrm{C,\ max}}$ represent the lower and upper limits of the cooling coefficient. The highest permissible energy usage of the heat pumps is denoted by $P_{\mathrm{HCS,\ max}}$. The amount of solar thermal energy transferred from the outdoor surface to the indoor air is expressed mathematically as follows:

$$\begin{aligned} \phi_{\mathrm{surface},t} &= \phi_{\mathrm{conv},t} + \phi_{\mathrm{solar},t} + \phi_{\mathrm{radiation\,correction},t} \\ &= h_{\mathrm{o}} \times A_{\mathrm{s}} \times (T_{\mathrm{outdoor},t} - T_{\mathrm{surface},t}) + \alpha_{\mathrm{s}} \times A_{\mathrm{s}} \times \varphi_{\mathrm{solar},t} \\ &\quad - \varepsilon \times A_{\mathrm{s}} \times \sigma \times (T^4_{\mathrm{outdoor}} - T^4_{\mathrm{surr},t}) \\ &= h_{\mathrm{o}} \times A_{\mathrm{s}} \times (T_{\mathrm{eq\_out},t} - T_{\mathrm{surface},t}) \end{aligned} \tag{7.9}$$

h_{o} denotes the transmission coefficient of sun irradiation, while A_{s} represents the surface area. The solar absorption is denoted by α_{s}, and ε is the surface's emission. φ_{solar} is the sun's irradiation, and σ is the Stefan–Boltzmann constant with a value of 5.67×10^{-8} W/(m^2. K^4). It is important to highlight that the section on the right-hand side of the formula denotes the heat transferred by convection to the exterior surface in situations where the outside and surrounding surface degrees are the same. The final segment of the formula adjusts for any differences in irradiation that arise when the outside and the surrounding surface degrees are dissimilar. Consequently, Eq. (7.9) can be rewritten as (7.10):

$$T_{\mathrm{eq\_out},t} = T_{\mathrm{outdoor},t} + \frac{\alpha_{\mathrm{s}} \times \varphi_{\mathrm{solar},t}}{h_{\mathrm{o}}} - \frac{\varepsilon \times \sigma \times (T^4_{\mathrm{outdoor}} - T^4_{\mathrm{surr},t})}{h_{\mathrm{o}}} \tag{7.10}$$

Based on this equation, we can assume that $T_{eq\_out}(t)$ is proportional to the ambient temperature outdoors, taking into account the effects of irradiation. The transferred heat from the outside to the inside by the walls and roof is modeled as follows:

$$\phi_{sa,t} = U \times A_s \times \left(T_{eq\_out,t} - T_{indoor,t}\right) = \frac{T_{eq\_out} - T_{indoor,t}}{R_{sa}} \tag{7.11}$$

The coefficient for heat transfer is denoted as U, while A_s represents the surface area, and R_{sa} corresponds to the impedance of the walls and ceiling. Finally, all the thermal models discussed, we can express the temperature of the floor and inside air in the sustainable building using Eqs. (7.12) and (7.13).

$$T_{floor,t} = T_{floor,t-1} + \frac{\Delta h_{step}}{m_f \times c_{p,f}}\left(\phi_{HCS,t} + \phi_{sf,t} - \phi_{fg,t} - \phi_{fa,t}\right) \tag{7.12}$$

$$T_{indoor,t} = T_{indoor,t-1} + \frac{\Delta h_{step}}{m_a \times c_{p,a}}\left(\phi_{fa,t} + \phi_{sa,t} + \phi_{ihg,t} - \phi_{ao,t}\right) \tag{7.13}$$

Δh_{step} represents the time step used in the simulation, which is assumed to be 1 h in this chapter. m_f and m_a are the mass coefficients for the floor and air, respectively. $c_{p,f}$ and $c_{p,a}$ denote the heat capacity coefficients for the floor and air. ϕ_{HCS} represents the heat absorbed by the floor, while ϕ_{ihg} represents the thermal energy emitted by the metabolism of the occupants and operation of devices within the sustainable building, typically ranging between 1 and 3 °C. Lastly, ϕ_{sf} signifies the heat absorbed from sunlight that enters the sustainable building directly through the windows, as stated in Eq. (7.14).

$$\phi_{sf} = \alpha_f \times \varphi_{solar,t} \times A_f \tag{7.14}$$

$\alpha_f$represents the sunlight absorption, while A_f denotes the sunlight absorbed by the floor area. Lastly, φ_{solar} represents the sun's irradiation.

7.2.2 The Fuel Cell Mathematical Model

The model being presented is comprised of three distinct parts. The initial part encompasses the fuel cell unit, while the auxiliary boiler constitutes another segment of the model [42]. The third part entails the backup boiler storage, all of which are elaborated upon in further detail below:

The description of the thermal power and electrical generated by the fuel cell unit is provided as follows:

$$P^{e}_{CHP,t} = P^{th}_{CHP,t} \times \frac{\eta_e}{\eta_{th}} = \frac{G_{FC,t}}{G_{ref}} \times \eta_e \tag{7.15}$$

$\eta_{\rm th}$ and $\eta_{\rm e}$ denote the thermal and electrical efficiency of the fuel cell unit, respectively. $G_{\rm FC}(t)$ represents the overall gas consumption by the fuel cell unit, while $G_{\rm ref}$ represents the gas consumption necessary to generate 1 kWh of power. It should be noted that the electricity and thermal energy generated are subject to minimum and maximum limits, which are expressed in Eqs. (7.16), (7.17), and (7.18).

$$u_{CHP,t} \times P^{\rm e}_{CHP,\min} \le P^{\rm e}_{CHP,t} \le u_{CHP,t} \times P^{\rm e}_{CHP,\max} \tag{7.16}$$

$$u_{CHP,t} \times P^{\rm e}_{CHP,\min} \le P^{\rm e}_{CHP,t} \le u_{CHP,t} \times P^{\rm e}_{CHP,\max} \tag{7.17}$$

$$\left| P^{\rm e}_{CHP,t} - P^{\rm e}_{CHP,t-1} \right| \le P^{\rm e}_{CHP,\rm ramp} \tag{7.18}$$

$u_{\rm CHP}$ denotes the on–off situation of the fuel cell unit. $P^{\rm e}_{CHP,\min}$ and $P^{\rm e}_{CHP,\max}$ represent the minimum and maximum limits of the electric power produced, respectively, while $P^{th}_{CHP,\min}$ and $P^{th}_{CHP,\max}$ denote the higher and lower amount limits of the thermal energy produced. As previously mentioned, another component is the auxiliary boiler, with the power produced by it formulated as Eq. (7.20), and its minimum and maximum limits mentioned as Eq. (7.19).

$$u_{aux,t} \times P^{th}_{aux,\min} \le P^{th}_{aux,t} \le u_{aux,t} \times P^{th}_{aux,\max} \tag{7.19}$$

$$P^{th}_{aux,t} = \frac{G_{aux,t}}{G_{ref}} \times \eta_{aux} \tag{7.20}$$

$\eta_{\rm aux}$ represents the efficiency of the auxiliary boiler, while $G_{\rm aux}$ denotes the total amount of gas consumed by the auxiliary boiler. P^{th}_{aux}, on the other hand, signifies the overall thermal energy produced by the auxiliary boiler.

The third component is water storage, which undergoes updates in its content and temperature at each time interval in accordance with Eqs. (7.21) and (7.22).

$$Q_{st,t+1} = Q_{st,t} + \left(P^{th}_{CHP,t} + P^{th}_{aux,t} - P^{th}_{{\rm demand},t} - P^{th}_{{\rm loss},t} \right) \times \Delta h_{\rm step} \tag{7.21}$$

$$T_{st,t+1} = \frac{V^{th}_{{\rm demand},t} \times \left(T_{cw} - T_{st,t} \right) + V_{\rm tot} \times T_{st,t}}{V_{\rm tot}} + \frac{P^{th}_{CHP,t} + P^{th}_{aux,t}}{V_{\rm tot} \times C_{\rm W}} - \frac{A_{st}}{R_{st}} \times \left(T_{st,t} - T_{{\rm b},t} \right) \tag{7.22}$$

$\Delta h_{\rm step}$ represents the time step used in the simulation, which is set at 1 h. P^{th}_{CHP} and P^{th}_{aux} denote the thermal energy produced by the fuel cell unit and the auxiliary boiler, respectively. $P^{th}_{\rm demand}$ represents the demand of thermal power from the storage, while $P^{th}_{\rm loss}$ accounts for the negligible losses of thermal power from the storage, considering the size of the storage.

$V^{th}_{\rm demand}$ denotes the demand for hot water, while $T_{\rm cw}$ represents the temperature of the water that entered the storage. $V_{\rm tot}$ represents the overall storage's volume, and

A_{st} accounts for the storage's surface area. R_{st} denotes the resistance of the anti-heat and temperature transfer materials, and T_b represents the basement temperature. The minimum and maximum temperature limits of the storage can be formulated using Eq. (7.23).

$$T_{st,\min} \le T_{st,t} \le T_{st,\max} \tag{7.23}$$

7.2.3 The Battery Model

There are various kinds of energy storage that are utilized by sustainable buildings and other city structures, including battery, pumped hydro storage, and electric vehicles [43]. Energy storage systems are an essential component that enhances the flexibility of a sustainable building, allowing for convenient management of household devices [44]. The mathematical representation for the battery can be stated as [45]:

$$P_{\mathrm{Batt},ch,t} \le P_{ch,\max} \times \eta_{ch} \times u_{\mathrm{Batt},t} \tag{7.24}$$

$$P_{\mathrm{Batt},dch,t} \le \left(\frac{P_{dch,\max}}{\eta_{dch}}\right) \times \left(1 - u_{\mathrm{Batt},t}\right) \tag{7.25}$$

η_{ch} and η_{dch} represent the charging and discharging coefficients of the battery, while u_{Batt} denotes the situation of the battery. The current situation of the battery in every moment and the corresponding constraints are presented in Eqs. (7.26) and (7.27), respectively.

E_{Batt} is the battery capacity, measured in kilowatt-hours (kWh).

$$SOC_{\min} \le SOC_t \le SOC_{\max} \tag{7.26}$$

$$SOC_{t+1} = SOC_t + \frac{\left(P_{\mathrm{Batt},ch,t} - P_{\mathrm{Batt},dch,t}\right) \times \Delta h_{\mathrm{step}}}{E_{\mathrm{Batt}}} \tag{7.27}$$

7.2.4 The Fix and Programmable Appliances

Appliances within the sustainable building are in two categories:

1. Fixed loads, such as refrigerators, which operate continuously for 24 h.
2. Shiftable loads, which operate for only 1 h within a 24-h period.

The overall energy consumed by the shiftable loads over 24 hours can be calculated as follows:

$$P_{\mathrm{Dschd},i,t} = \frac{EEC_i}{\mathrm{LOT}_i} \times s_{i,t} \tag{7.28}$$

EEC represents the estimated energy consumption of each device, and LOT represents the duration of time that the devices operate. It is important to note that the operation of each device should be completed within the optimization time. For this reason, Eq. (7.29) is presented as follows:

$$\sum_{h=h_{s,i}}^{h_{f,i}} s_{i,t} = \mathrm{LOT}_i \tag{7.29}$$

s represents the state of the element, in which 1 shows an active element and 0 shows an inactive element. Some appliances are designed to be active after another appliance has been inactive, such as a clothes dryer that must start after the washing machine has finished. In this chapter, a maximum allowable gap of 2 h for operating the second device after the first one is considered, as presented in Eq. (7.31). This constraint is incorporated in the optimization model to ensure efficient scheduling of devices, as shown in Eq. (7.30).

$$\sum_{h=h_{s,i}}^{h_{f,i}} s_{j,t} \times H\left(\lambda - \mathrm{LOT}_i + \sum_{h=h_s}^{h} s_{i,t}\right) = \mathrm{LOT}_i \tag{7.30}$$

$$\mathrm{Ord}_t \times H\left(s_{j,t} - s_{j,t-1} - \lambda\right) \le \left(\mathrm{Ord}_{t-1}\right) \times H\left(s_{i,t-1} - s_{i,t} - \lambda\right) + \Lambda_{i,j} \tag{7.31}$$

$H(.)$ represents step function introduced by Oliver Heaviside, while Ord(.) is a function used to locate the relative position of a given array member. λ is a bounded value among [0,1], and $\Lambda(i, j)$ represents the largest acceptable interval between the conclusion of the initial device and the beginning of the subsequent device. In this chapter, a gap of 2 h is considered. The limitation on the power consumption of sustainable building devices at each time period is incorporated as follows:

$$P_{\mathrm{D},t} = P_{\mathrm{Dfix},t} + \sum_{i=1}^{N} P_{\mathrm{Dschd},i,t} \le P_{\mathrm{House}}^{\max} \tag{7.32}$$

Another constraint that is taken into account in this study is the limitation on the power exchange between the sustainable building and the electricity market at each time period. This is formulated as Eq. (7.33) to ensure compliance.

$$P_{\mathrm{grid}}^{\min} \le P_{\mathrm{grid},t} \le P_{\mathrm{grid}}^{\max} \tag{7.33}$$

And finally, to maintain a balance between the power consumption and production at each time period, a mathematical formulation is presented as Eq. (7.34) to ensure equilibrium.

$$P_{\mathrm{grid},t} + P^{\mathrm{e}}_{CHP,t} + \left(P_{\mathrm{Batt},dch} - P_{\mathrm{Batt},ch}\right) = P_{\mathrm{D},t} \tag{7.34}$$

7.3 Numerical Situation

This write-up analyzes a residential property in a region of Australia situated at 33.86°S and 151.21°E, serving as a case study [46]. The dwelling features several elements, such as:

- Heating and cooling technology
- Battery and smart appliances
- Fuel cell and auxiliary boiler
- Storage of hot water

The proposed model is capable of interacting with the electricity market by exchanging power.

The proposed model is developed as a mixed-integer nonlinear program (MINLP) and implemented using GAMS [47, 48].

7.3.1 Input Data

The information required for each of the discussed topics in this chapter is listed in Tables 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, and 7.8:

7.4 Simulation Results

To assess the effectiveness of the sustainable building management system, the objective function was analyzed under two distinct scenarios.

The first scenario, dubbed the "normal scenario," entails the sustainable building management system receiving actual rate signals and optimizing the operation in response to variations in electricity market prices, while also striving to maintain the temperature within the desired range. Notably, the preferences and priorities of the residents are not taken into account.

The second scenario, referred to as the "smart scenario," involves the full activation of the sustainable building management system to ensure the optimal functioning of devices and other equipment within the home, taking into account the

Table 7.1 The grid and the sustainable building's input data

Constant	Amount	Constant	Amount
$P_{\text{grid}}^{\text{min}}$	−5.5 kW	$P_{\text{House}}^{\text{max}}$	5.5 kW
$P_{\text{grid}}^{\text{max}}$	5.5 kW	R_{ao}	6.2
h_{o}	17 W/m²•°C	R_{fa}	6.2
m_{f}	2300 kg/m³	R_{fg}	7.5
m_{a}	1.2 kg/m³	R_{sa}	6.2
ε	27%	α_{f}	53.7%
α_{s}	27%	A_{f}	1.2 m²
$c_{\text{p, f}}$	0.85 kJ/kg•°C		
$c_{\text{p, a}}$	1 kJ/kg•°C		

Table 7.2 The co-generation technology model input data

Constant	Amount	Constant	Amount
$P_{CHP,\text{min}}^{\text{e}}$	0.3 kW	η_{e}	30%
$P_{CHP,\text{max}}^{\text{e}}$	1.5 kW	η_{th}	70%
$P_{CHP,ramp}^{\text{e}}$	0.9 kW/h	η_{aux}	86%
S_{CHP}	8 ¢/start	$P_{aux,\text{min}}^{th}$	4 kW
G_{ref}	$92.3*10^{-3}$ m³/h	$P_{aux,\text{max}}^{th}$	19 kW

Table 7.3 The storage input data

Constant	Amount	Constant	Amount
A_{st}	1.99 m² m^2	V_{tot}	200 L
R_{st}	2.8 m²•°C/W	T_{cw}	10 °C
C_{w}	0.00117 kWh/L•C	$T_{\text{st, min}}$	60 °C
		$T_{\text{st, max}}$	80 °C

Table 7.4 The battery input data

Constant	Amount	Constant	Amount
E_{Batt}	24 kWh	SOC	20–80%
P_{ch}^{max}	3.3 kWh	η_{ch}	87%
P_{dch}^{max}	3.3 kWh	η_{dch}	90%

preferences and priorities of the residents. In this scenario, similar to the previous one, efforts are made to maintain the temperature into a suitable range.

As shown in Table 7.9, the cost incurred in the normal scenario amounted to 645 cents, while in the smart scenario it was 640 cents. The 0.8% disparity between the two scenarios highlights the advantage of the smart scenario over the other one.

Table 7.5 The cooling and heating system input data

Constant	Amount	Constant	Amount
$P_{HCS, max}$	2 kW	$\eta_{H, min}$	100%
t_C	10 °C	$\eta_{H, max}$	400%
t_H	40 °C	$\eta_{C, min}$	100%
Δt_{CO}	40 °C	$\eta_{C, max}$	300%
Δt_{HO}	−10 °C	T_{set}	25 °C
ΔT_{ther}	3 °C		

Table 7.6 The functioning of the device's scenario details

Devices	Normal	Smart	LOT	EEC
Refrigerator [35]	All day	All day	24	0.15
Washing machine	8 AM–2 PM	7 AM–9 PM	1	1
Dishwasher	2 PM–6 PM	6 AM–6 PM	1	1.4
Clothes dryer	11 AM–5 PM	9 AM–9 PM	1	1.8
Iron	5 AM–7 AM	1 AM–1 PM	1	1.1
Vacuum cleaner	9 AM–12 AM	8 AM–20 PM	1	0.65
Microwave	11 AM–2 PM	8 AM–7 PM	1	0.9
Rice cooker	2 PM–5 PM	10 AM–6 PM	1	0.6
Electric kettle	6 AM–7 AM	4 AM–12 PM	1	1
Toaster	6 AM–8 AM	1 AM–10 AM	1	0.8

The configuration of the devices, encompassing both fixed and shiftable loads, is depicted in Fig. 7.1. To facilitate analysis, the arrangement of shiftable loads in both scenarios has been organized chronologically and is displayed in Table 7.10.

The information depicted in Fig. 7.1 reveals that there are variances in the count of operational devices between the normal and smart scenarios. The smart scenario witnesses a greater number of active devices during non-peak hours, whereas the normal scenario has a higher count during peak hours. For instance, at hour five, three types of devices are active in the smart scenario, whereas only one is active in the normal scenario. The smart scenario is susceptible to high electricity market rates and therefore restricts the use of devices between 11 and 14 h, while in the normal scenario, four types of devices are active during this period. Consequently, the operational expenses of the sustainable building are lower than those of the normal scenario due to its sensitivity to price changes. The traded power of the sustainable building is depicted in Fig. 7.2.

It is apparent from this diagram that the smart scenario tends to purchase more power during off-peak hours compared to the normal scenario. On the other hand, the smart scenario purchases less power during peak demands than the normal scenario. In other words, the smart scenario is more inclined to sell power during peak periods, indicating the advantage of buying more power during off-peak hours and selling more power during peak periods. This advantage results in a 0.8% difference between the two scenarios. The battery's charging and discharging power and the condition of the battery are shown in Figs. 7.3 and 7.4, respectively.

Table 7.7 The 24-h temperatures and hot water demand amount

	Outside °C	Basement °C	Demand of hot water (L)
Hour	Amount		
1 AM	19.35	24.37	0
2 AM	19.34	24.37	0
3 AM	20.5	24.37	0
4 AM	19.3	24.38	1
5 AM	18.75	24.38	0
6 AM	19	23.75	7
7 AM	19.5	23.45	15
8 AM	19.4	24.37	20
9 AM	20.6	24.37	14
10 AM	23.2	28.1	10
11 AM	25.6	28.7	0
12 AM	28.7	33.1	0
1 PM	31.9	36.2	1
2 PM	34.4	37.5	3
3 PM	34.8	38.7	0
4 PM	36.2	39.3	0
5 PM	36.2	41.2	8
6 PM	35.2	38.7	10
7 PM	33.1	36.9	13
8 PM	30.6	34.4	21
9 PM	28.4	30.6	18
10 PM	25.9	28.1	15
11 PM	23.4	25.6	11
12 PM	21.2	23.7	0

Based on the results obtained, the efficiency of the battery remains unaffected by the sustainable building management system's operation. The system focuses on charging the battery during peak hours and discharging it during off-peak periods to minimize operating costs. The consumption of power by the auxiliary boiler and the heat produced by it are illustrated in Figs. 7.5 and 7.6, respectively.

In this particular device, the produced heat has a direct relationship to the amount of consumed gas due to the similarity between Figs. 7.5 and 7.6. The sustainable building management system in the smart scenario attempted to fulfill the heat demand during off-peak hours using this equipment and minimize its reliance on it during peak hours, which in general resulted in a decrease in operation costs. The water storage is another piece of equipment integrated into the sustainable building, and its contents and temperature are displayed in Figs. 7.7 and 7.8.

From the analysis of the figures, it can be deduced that during off-peak periods in the smart scenario, the water storage content is higher than in the normal scenario, while the temperature of the water storage remains constant. During peak periods, the energy management of the sustainable building relies on this equipment, leading to higher water content than in the normal scenario. The main

Table 7.8 Characteristics of the radiation and the market rates for electricity

	Radiation from the sun (w/m^2)	Prices in the electricity market ₡
Hour	Amount	
1 AM	0	6.05
2 AM	0	5.75
3 AM	0	5.71
4 AM	0	5.71
5 AM	0	5.64
6 AM	62.8	5.72
7 AM	100.5	5.93
8 AM	274.5	6.24
9 AM	424.5	6.5
10 AM	488	6.92
11 AM	744	7.1
12 AM	962	7.27
1 PM	1100.5	7.27
2 PM	1262	7.33
3 PM	712	7.78
4 PM	637	7.78
5 PM	600.5	7.78
6 PM	225.75	8.14
7 PM	137.5	8.14
8 PM	74.5	7.68
9 PM	0	7.45
10 PM	0	7.05
11 PM	0	6.94
12 PM	0	6.53

Table 7.9 The operational costs of the model under case studies

	Operation cost under scenarios $
Case one (normal)	645
Case two (smart)	640

Table 7.10 The organization of the operational schedule for shiftable loads in scenarios

Hour	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	2 PM
Normal	Iron	Electric pot Toaster			Washing machine Vacuum cleaner		Clothes dryer Microwave	Dishwasher Rice cooker
Smart	Iron Electric pot Toaster	Dishwasher	Washing machine	Vacuum cleaner Microwave	Clothes dryer	Rice cooker		

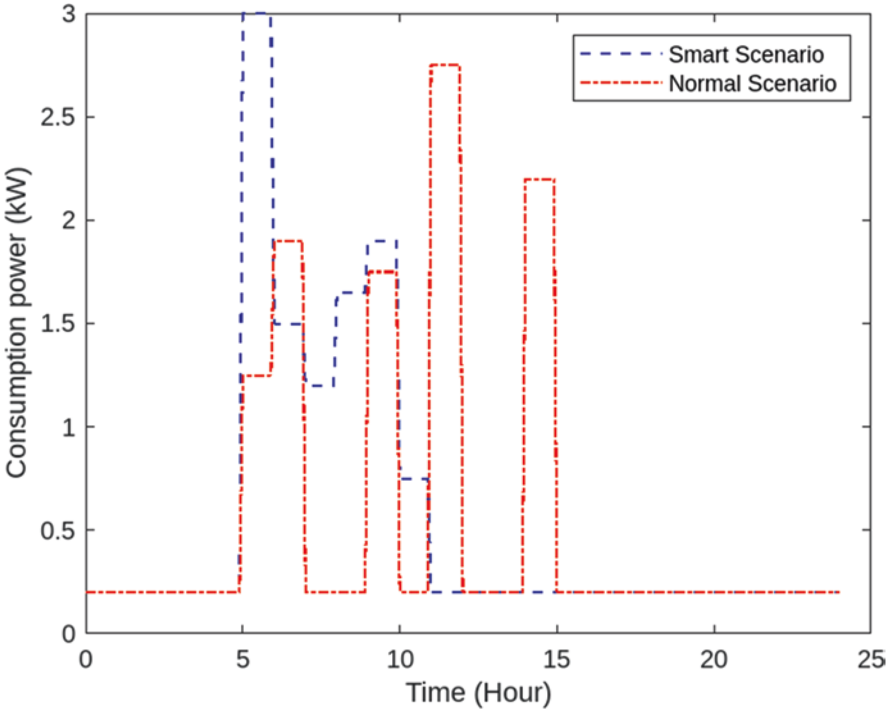

Fig. 7.1 Consumed power by the total load (kW)

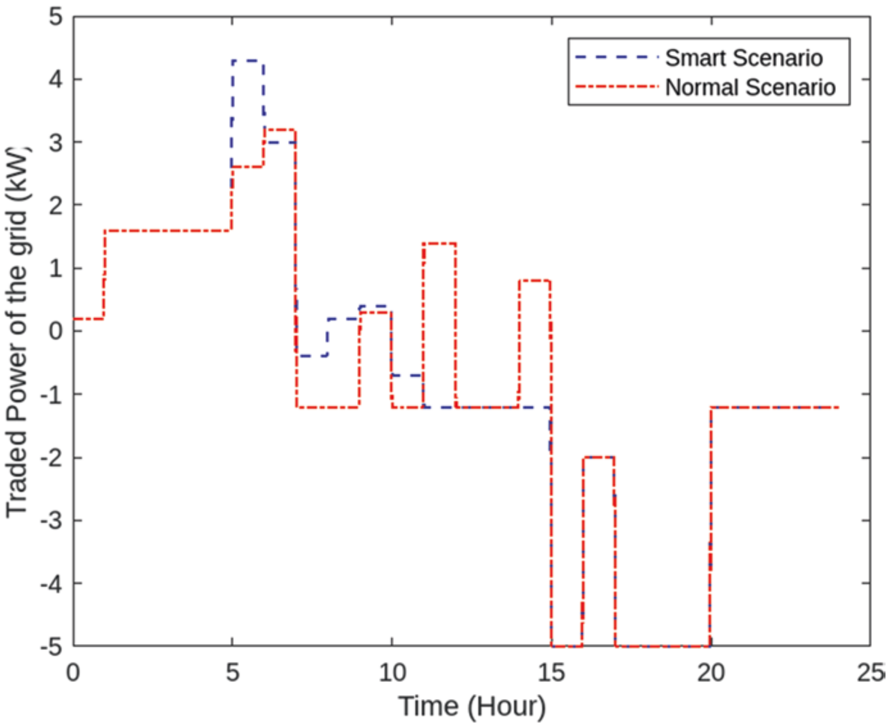

Fig. 7.2 Traded power of the grid (kW)

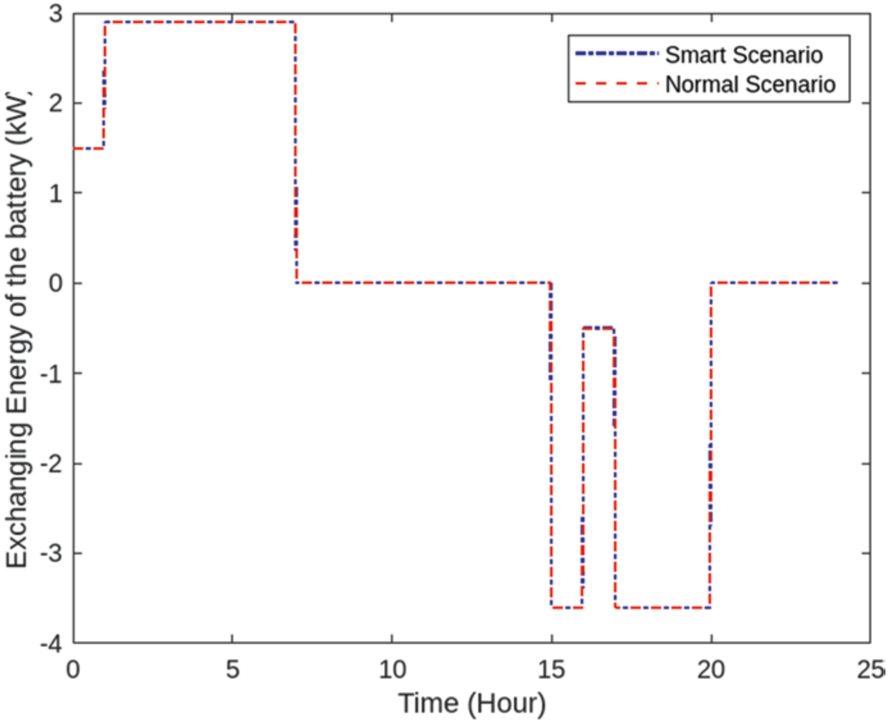

Fig. 7.3 Exchanging energy of the battery (kW)

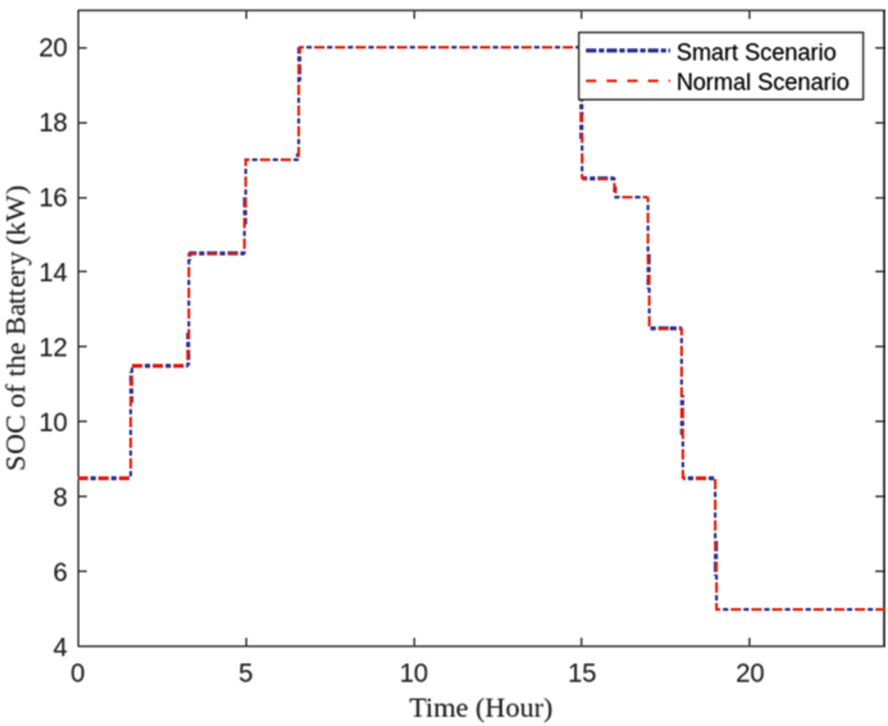

Fig. 7.4 SOC of the battery (kW)

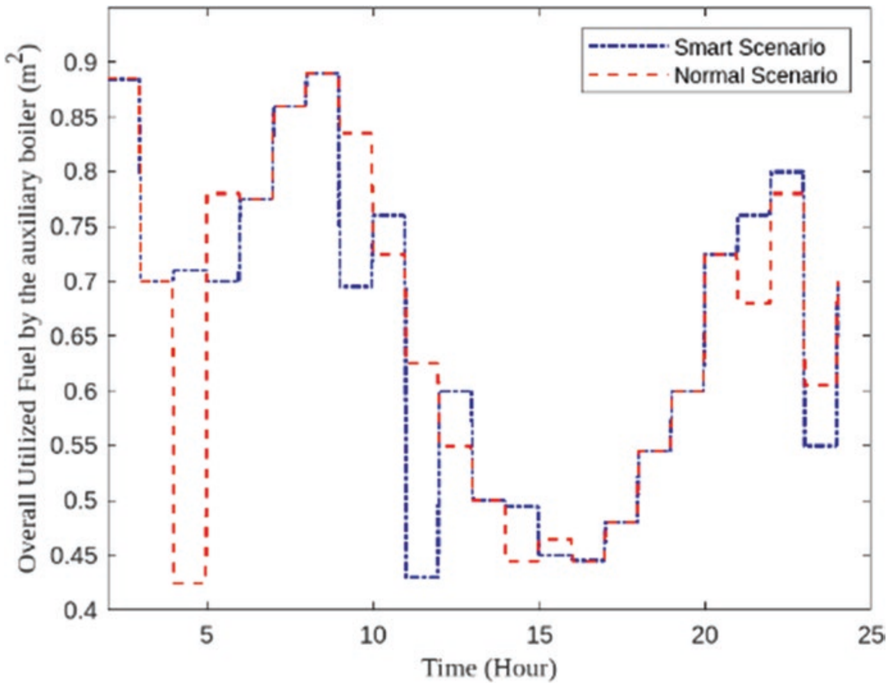

Fig. 7.5 Consumed power by the auxiliary boiler (m^2)

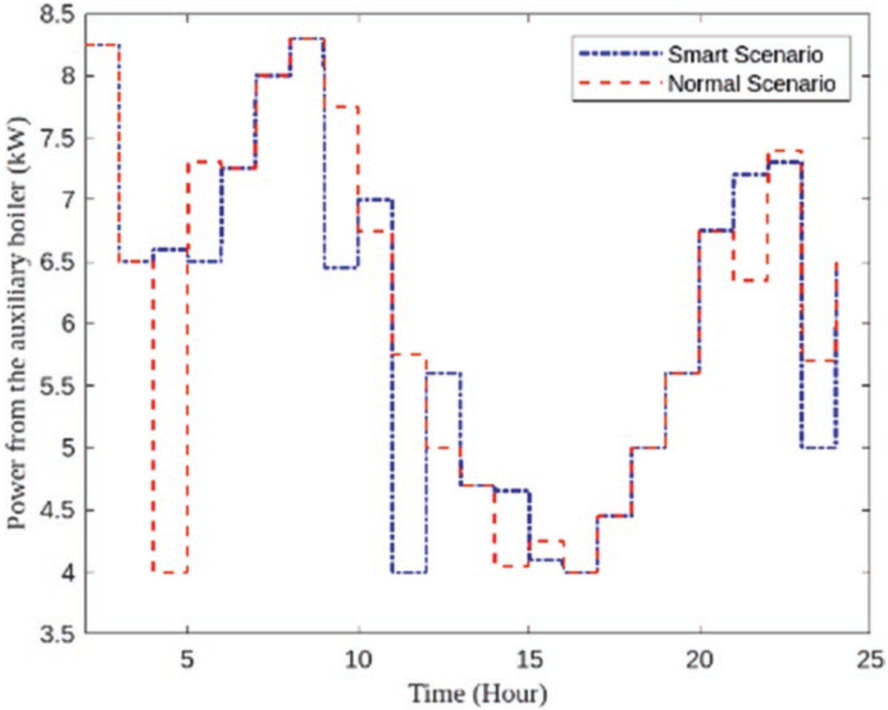

Fig. 7.6 Output heat from the auxiliary boiler (kW)

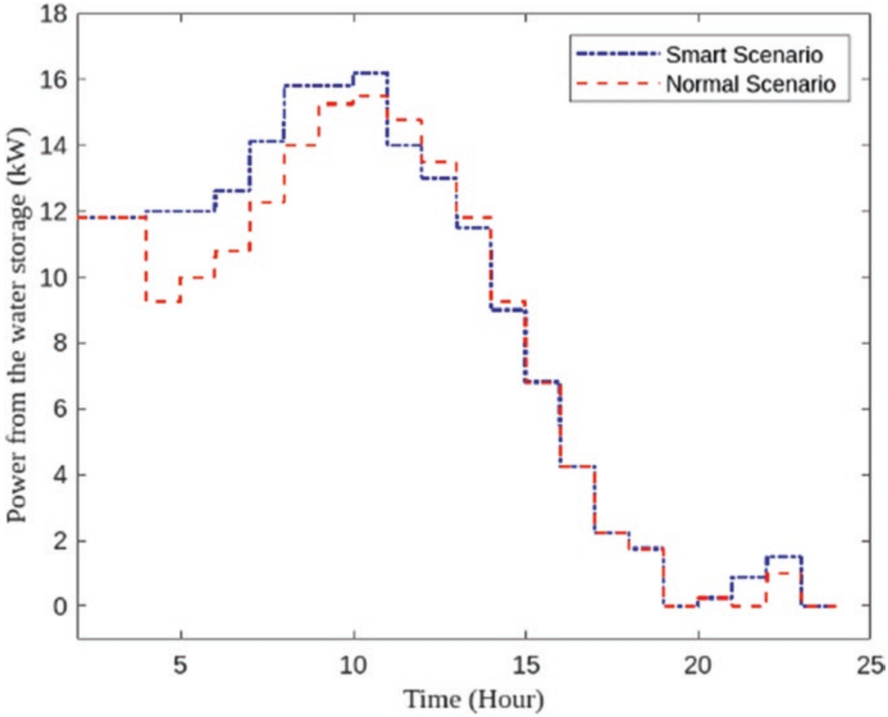

Fig. 7.7 The material inside the water container (kW)

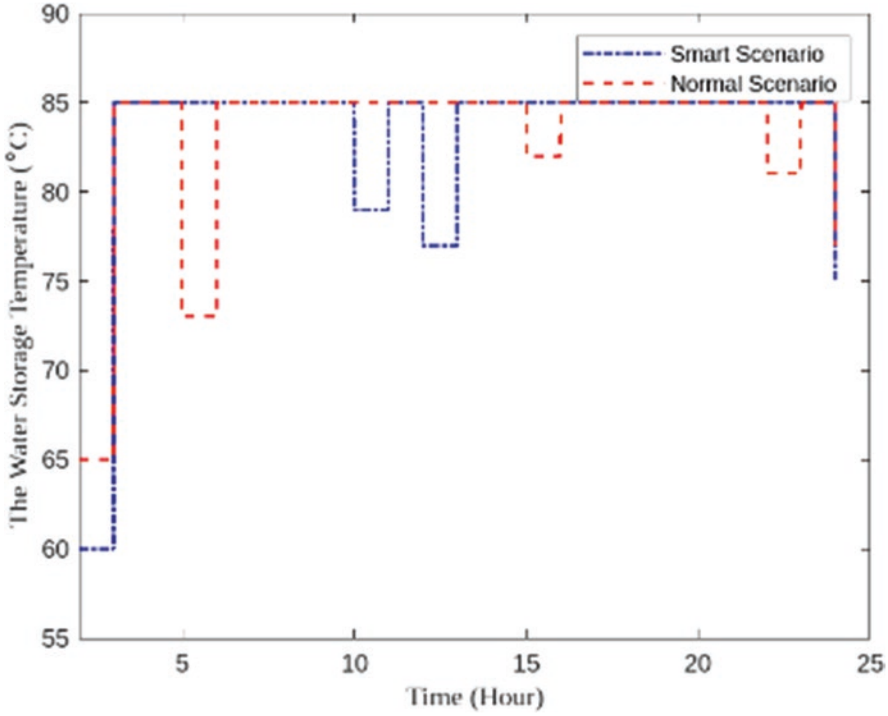

Fig. 7.8 The heat level of the water reservoir (°C)

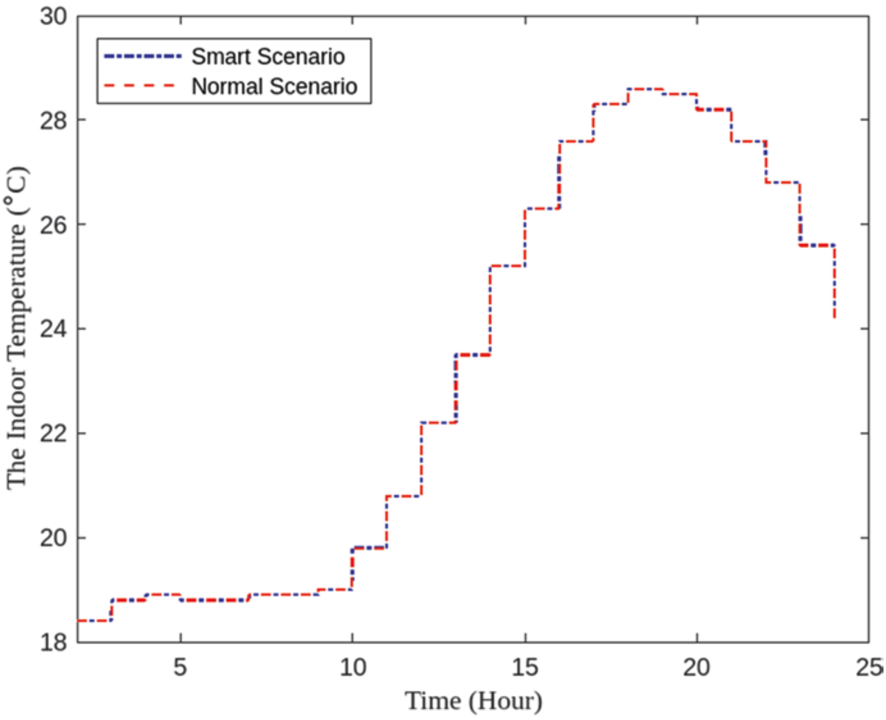

Fig. 7.9 Temperature of the indoor (°C)

objective of the heating/cooling equipment in the sustainable building is to maintain the indoor temperature within the allowable range. The indoor temperature of the sustainable building is shown in Fig. 7.9.

It is evident from this diagram that the efficiency of the heating and cooling system appears to operate autonomously of the sustainable building management system. Irrespective of this, the indoor temperature is consistently maintained within an acceptable range by the management system.

7.5 Conclusions

In this chapter, we examine sustainable buildings that include heating/cooling systems, fuel cell co-generation systems, and batteries. We have prioritized and optimized the operation of shiftable loads and devices during the summer season to reduce operational costs. We should note that the objective function we proposed is formulated as a mixed integer nonlinear programming (MINLP) optimization problem and is solved using a standard optimization software called generalized algebraic modeling system (GAMS). The results show that the proposed model has the ability to optimize sustainable building.

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Chapter 8
Design of Sustainable Buildings with Renewables

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Abstract Sustainable buildings, also known as green buildings, have received significant attention globally in recent decades. This is the key solution to tackle the energy crisis caused by conventional buildings, which currently consume 30–40% of the world's annual energy. The usage of such a higher energy further causes an increase in the prices of fossil fuel oils and, consequently, conventional buildings contribute a high amount of CO_2 emission to greenhouses. The purpose of this chapter is to create a model of a conceptual sustainable building simulation that reduces the impact of CO_2 emission, consumes less fossil fuel oil, and is materially sustainable under natural conditions. The design uses the maximum efficiency of renewable energy of wind turbines and solar panel cells, where the basic solar panel cell efficiencies are 5–20% and optimized for higher performance using intelligent mechatronic system methods. In addition, this chapter develops a method that eases the process of increasing solar panel cell efficiency. To obtain optimized designed solar panel cell generation, solar panel cells are modeled using simulation software applications, "Autodesk Revit and Dynamo (script programing language)", which enable solar panel cells to trace the maximum sunlight intensity. Furthermore, the achievement of optimized energy usage and the integration of renewable energy with smart grids and the Internet of Things (IoT) can provide smart control applications and wise operational systems.

8.1 Introduction

Earlier sustainability definition was briefly explained as a building that "meets present needs without compromising future generation" [1]. The latest definition is significantly different from the earlier one, as it focuses on practical aspects related to

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environmental pollution and energy-saving actions. The definition states that a sustainable building design is ecofriendly with the natural environment, considering the social environmental and economic aspects of decisions, minimizing CO_2 emissions by consuming less energy, and restoring natural resources [1, 2]. In the latest definition, social sustainability is significant, assuring practical action toward a healthy and the connected safer community approach with economic and environmental endeavors. Sustainable building design is necessary because buildings are among the highest energy consumers. For example, US buildings consume 40% of the USA's overall annual energy and 75% of the electricity demand [3] and contribute 30% to the total CO_2. This is because the majority of the current energy used in buildings is still from nonrenewable resources, even though the building sector has the highest potential for energy utilization with renewable energy resources [4], which could be implemented using a comprehensively integrated approach to reduce heating, cooling, and lighting demands using passive strategies of a dynamic climate [5] responsive design. Climate responsive design currently attracts many architectures and builders due to less impact on the natural environment [6]. Hence, in this chapter, the concept of design of sustainable building with renewables refers directly to building design that has been energy sustainable throughout lifecycle time. This requires the implementation of considerable renewable energies. Hence, to meet the sustainable building definition/objectives, the energy produced from the renewables and the energy reduction obtained from simulation results have to approach equilibrium. The building design needs to consider the amount of energy consumed by the building in relation to the amount of energy generated from the renewables. Prior-construction energy simulation is required to achieve the same.

8.2 Literature Review of Sustainable Building Design

Sustainable buildings are also known as green and environmentally eco-friendly high-efficiency buildings [7]. Furthermore, the concept of green building is defined as proportionally implemented with sustainable technological resources while preserving most of the natural environmental substances around the building [8] throughout its lifetime [9]. Historically, the name of green building started, since the oil crisis began in 1973/74 [10, 11], when governmental institutions and private companies started searching for alternative methods on how to use their existing energy wisely in order to minimize unnecessary usage. This opportunity opened the research area to a number of energy researchers to reduce energy consumption in buildings. As a consequence, the sustainable building design research literature review shows that traditional buildings waste significant amounts of energy and produce considerable CO_2 [12], which has a significant negative impact on building performance. The negative impact encouraged stakeholders to implement sustainable building globally and to define its objectives [13–15]. Furthermore, this opportunity invited designers, architecture, owners, contractors, and builders to play a significant role in creating sustainable buildings by planning, designing, and selecting sustainable energy-efficient building materials, e.g., itemization of the materials such as insulation levels, shading details, window performance, wall performance, appliance performance, and durability of materials. Implementation of these led to a reduction in the environmental impact and improved the social cohesion that ensured the continuation of economic development without severe harm to the surrounding environment [16]. Moreover, the early stage designs and architecture orientations played a role in implementing sustainable reforms that bear responsibility for the sustainable performance of the building. This is because of the most important decisions affecting the lifetime performance of buildings are made during these early design stages [16]. A clear understanding of a building's design and lifetime operating methods reduces the operational and maintenance impacts of the building [17] while improving comfort, health, and economic aspects. Furthermore, occupants and owners play a major role in the building to be effectively sustainable, in addition to creating an awareness of sustainable design objectives [18], by expressing the preferences of sustainable buildings to manufacturers, marketers, and communities and making significant changes toward sustainable building design. Manufacturers provide products that meet regulatory standards and customer demand-driven preferences to the market. Currently, many manufacturers are discovering and claiming to gain a distinct market advantage owing to the effective marketing performance of sustainable products. This is also true for designers, builders, and developers because the demand for sustainable building design has influenced the market, which satisfies manufacturers', developers', and builders' expectations to respond more to market needs [19]. However, sustainable building design suffers from several unsustainability, but the focus of this chapter is to design with renewable energies as follows:

- Difficult to meet its objectives [20] and goals in terms of clean energy adequate and continuous uninterrupted supply.
- Unsustainable practice and lacks clear general governing mathematical model.
- Rooftop space is limited for an adequate number of renewable energy installation.
- Renewable energy market is inconsistent with continuous customer demand.

Success depends on consumers' ability to meet their needs through cost-competitive products. To meet the demands, governments and building regulatory bodies' involvements are necessary. Thus, government-responsible authorities and government agents are encouraged to contribute significant efforts by implementing sustainable building objectives and strengthening its reforms. There is a need to obtain effective support from the community to approach sustainable building reforms, which could be conducted by raising awareness among the communities and also providing solutions to the questions raised by community members to exercise community support reforms [21].

In recent decades, sustainable building design has attracted rapid growth, and there are a few challenges in sustainable building designs:

1. Resistance to change from conventional/traditional buildings.
2. Recently designed smart sustainable buildings still suffer from sensor network diversity [22].

3. Lack of clear guides/regulations from the government defining the classification of smart sustainable building levels.
4. Being continuously technological sustainable, it loses its partial sustainability and smartness during full or partial internal electrical fault occurrences.

8.2.1 Renewable Energy

Integrating sustainable building designs with renewable energy covers several new modern energy sources [23]. However, the current most efficient devices, especially in smart sustainable buildings, are solar panel cells and wind turbines. Hence, these two renewable energies (which are economically beneficial) and their integration with smart grid and IoT to obtain the optimized output of them are briefly discussed in this chapter.

1. *Wind energy:* It significantly contributes to the economy. There are over 120,000 people working in wind energy industries in the USA alone. According to the US Bureau of Labor Statistics, wind turbine service technicians are the second fastest-growing US job of the decade, offering career opportunities ranging from blade fabricators to asset managers. The wind industry has the potential to support hundreds of thousands of jobs by 2050. Wind energy is a domestic resource that enables economic growth in the United States. In 2021, wind turbines operating in all 50 states will generate more than 9% of the total net energy of the country. In addition to investments, in new wind energy projects, there is a contribution of additional $20 billion to the US economy. Manufacturing of renewable energy is from natural sources, which constantly replenishes at a high rate.
2. *Solar energy:* Sun provides solar energy to the earth for 1 h to meet the global energy needs for 1 year [24]. Sun is a powerful energy source, although the world has not yet been able to collect a fraction of this energy. Building design with optimized solar panels can make a significant difference to the sustainable building sector.
3. *Renewable energy integration:* A smart grid is an electricity network that uses advanced digital, analog, and other advanced technologies in an integrated system, intelligently control, and securely manage electricity transport. Smart grid infrastructure includes associated technologies, such as smart metering, smart energy storages, smart human machine interface (HMI), and dynamic response demand-management-system of technologies. Renewable energy sources generated from a building are interfacing with a smart grid using smart HMI and advanced PC-controlled software.
4. *Connected device/IoT:* Conventional building owners and operators raise certain concerns that, nowadays, their buildings face hardship in maintaining the proper functionality of the building due to decreasing energy consumption with rising operational and maintenance costs while shrinking budgets. To address these concerns, building owners and operators can challenge their concerns by consid-

ering (IoT) [25] to innovate their buildings into smart and sustainable buildings. IoT, sensors, and the cloud-based building automation show the capability of minimizing energy usage and reducing operational and maintenance cost.

8.2.2 Building's Energy-Efficient Rating Schemes

Sustainable building design is a clean building because it has designed energy-efficient materials, which preserves natural resources and minimize the contribution of CO_2. Thus, the modern building has to be sustainable in terms of clean energy, efficient with proven practical work and assessed by certified accredited authorities. Therefore, to identify the building's energy-efficient level, energy rating scheme is used. The accredited authorities assess the environmental impact from the building side, using specific measurements, quantify the building's performance, explore, and compare if different alternative resources are used. Once the accreditation authorities endorse the building that the building complies with the energy-efficient objectives, then it becomes "sustainable" or "green." Globally, there is a wide range of rating schemes (Fig. 8.1), in which the classification of rating schemes is according to the building energy rating values, where the sustainable design is tested to

Fig. 8.1 Sustainable building design rating scheme of different countries and organizations

comply with the energy rating credit system designed by the responsible country's accreditation authorities. Consequently, credit rating system codes differ for each country's credential-authority codes. For instance, Australian Green Building Council (AGBC) uses a design-as-built, star rating system, and Leadership in Energy and Environmental (LEED) uses a LEED Accredited Professionals (AP) [26]. The sustainable building design rating-scheme bodies, as shown in Fig. 8.1, are a few of the well-known nonprofit organizations in the world.

8.2.3 Conceptual Building Simulation and Case Studies

The aim of this chapter is to design sustainable buildings using renewable energy. Practically, this refers to designing an advanced building in terms of clean energy while complying with the current objectives of sustainable building design objectives. Thus, a conceptual building design case study is used to estimate the average annual solar radiation energy absorbed by the building. The design uses an "Autodesk Revit architectural drawing template" student version. Autodesk Revit is computer-aided architectural design and simulation software developed by Autodesk Company. Furthermore, Autodesk Revit is an excellent architectural design software application, and its usage worldwide allows architects to create detailed building designs and solar energy analysis and visualize the architecture in 3D. In this chapter, adoption is due to its capability in analyzing building radiation solar energy absorption. Hence, in this chapter, first, a case study building model is utilized, which uses a virtual design of the building using randomly selected construction materials. Then, the base-energy primary simulation conducted is the base-energy simulation run to estimate the building's solar radiation energy simulation initial analysis. For further analysis and multiple alternative design runs, BIM engineering data (gbXML) files are exported automatically to Green Buildings Studio (GBS) and cloud insight energy-optimizing cloud sites.

8.3 Design of Sustainable Building with Renewables

The conceptual meaning of "design of sustainable building with renewables" refers to the design of building, which is sustainable in terms of energy. On the other hand, "renewable energy" is an energy source that is able to supply continuously clean energy [27]. Hence, the building has to be sustainable in terms of clean energy supply. This will help the building to minimize the ecological footprint emission and to satisfy the "environment-friendly building" definition, which is one of the objectives of sustainability. Thus, implementation of sustainable building design requires an adequate number of renewable energy devices or has enough number of renewables to produce equivalent to the building's annual energy consumption. To obtain the annual estimated consumed energy, the energy reduction from the building solar radiation energy simulation and the energy reduction from the smart building automation control system are necessary. To put this into practice, first the following steps are required:

(1) Run building's solar radiation absorption and obtain base/primary-run simulation results.
(2) Run alternative design using energy package provided by the simulation software application.
(3) Estimate the annual energy reduction obtained from smart building automation control system.
(4) Estimate the number of maximum available spaces for renewable energy installation for both rooftop and side mounting spaces, as shown in Fig. 8.4 and formulate the conceptual equation, which lets the building be sustainable in terms of energy supply. However, in practice, the equation might not be helpful or difficult to achieve the desired outcome because the number of renewable sources will not match with the available building rooftop space.

Consequently, the formulation of sustainable building design mathematical model expression for consumed energy is shown in Eqs. (8.1) and (8.2), where Eq. (8.1) is for single- and Eq. (8.2) is for multiple-renewable devices. In Eq. (8.1), A_c and E_g are fixed values but A_{run} values range from 1 to 254 simulation energy results; here, there is an opportunity to select the best energy reduction among the 254 alternative lists. In Eq. (8.2), A_{run} and E_g are not fixed values. Hence, there are opportunities to choose the best energy reduction from the 254 lists and to add the number of renewable energy to satisfy Eq. (8.2).

$$E_c = B_{run} - \left(\sum_{N=1}^{N_m=254} A_{run} + A_c + E_g \right) \tag{8.1}$$

$$E_c = B_{run} - \left[A_c + \left(\sum_{N=1}^{N_m=254} A_{run} + \sum_{S=1}^{S_m} E_g \right) \right] \tag{8.2}$$

where

E_c is the annual estimated energy consumed by the building.
B_{run} is the primary-run annual energy potential obtained from the first simulation result.
A_{run} is the annual alternative design energy reduction selected from the alternative design results.
A_c is estimated energy reduction obtained from control systems, IoT, and daylight savings.
E_g is the calculated or simulated annual energy generated from renewables.
N_m is the maximum number of alternative design-energy package lists.
N is the selected number of energy packages.
S_m is the maximum number of available spaces for renewable energy installation.

S is the number of installed renewable energy.

Solar panel and wind turbine, rooftop space limitation, and the wall-mounted solar and wind turbine energies have significant advantages over the rooftop, especially for future designs as building lands are getting smaller. High-rise premises are becoming preferable for residential living and business hubs. However, solar panels and wind turbines mounted on the side of the wall require more mounting materials than the rooftop. This adds additional cost, which will reduce the overall efficiency. The conceptual and practical performance of wall/façade mounted PV cells [28] is lower than the rooftop mounted. This is due to the building shape, where most of the buildings are rectangular, circular, or L-shaped. For instance, on mounting the PV cell on each side of the walls, the following occurs:

- During the morning, only the PV cells facing east will have access to the sun, and other PV cells facing north, south, and west will produce almost zero energy.
- Similarly, during the afternoon, only PV cells facing west will have access to the sun.

It is a known fact that PV cells produce the highest output during noon. Hence, PV cells mounted on the wall are unlikely to obtain optimum sun intensity even during noon. Vertical/horizontal axel wind turbines [29] mounted on the side of the building wall are also similar to PV cell phenomena. A wind turbine mounted on the side of a building wall will experience wind speed (wind drag and lift forces), only when the wind direction is in favor of its side, and it is also unlikely to change the blades toward the wind direction while the rooftop wind turbine blades can be changed according to the wind direction. PV cells and wind turbines mounted on the side of the building wall will experience limited hours of sun intensity and wind direction. Increasing the number of PV cells and wind turbine devices, as shown in Fig. 8.4, will compensate for this but will reduce the overall efficiency.

In addition, well-planned and designed sustainable buildings have the advantage of minimizing energy use and pollution contributions. Hence, this creates a resilient impact on environmental stability, which leads to long-term environmentally friendly benefits within the building. To implement this, there is a need to consider a number of sustainably designed solution packages:

A. Methods to save money, energy, and time.
B. Consider the major designs of buildings to construct buildings with future lifetimes.
C. Use cooperative work methods that all responsibility bodies incorporate into the design to make it truly sustainable, which will contribute to energy efficiency and reduce CO_2 emissions.
D. Model environmentally capable buildings that are resilient to resist the natural disasters of the region and fulfill the sustainable building design objectives, as shown in Fig. 8.2.

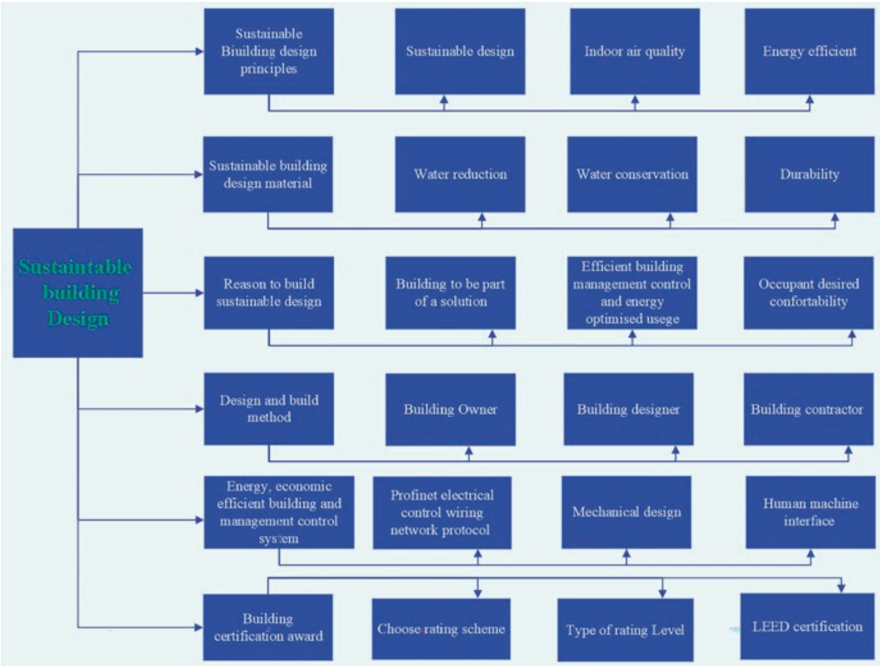

Fig. 8.2 Sustainable building design objectives and its elements

8.3.1 Sustainable Building Design Case Study

For the purpose of the conceptual case study, the location of the sustainable building design [30] chosen was in Port Melbourne, Melbourne, Victoria, Australia. Port Melbourne weather file was loaded into the conceptual building design to process the correct simulation results. The actual design, construction modeling of sustainable buildings, and documentation are through the collaboration of teams. Teams are responsible for creating models and documentation and leveraged across planning, designing, construction, remediation, visualization, and asset management using software architectural application assistance. Some of the Autodesk Revit's architectures are commercial building design, modeling, architecture, engineering, and construction modeling. Consequently, the design procedure flowchart (as shown in Fig. 8.3) modeling is for a conceptual building solar radiation energy simulation, as shown in Fig. 8.4. By selecting the location of the conceptual building, particular weather files were loaded from the nearest weather file station. For the purpose of energy reduction, the design and modeling of the sustainable building chosen are semi-square shaped, five-story commercial office buildings. Selection of this shape was to obtain the optimum daylight during the morning and afternoon periods. The design focused on energy reduction simulations related to solar radiation from the sun to the building. The sun's solar radiation energy simulation concentrates on the

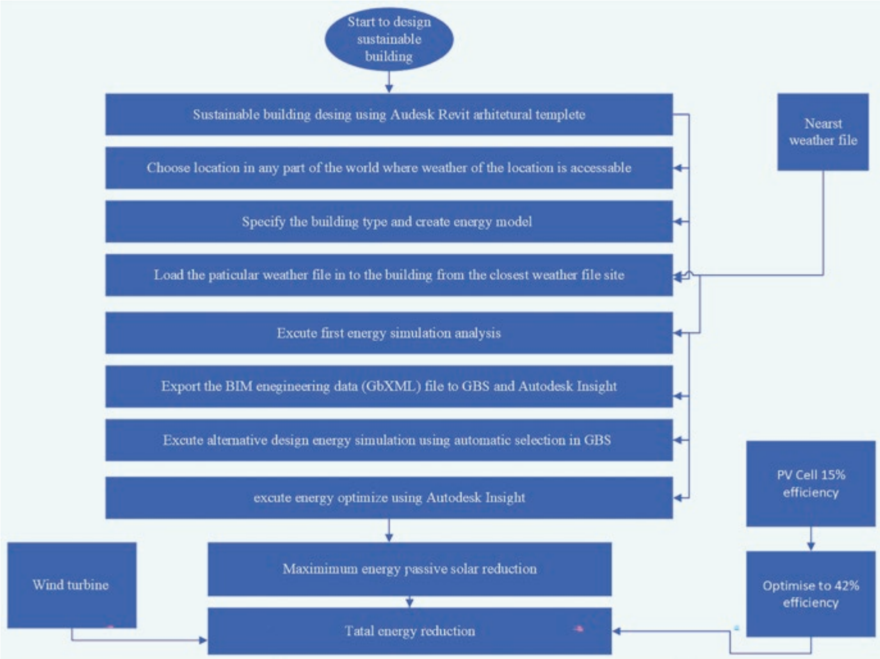

Fig. 8.3 Sustainable building design procedure flowchart

amount of solar radiation energy absorbed by the building elements during a non-cloudy day.

Simulation methods conducted use different techniques; in fact, it depends on the designer's skills to select the appropriate energy-efficient elements and tools as follows:

(i) *Building-orientation techniques:* Building orientation is classified as how the positioning of a building aligns with the sun's path because the solar radiation intensity varies according to the path over a period of different seasons. Hence, optimized building orientation increases the energy efficiency of the building, making the building more comfortable for occupants and making building operations less expensive.

(ii) *Building energy-simulation techniques and the integration of renewable energy sources:* The renewables are clean and inexhaustible. Furthermore, renewable energy is abundant and has the potential to be used anywhere in the world. In addition, the price of renewable energy is currently decreasing, whereas the general price trend for fossil oils is going in the opposite direction despite their present volatility. "Growth in renewable energies is currently unstoppable, as reflected in the 2015 statistics of the International Energy Agency (IEA). Renewable energy represented almost half of all new electricity-generated

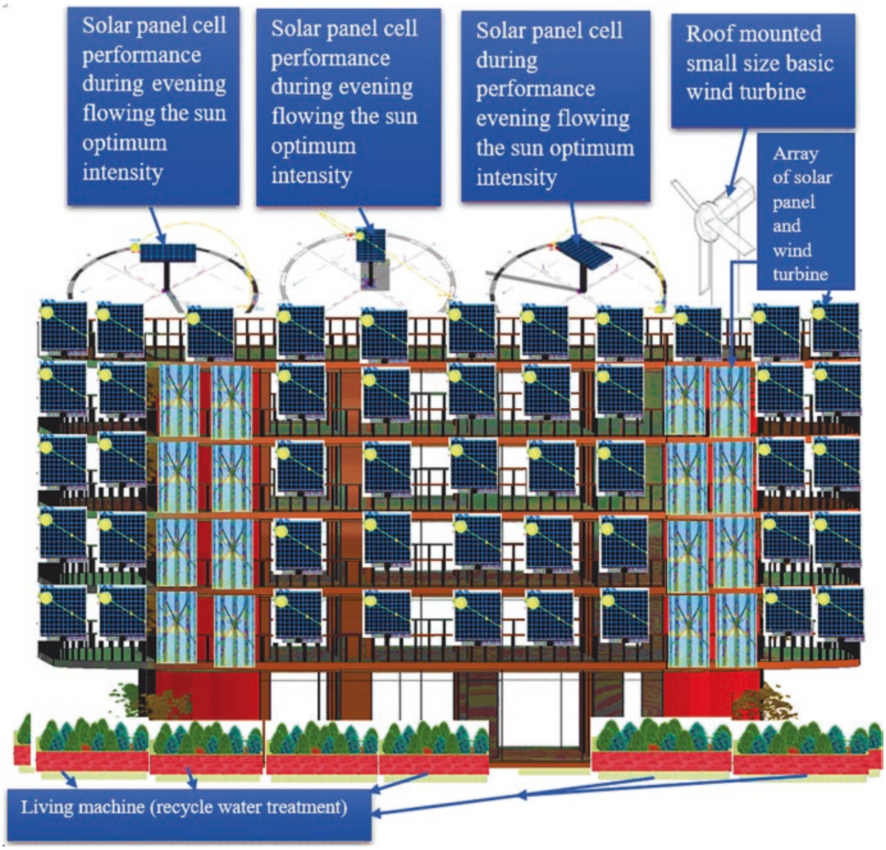

Fig. 8.4 Conceptual sustainable building design for energy simulation and recycled water treatment living machines planted on the base area of the building

capacities installed in 2014. According to the study, world electricity demand will increase by 70% by 2040" [31]. Thus, renewable energy development is crucial for combating climate change and limiting its most devastating effects. Sustainable building design with renewables is of key significance and important to sustain natural resources for the present lives and for the future generation.

8.3.1.1 Building Solar Radiation Energy Simulation Initial Analysis

The winter cooling and summer heating simulation input parameters values are in Tables 8.1 and 8.2. Table 8.1, column 1 data show the threshold of annual design data of weather conditions in terms of percentage at the time of simulation. Columns 2 and 4 data show the average annual cooling and heating of dry-bulb temperature, respectively. Dry-bulb temperature refers to ambient air temperature, at which there

Table 8.1 Primary-run annual design data weather conditions

Annual design conditions				
	Cooling		Heating	
Threshold	Dry bulb (°F)	MCWB (°F)	Dry bulb (°F)	MCWB (°F)
0.1%	105.5	70.5	36.0	36.5
0.2%	99.1	70.4	70.0	36.6
0.4%	97.9	69.9	38.1	37.3
0.5%	96.6	67.1	38.3	37.3
1%	92.1	68.4	39.6	38.6
2%	86.4	66.7	41.2	39.7
2.5%	84.7	66.3	41.7	40.2
5%	79.2	64.9	43.5	41.7

Table 8.2 Basic annual cooling and heating temperature degree-day

Cooling degree-day		Heating degree-day	
Threshold	Value	Threshold	Value
65 °F	542	65 °F	2697
70 °F	240	60 °F	1483
75 °F	95	55 °F	592
80 °F	28	50 °F	86

is no effect on the measurement of the temperature by the moisture of the air. Columns 3 and 5 data show the cooling and heating of Mean Coincident Wet-Bulb (MCWB) temperature, respectively. Wet-bulb temperature refers to the temperature of adiabatic saturation when the flow of wet air is moist or effected.

Similarly, Table 8.2, columns 1 and 3 data show the threshold of the cooling and heating degree-day at the time of simulation. Columns 2 and 4 data show the values of cooling and heating degree-day, respectively. The cooling/heating degree-days are the difference between the day mean/average temperature and the threshold temperature. Hence, if the difference is above the threshold temperature, it is a cooling degree-day, and on the other hand, if the difference is less than the threshold temperature, it is a heating degree-day. The two table's simulation inputs demonstrate significant contribution effects on the building solar radiation-energy simulation process to produce significant energy reduction results. Consequently, the output results produced from the solar building radiation simulation come up with significant cost-effective economic values, which leads to sustainable building and approaches sustainability objectives. Additionally, the primary-run building solar energy simulation initially analyzed acts as a reference point to compare the results of the alternative design simulations. The results are as follows:

- Building performance.
- Annual estimated energy usage.
- Lifecycle energy use.
- Renewable basic roof-mounted solar panel cell potential energies.

- CO_2 emissions.
- Annual total energy cost.
- Annual fuel energy use.
- Annual electric energy use.
- Annual heating/cooling end-use loads.
- Annual fuel/electricity consumption.
- Annual peak demand.

Furthermore, in this section, weather file parameters, such as annual wind speed frequency distribution, monthly weather file design data, annual average diurnal temperature, and average annual humidity, are major contributors to building solar energy simulation [32]. The weather files influence the building's size and area to produce the corresponding output results. In addition, the weather file helps alternative design energy simulations to produce output in detail with significantly reduced results. Specific annual regional weather files and annual wind speed frequency distribution characteristics in general are used to determine the process for building's energy usage estimations. Hence, the specific region weather station used in this chapter uses the Melbourne weather station, as specified in the Location Weather and Site dialog of Melbourne. Accurate and updated forecasted weather files for this region accessed are from this station.

During the simulation, the maximum and minimum temperatures at the building location are used, and the gross floor area of the analyzing building model space is determined by subtracting the net wall area. The building's space heating and cooling loads were driven by internal gains, such as the heat emitted by occupants, lighting, equipment, and building envelopes. This indicates that the HVAC loads directly depend on the weather files, and the light loads depend on the building-conditioned indoor space. The primary-run building's solar radiation energy simulation is part of the building heating/cooling requirements, but it is more in-depth and covers all parts of the buildings.

A building solar radiation energy simulation performed uses two methods:

(a) Conceptual mass.
(b) Whole-building elements.

The "conceptual mass" simulates the building as a block of mass, and conversely, the "whole-building element" simulates every part of the building's element presence inside the building; for example, roofs, floors, windows, and room/space elements are among the few elements. Export of the building's energy analytical model can be to different third-party applications for further performance analysis. For example, gbXML can be exported to the "US Department of Energy (DOE-2) and Energy Plus" [33] building energy simulations.

For the purpose of this chapter, building solar radiation simulation, the case studies considered included a single day for a period of 8 h from 10 am to 6 pm during summer to optimize sunlight intensity duration period. During these 8 h, the building's solar radiation simulation sunlight intensity continued to increase until it approached the maximum intensity at 2:00 pm. During this period, the building absorbed the optimum solar radiation energy. During the evening, the sunlight intensity steadily decreased, and its optimum intensity reduced to zero after 6 pm. Hence, this eight-hour simulation period is an adequate length of time to calculate the building's average annual energy consumption, particularly the HVAC load consumption. The solar energy simulation process of the building tested included every building element to determine its solar radiation intensity absorption. This ensured the nonexclusion of any part of the building from testing for solar energy absorption.

8.3.1.2 Sustainable Building Solar Radiation Simulation on Energy-Efficient Materials

The use of durable, attractive, and environmentally friendly building materials results in higher building performance. In addition, the use of naturally healthier materials contributes to the well-being of building occupants. Consequently, environmentally attractive building materials with minimal environmental impacts can be through resource conservation and the selection of nontoxic building materials. Traditionally, the resources used to manufacture construction-building materials have affected the environment by depleting natural resources and releasing pollutants into indoor building areas. Consequently, a minimized environmental impact, known as environmentally preferable (EP) materials, is necessary to use or needed to be selected by applying the selection criteria. The selection criteria for EP construction materials depend on the overall functional building performance, such as the economic, annual, and lifecycle costs of the sustainable building materials that take into consideration in order to ensure a balanced performance. Figure 8.5 shows the basic possible minimized annual cost USD/m^2/year using "Autodesk Insight cloud-based energy optimization simulation software." The semi-green part of the rectangle to the left end shows that the building is approaching sustainability objectives/goals by 2030. Similarly, Fig. 8.6 shows the individual building elements' annual maximum and minimum energy cost savings per USD/m^2/year, which can help the building owner/operator identify the maximum energy reduction.

Energy-Efficient Wall's Role Usage of massive concrete walls is for commercial purposes. This is because the massive amount of concrete provides significant building envelopes as primary functions. In addition to their primary functions, massive concrete walls also play a major role in heating/cooling zones because of their natural thermal mass characteristics, which enable them to absorb, store, and release heat [34–36]. These materials exhibit natural behavior in that they absorb energy slowly and retain it for much longer periods. This delayed response reduces the heat transfer through the thermal mass and shifts the energy demand to an off-peak time. Saving of energy happens when a reversal in the heat flow occurs within the walls. In addition, mass and heat flow play major roles in balancing temperature fluctuations.

Furthermore, the window-to-wall ratio (WWR) [37] plays an important role. In winter, the WWR allows excess light into the building and, on the contrary, allows

Fig. 8.5 Sustainable building design energy annual total reduction cost

significant heat to be lost during the opposite season. However, cement manufacturing has significant environmental impacts, energy consumption, natural resource depletion, and CO_2 emissions. Hence, it is necessary to minimize the impact and emission. The amount of cement used in concrete has been reduced by a "portion of the cement with coal fly ash or Ground Granulated Blast Furnace (GGBF) slag" [38]. The level of fly ash in concrete typically ranges from 15 to 35% of the total cementitious material but can reach 70% in massive walls. Furthermore, EP concrete has the potential to contribute to energy efficiency by providing thermal mass to the building envelope, which slows heat transfer.

Sustainable Building Design Green Roof Dark, nonreflective roof surfaces [39] create heating effects by absorbing energy from the sun and radiating it as dissipated heat. This effect causes ambient temperatures to rise, which increases the cooling requirements in the opposite season. This leads to the use of larger HVAC equipment, which increases building energy consumption. However, a roof system with light colors can reflect heat instead of absorbing it. This helps reduce HVAC equipment, energy use, solar reflectance, and thermal emissivity requirements. Hence, it is important to advise manufacturers of roof products to comply with these requirements.

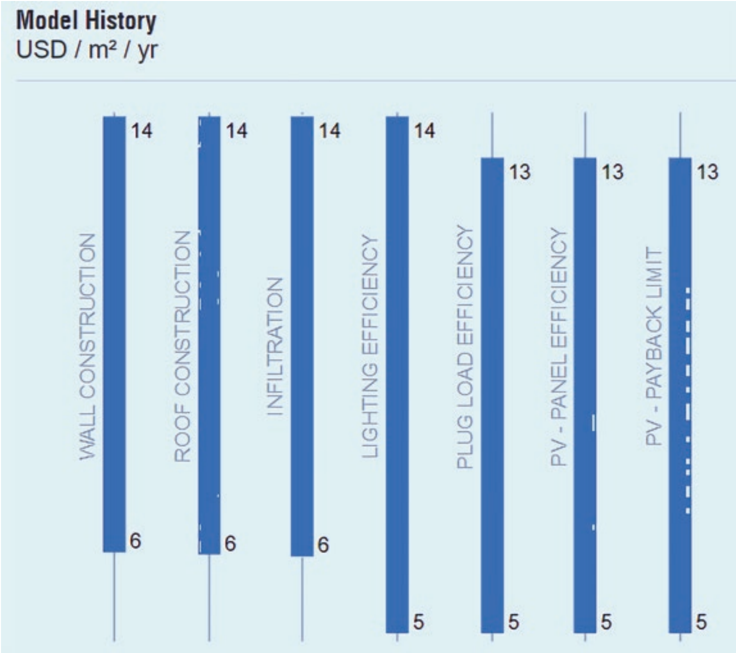

Fig. 8.6 Sustainable building elements' annual individual energy saving

Energy Reduction in Windows Windows are a critical component for energy-efficient buildings. Windows affect the thermal performance of a building by providing natural daylight, hence the reduction in electric-lighting requirements of a building. In addition, the orientation of windows, doors, and the type of building materials used for construction have significant effects on energy consumption. Furthermore, windows and doors also contribute to the exterior part of the building envelope, which has a significant effect on reducing heating/cooling energy usage. An energy-efficient window and door design maximizes the benefits of daylighting while minimizing energy use. Sustainable building design and its objective goals provide 80% of the interior lighting with natural lights and provide adequate natural ventilation to minimize/maximize window sizes. In addition, minimization of energy can be from reuse water using water recycle. Biological wastewater treatment [40] is shown in Fig. 8.4; at the bottom ground level of the building is a living machine. Living machines are the latest generation of ecological sewage technology. Recycling building wastewater by a living machine – it is practically proven, helps optimize water usage performance, and saves a significant amount of water.

Design Energy-Efficient Building Using Super Insulating Materials Energy-efficient concrete is manufactured with cast-in-place insulating concrete forms (ICF) [41], which are squashed between two layers of insulating materials. The thermal efficiency of ICF construction is attributable to the insulation properties of the form material, temperature stability from the thermal mass of concrete, and reduced air infiltration. The ICF walls can have a thermal resistance R-value of approximately R-15. Both the insulation material of the forms and the concrete used in ICF construction could contain recycled content material. The potential for toxic emissions from ICF walls is low, based on the materials used for construction. Expanded polystyrene is the most common insulation material used in ICF construction, and these materials generally do not emit emissions. The relative cost of ICF construction is approximately equivalent to that of poured concrete or concrete block construction. ICF construction is marginally more expensive than wood or steel-frame construction. However, the energy savings resulting from ICF construction may result in a lower overall lifecycle cost compared to conventional wall construction techniques.

Design Energy-Efficient Buildings Using Exterior Finishing Styles Exterior finishes prevent water and air infiltration [42]. The moisture barrier provided by an exterior finish protects interior wall materials, such as wood, steel, and insulation from degradation caused by contact with water. Newer manufactured sidings require less maintenance than traditional exteriors. Exterior shades installed between each level above the windows and doors react dynamically to the intensity of sunlight and bend or straighten automatically to reduce artificial lighting usage. To be durable and withstand the effects of sun and severe weather conditions, recycled-content materials are effective and efficient. Furthermore, exterior weather characteristics resistance design can achieve the best performance; e.g., exterior insulation finishing systems (EIFSs) [43] refer to a specific category of exterior finishes that reduce air infiltration and energy consumption.

8.3.1.3 Decarbonization for Sustainable Building Design

Carbon emissions release toxics that spread into the atmosphere. CO_2 is the most abundant fuel in terms of the quantity produced through the burning of fossil fuels. CO_2 emissions from human activities are also major contributors to rising CO_2 levels. CO_2 emissions and other related greenhouse gases [44] are leading causes of climate change and global warming. Research on climate change shows that over the last decade, average global temperatures have risen by 1.5 °C [44] and are expected/predicted to continue rising. Different greenhouse gases have different effects on earth's atmosphere; e.g., a ton of methane in the atmosphere is more climate-potent than a ton of CO_2, but it lasts approximately 12–15 years in the atmosphere. CO_2, however, can last in the atmosphere for 300–1000 years. This shows that CO_2 emissions today can contribute to rising temperatures in future centuries. In addition, types of greenhouse gases refer to numbers of gases that when released trap heat in the atmosphere, which leads to an increase in the global temperature. This phenomenon is the "greenhouse effect." Greenhouse gases mainly consist of CO_2, methane, and NO_x. CO_2 accounts for most of the greenhouse gases. This shows that the CO_2 and carbon equivalent ($CO_{2\text{-e}}$) [44] quantities are causing climate change. $CO_{2\text{-e}}$ emissions are equivalent quantities of non-CO_2 gases that could contribute to the greenhouse effect, causing the same effect as CO_2. Global warming potential (GWP) factors can convert the emissions of non-CO_2 greenhouse gases. However, GWPs are currently an ongoing scientific research topic, and the exact equivalent of non-CO_2 gases is unproven; e.g., in the first simulation, the GWP of methane was 21 tons, and on subsequent simulation, it was reported that the contribution of methane was 28. Assuming that the further assessment is valid, one ton of methane causes the same amount of tons as 28 tons of CO_2 could cause. Although each greenhouse gas has its own GWP, the largest GWP of the non-CO_2 greenhouse contributor is sulfur hexafluoride (SF6). Hence, for sustainable building design, comprehensive indoor and outdoor environmental assessments of poisonous gases are necessary.

8.3.1.4 Building Orientation to Use Natural Energy Efficiently

Building orientation [45] is defined as the positioning of a building considering seasonal variations in the sun's path because the solar radiation intensity varies correspondingly. Hence, the optimum building orientation can help increase the energy efficiency of buildings, offering maximum comfort for occupants to live or work in the building and make the operations of the building less expensive. For effective orientation, the principle of orientation and local climate are two important parts. It is the most important factor for consideration to determine the climate of the region, the true north and the sun's angles for the optimum solar radiation-energy building absorption. Choosing the optimum orientation for the climate in a region where the building is located maximizes the buildings' potential solar radiation passive heating and cooling, which complies with the principles of building orientations. However, the local climate dictates heating and cooling needs. Depending on the local weather and location of the building site, climates require mainly passive heating, passive cooling, or a combination of both. The trend of the cool/heat climate indicates that the climate is warming, and hotter summers with more extreme heat waves will become the norm during a building's lifetime. True north and sun angles are important to consider; e.g., in Australia, the main source of solar access comes from the sun's path in the north. Solar orientation generally refers to how the building is orientated with regard to true north because true north is not the same as magnetic north. Solar north can be significantly different from magnetic north, which depends on where the building is located, and building oriented with true north [46] helps maximize natural solar energy. Building orientation can also help sustain/withstand earthquakes. Sustainable building can survive natural and artificial dangers, such as earthquakes. Sustainable building, designed with concrete slabs, allow the building to twist and bend but correct itself and self-center [47] after the earthquake ends. This type of sustainable design absorbs energy from the earthquake to deform, reshape, and restore its originality. In addition, building the best orientation can optimize natural energy usage. The optimized building natural energy uses the following steps:

1. Specify efficient HVAC and lighting load conditions.
2. Implement renewable energy sources such as solar heating for hot water, geothermal space heating, and groundwater cooling.
3. Optimize building performance by employing an energy-modeling package during design and building orientation.
4. Optimize system control strategies by considering occupancy and CO_2 sensors during operation.
5. Monitor project performance using commissioning, metering, annual reporting, and periodic re-commissioning.
6. Integrate water-saving technologies to reduce energy consumption.
7. Use building daylight energy saving.

Automate the Building to React According to the Sensor Input Sensors that sense the sun radiation intensity can send the proportional signal strength to the building automation algorithm to allow proportional sun energy to the building during different weather conditions and seasons; e.g., shades, windows, and curtain walls react according to the sun intensity. Moreover, use sustainable building operating systems for energy reduction purposes. Wise building operation is significantly important in sustainable building design. Wise building operations can include many types of operation methods, but the most valuable methods are:

1. Building operating hours per day method.
2. Control and monitoring technology method.
3. Space occupancy operation techniques method.

Hence, the practical implementations of these methods can lead to the use of reduced energy.

8.3.1.5 Building Solar Radiation Energy Alternative Design Simulation Analysis

To further analyze the building's solar radiation, primary-run simulation result (gbXML) files of BIM data are exported to the GBS cloud database [48]. GBS inserts and sets a variety of input-simulating energy packages automatically using alternative energy-efficient packages; e.g., some of the energy lists are WWR energy packages, high-performance material energy packages, ASHRAE energy packages, building orientation energy packages, lighting efficiency energy packages, and scheduled building operational hours energy packages. These types of energy packages are loaded to the GBS database using insertion methods. Hence, GBS is similar to the primary-run simulation, but more advanced, and the alternative design simulation demonstrates the building's solar energy simulation in numerous alternative runs, using an automatic replacing insertion method. The processing of energy packages – energy-efficient building (EEB) elements are sequential, using periodically updated actual regional weather files. This ensures that the process and the estimation of the performed simulations are an effect of environmental weather files

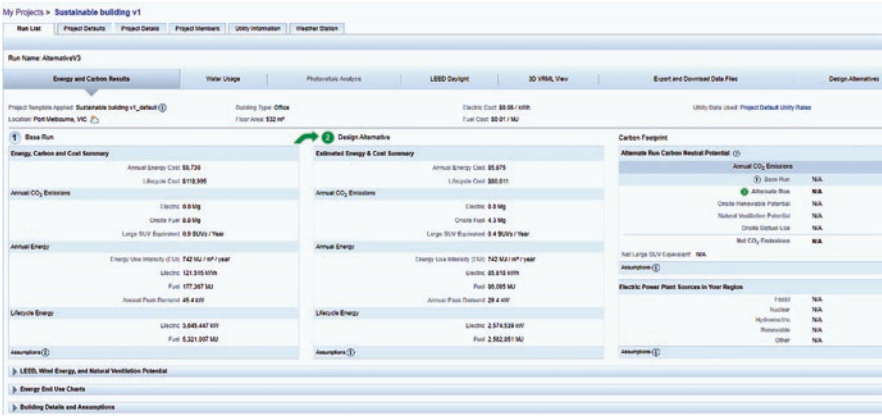

Fig. 8.7 Sustainable building design energy GBS simulation results of the base run, alternative design run

[32, 49]. The action of weather files (Fig. 8.7) helps the alternative design run demonstrate the annual energy consumption details with significantly reduced results as follows:

- Annual electricity use intensity per kWh/m^2/year.
- Annual fuel use intensity per MJ/m^2/year.
- Total annual EUI per MJ/m^2/year.
- Average estimated lifecycle electricity use in kWh.
- Average estimated lifecycle fuel use in MJ.
- Average estimated lifecycle cost in Australian dollars.

Furthermore, the GBS energy simulation processed 254 insertions of different alternative list packages, and these alternative run list packages conducted were sequential by changing/replacing their best EEB elements. This allows the owner/builder of the sustainable building to choose the best reduction package out of the 254 list of packages; e.g., Figs. 8.8 and 8.9 show total list numbers 15 and 21, respectively. Figure 8.9 is analyzed as the best alternative design because of list number 8 showing the lowest annual fuel energy use and the corresponding electric use. Further to the automatically selected simulation, a manually selected alternative conducted shows the design of solar building energy simulation. Several alternative energy-efficient building materials and lighting power densities (LPDs) simulated can aim to find the best energy package. The solar energy of a building provides the largest untapped potential for global energy generation. It is possible that the onsite production demonstrates the capability of buildings to entirely erase their carbon footprint. This is true when buildings are properly implemented and operated with solar energy to reduce heating in winter, cooling in summer, and lighting energy usage throughout the year [50]. The main criteria for selection are

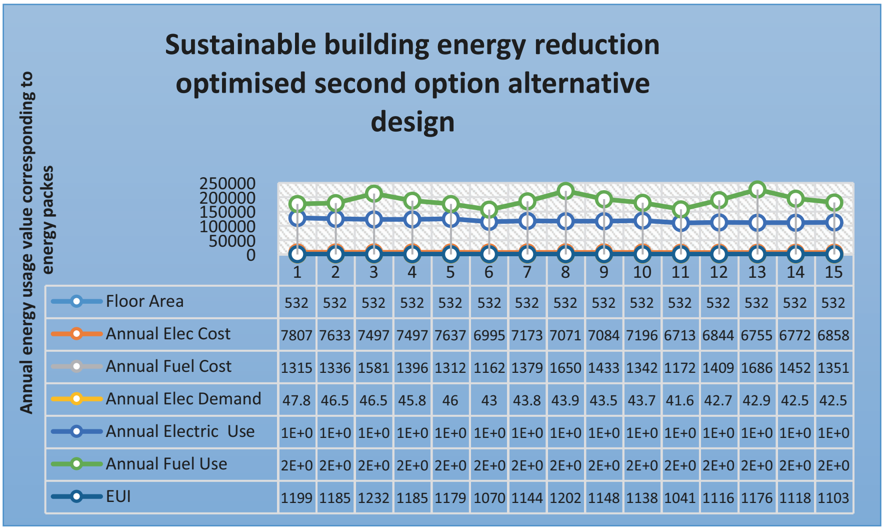

Fig. 8.8 Sustainable building design energy simulation, second option alternative design

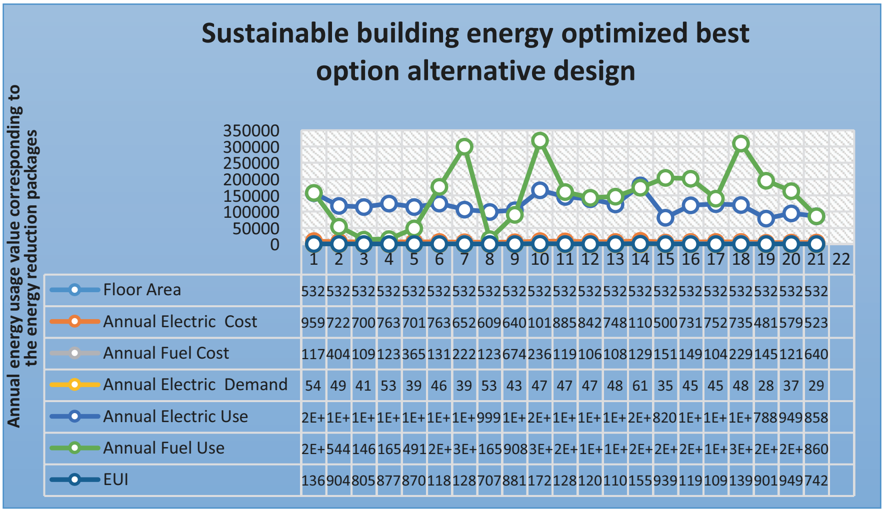

Fig. 8.9 Sustainable building design energy simulation, best option alternative design

interchangeable building elements: WWR, window shading, window shading height, window glass type, building orientation, wall insulation type, roof insulation type, infiltration, lighting efficiency, daylight control, occupancy energy control, plug-load efficiency, and LPD.

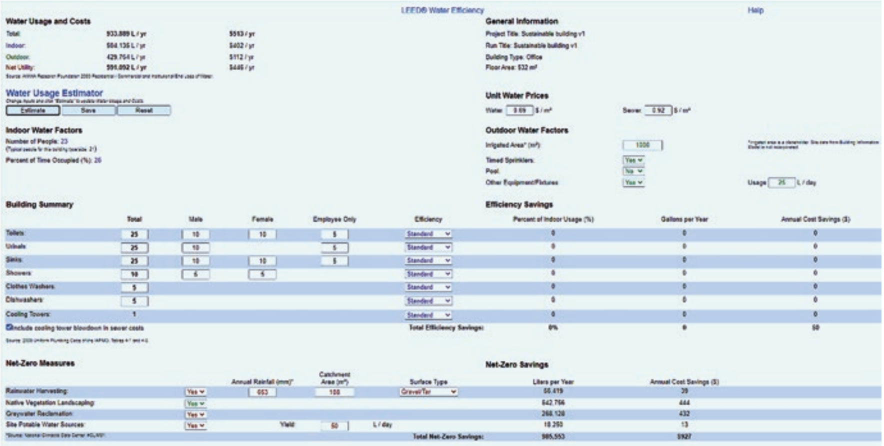

Fig. 8.10 Sustainable building design energy GBS simulation standard water efficiency

8.3.1.5.1 Sustainable Building Solar Radiation Simulation Usage Water Efficiency

The usage of building solar radiation energy simulation (Fig. 8.4) is to achieve significant savings in sustainable building design annual water usage that enables water efficiency to increase and minimize corresponding energy prices. Studies in this field have shown that up to 30% [51] of reduction in commercial building energy usage is from water heating. Implementing highly efficient hot water usage and considering alternative methods, such as "geothermal heating" (subject to availability), could lead to improved energy reduction and minimize the amount of pollution related to energy consumption. The water efficiency of an alternative design run is a continuation of that of the primary run. In the primary-run simulation, all the water sources are configured as standard usage, as shown in Fig. 8.10, owing to which no significant measures are taken to reduce water use, while in the alternative design run, significant measures are taken to reduce water usage, as shown in Fig. 8.11.

8.4 Sustainable Building Design IoT Integration

Conventional building owners and operators have concerns about building functionality requiring a decrease in energy consumption and dealing with rising operational and maintenance costs. To address these concerns, building owners and operators consider the use of IoT [52] applications, as shown in Fig. 8.12, to turn the buildings into smart and sustainable buildings. Hence, the increase in IoT-connected sensor network elements has made building automation possible.

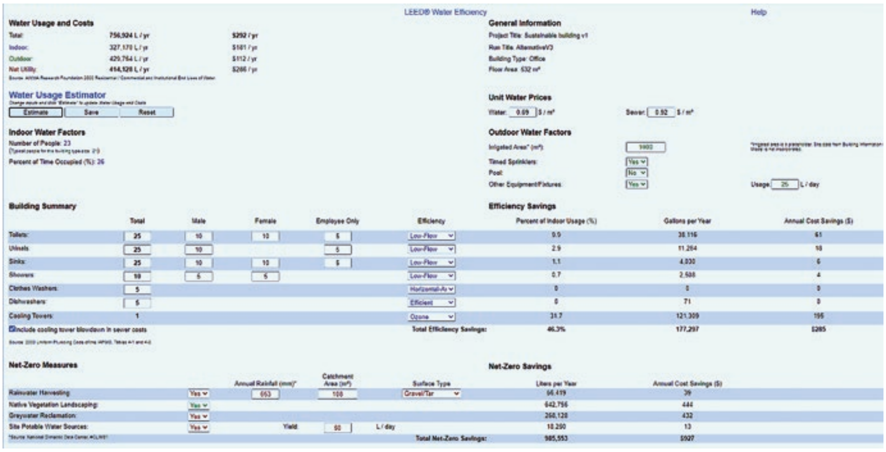

Fig. 8.11 Sustainable building design energy GBS simulation optimized water usage efficiency

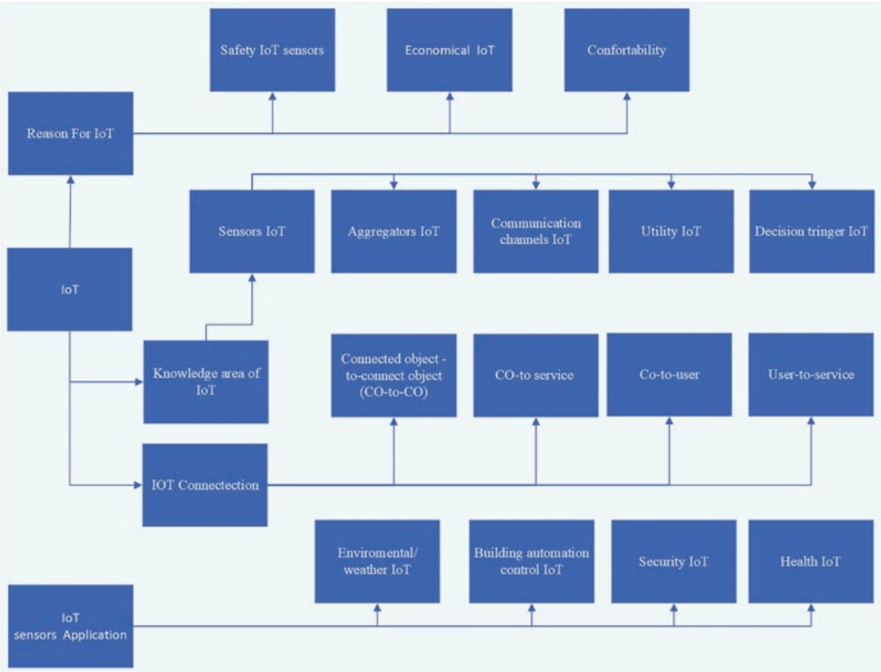

Fig. 8.12 Sustainable building design IoT integration elements

Reason for IoT in Sustainable Building Design Complex buildings such as university, colleges, commercial buildings, manufacturing buildings, and health facility buildings use connected objects such as IoT applications to drive faster, reliable, and secure technology to reduce energy consumption, lower building, operational, and maintenance costs, and utilize the work area to be efficient.

Knowledge of IoT Buildings connected with IoT devices have a wide area of positive impact on the occupant's life, sense, and actions. Examples include IoT machine learning, voice activating/deactivating automated building sensors/actuators, object detection surveillance cameras, and security alarm smart devices. IoT connection can be as follows:

- Building's IoT devices connected to each other to exchange information.
- IoT devices connected to services.
- IoT devices connected to users.
- IoT devices connected to mobile devices and other personal devices.

IoT Sensor Application The growing need for pervasive connectivity, storage, and computation has resulted in the growth of various IoT applications. For example, a few IoT applications are weather IoT, which regularly reports the climate conditions of the surrounding indoor and outdoor areas. Building automation control, IoT helps in feeding digital and analog signals to the main controller processor. Security IoT reports suspected objects to the responsible persons and can control/monitor in-and-out movements of the buildings. Hence, rejection of an unknown person from entering the building or the object's image can be sent to the responsible person for analysis and return the result with the object details; once the object or person details are confirmed to be correct, the entrance may be granted.

Health IoT to Replace Basic General Practitioner (GP) Skills IoT health sensors are installed in different locations as follows:

- Parts of the building.
- In-human parts of the body, such as future IoT devices installed in a mirror (glass) bathroom, can inspect the face while occupants of the building wash their face, and toilet bowls can inspect bowel health conditions for hemorrhoid disease and other related diseases. Body-planted personal IoT can report and monitor the condition of the body and report to the medical practitioner; therefore, the responsible person will have daily health information of their client and respond to them without the client approaching their medical institution.

8.5 Sustainable Building Design Integrated with Optimized Renewable Energy Supply

Renewable energy is an emerging energy source derived from natural sources manufactured at a higher efficiency; e.g., sunlight and wind are constantly replenishing sources and are abundant in nature. Implementing renewable energy contributes significantly to lowering emissions compared to burning fossil fuels.

In addition, renewable energy has its own preferences, viz. integration of wind turbine energy into rural or remote areas, such as farms, ranches, and coastal and island communities, where there are highly dense wind sources. Currently, wind power competes with other low-cost energy sources. The cost of energy associated

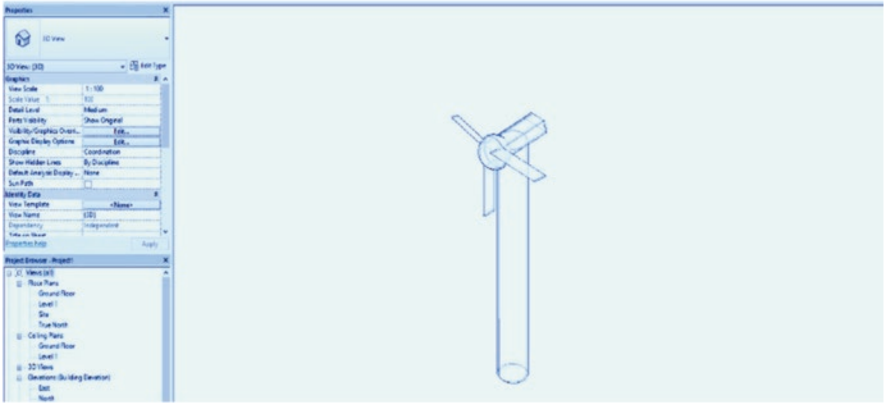

Fig. 8.13 Conceptual basic design of wind turbine that can easily be mounted on the rooftop

with power plants is competitive, except for locations that experience low wind sources. Wind turbines are becoming economically comparable to gas, geothermal, coal, and nuclear power plants (NPPs). However, these competing energy sources, which cannot be planted on the building, have negligible effects on the building-planted wind turbine energy. Figure 8.13 shows the basic wind turbine conceptual model mounted on top of the building roof without negatively affecting the structure of the building.

8.5.1 Optimizing Wind Turbine Power

Wind turbine energy is the process used to convert kinetic mechanical energy to electric energy. The most important concept when designing an effective wind turbine is aerodynamics. However, the size also matters, and the longest turbine blades correspond to the longest rotor diameter. Consequently, the more the turbine can experience drag and lift forces from the wind speed, the higher the electricity generating capacity. Doubling the rotor diameter produces a fourfold increase in energy output [53, 54]. In some cases, the reverse results are in better performance, such as in a lower wind speed building, where a smaller diameter rotor can produce more wind power than a larger diameter rotor. This is because with a smaller rotor diameter and shorter blades, less wind power is required to spin the smaller generator. Thus, the turbine can operate continuously at full capacity. In addition, building and tower heights are major factors in wind turbine productivity. The higher the turbine, the more energy that the wind turbine can capture. This is because the wind speeds increase proportionally with elevation height; by doubling the elevation height approximately, a 12% increase in wind speed can occur. Currently, the most effectively used wind turbine sizes and configurations are either horizontal or vertical axes; however, horizontal-axis turbines with three-blade configurations are widely used globally owing to their speed and aerodynamic turbulence stability.

Theoretically, the design of the wind turbines is to meet the maximum optimization requirements of it. Consequently, the aerodynamic blade design and rotor diameter are for the maximized output.

A recent study on wind turbines for maximum extraction showed that maximum power extraction involves many complex issues. According the study, in order to maximize the output power, there are three main types of proven methods. The three main methods that wind turbine output power optimized are:

(a) "Wind turbine power coefficient" (C_p)
(b) Tip speed ratio (TSR).
(c) Optimum torque control (OTC).

1. *Wind turbine optimization using power coefficient*:

$\left(C_p\right) = \dfrac{\text{Wind turbine actual produced power}}{\text{Wind power provided in to the tuebine}}$, and power coefficient is a measurement of the wind turbine efficiency. C_p is the ratio of the actual electric power produced by a wind turbine to the total wind power moving into the turbine blades at a specific wind speed. The power coefficient represents the combined efficiency of the various components of the wind power system. The manufacturer calculates the C_p for a particular turbine, provides it for various wind speeds, and varies with operating conditions, such as wind speed, turbine blade angle, and turbine rotation speeds. The optimized wind coefficient demonstrates that as the wind power approaching the turbine blade increases, the extracted electrical power increases [55].

2. *Optimizing wind turbine power using tip speed ratio:*

$\left(\text{TSR}\right) = \dfrac{\text{Wind actual tiping speed of the blade}}{\text{Current speed of the wind}}$, and the usage of TSR is optimized for each particular generator location. The effective TSR depends on the blade of the aerofoil, the number of blades, and the type of wind turbine. A wind turbine with three blades that operate between 6 and 8 TSR is preferable for optimizing the output power [56] and also works efficiently comparing with TSR less than 6 or greater than 8.

3. *Optimize wind turbine output power using optimum torque control:*

OTC depends on the torque equation (P_m) = $T_m\omega$.

where P_m is the maximum torque and ω is the angular speed of the winds.

OTC is a method used for maximum power point tracking (MPPT) extraction. Owing to the sluggish response of wind turbines with high inertia, the improvement of conventional OTC method was through increasing wind turbine efficiency by dynamically modifying the generator torque versus rotor speed. An effective tracking range (ETR) that corresponds to the local interval of wind speed with a concentrated wind energy distribution is preferable for an improved OTC based on ETR [57].

8.5.2 *Sustainable Building Integrated with Optimized Solar Panel Energy*

The portion of energy provided by the sun to earth for 1 h is equivalent to the annual energy consumed by the entire world. Although solar energy is expensive or inefficient, it has proven to be significantly beneficial to communities and private companies. In the last few decades, solar energy technology has been rapidly progressing and improving its efficiency. Furthermore, by adding solar battery storage systems, it converts solar energy into a significantly efficient source of renewable energy.

Optimization and testing of a solar panel cell's basic energy generation is by using the standard testing method. Light is an electromagnetic wave that contains particles or photons. When these photons are incident on the surface of a flat semiconductor, the light is either reflected from the top surface or absorbed in the semiconductor material or, missing these two chances, transmitted out through the material. Hence, solar panel cells that reflect and transmit light are typically considered to be lost because photons are not absorbed and consequently do not generate energy. When photons are absorbed, electrons can be excited from the valence band to the conduction bands. Energy generation occurs when photons have enough energy to knock the electrons and accelerate it into the conduction band from the valence band and when the energy of a photon is equal to or greater than the bandgap energy of the material. Furthermore, materials with a higher absorption coefficient ($a = 4\pi K/\lambda$) are likely to readily absorb photons [58, 59]. The absorption coefficient determines how far into a material can light of a particular wavelength penetrate before it is absorbed. The absorption coefficient depends on the material and on the wavelength of light being absorbed. The main conditions to generate adequate solar panel cell energy are that the material should able to absorb sufficient photons of short wavelengths and material must have higher absorption coefficients.

Figures 8.14 and 8.15 show solar panel cell's ideal and nonideal diode characteristics with respect to light intensity penetration and maximum output voltage generation – IV characteristics. Description of diode characteristics, such as its dark

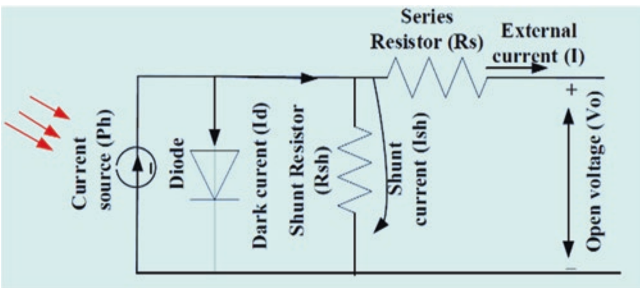

Fig. 8.14 Basic solar panel cell energy generation

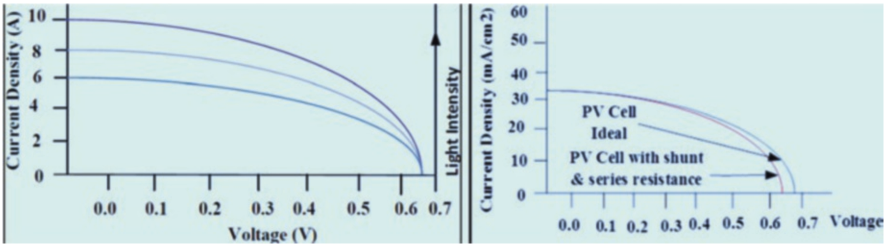

Fig. 8.15 Solar panel cell testing characteristics

energy, shunt series currents, current density, light intensity density, and open voltage, is available in the literature.

8.5.3 Sustainable Building Design Integration with Smart Grid and with Renewable Energy

A smart grid is an electricity supply line that connects each section of the substation, forming a network function using advanced digital technologies to intelligently monitor and securely manage the transfer of electricity. The smart grid function spans the smart grid infrastructure, smart metering, energy storage, HMI, demand-side management, artificial intelligence, and cyber security. Integration of smart grids is through renewable energy sources, mainly wind turbines and solar panel cells. The desire to work for the collaborative efforts of consumers helps the power grid be smarter, reliable, and cost-effective. The smart grid starts at the generator and ends at the end-user appliance; understanding the role of smart grids in each section is important in order to keep a sustainable supply power connection and to avoid nuisance malfunction interruption.

8.6 Sustainable Building Design Controlling and Monitoring Structure

Building automation control and monitoring are key tasks in building design, operation, and monitoring. Over the last few decades, building automation has rapidly grown, with the aim of minimizing energy usage and maximizing safety, security, and comfort. Various building automations have been developed and implemented in practice using different protocols; e.g., C-bus and ZigBee are among the many controls that perform considerably in terms of energy consumption and safety purposes but have less contribution in economical installation to minimize the bulk amount of control wiring cables. To minimize the bulk control wiring, it is

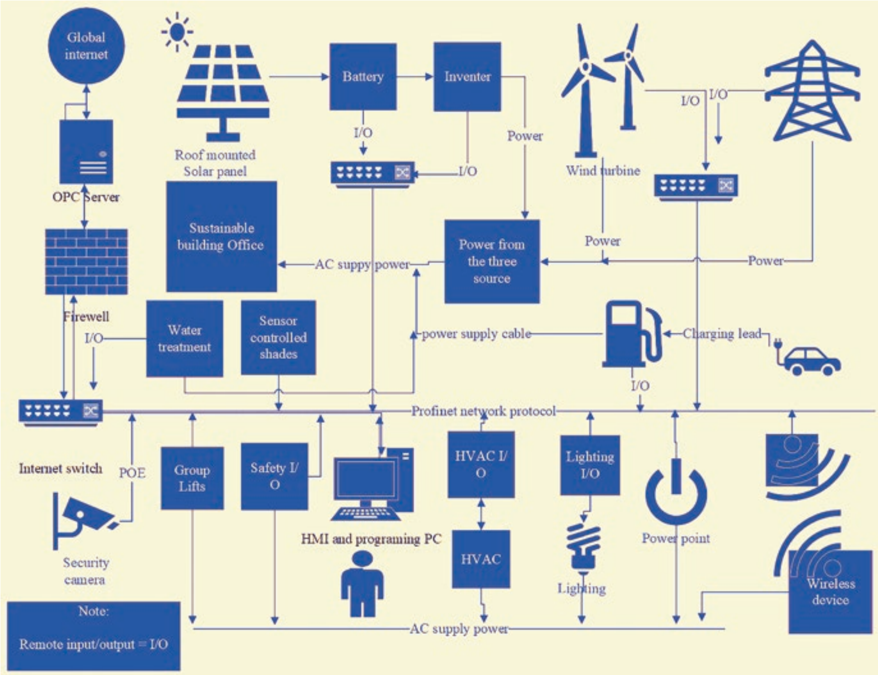

Fig. 8.16 Sustainable design building automation management control, PROFINET-protocol network system architecture

important to adopt the industrial wiring method to building control wiring method such as "PROFINET network wiring method" [60], which uses the internet remote I/O network protocol system. The prototype protocol architecture is shown in Fig. 8.16, which has more flexibility for expansion to add another type of network, such as wireless networks, and it has the capability of a simple parameter setup and configuration.

Furthermore, the human machine interface (HMI) is another part of the protocol. It is a dashboard connecting humans to a machine or interfacing system. Usage of HMI is in industrial and building automation processes. HMI is similar to graphical user interfaces (GUIs) and supervised data acquisition (SCADA). HMI visually displays data to track production time, trends, tags, and monitors I/O status. Specifically, building automation can interact with humans, such as HVAC, lighting, water systems, and elevator control. Nowadays, a group of elevators works corporately by specifying which elevator to use. This depends on the number of users at a given point in time; e.g., the user presses the button on the HMI, which is located outside of the lifters place, the HMI system directs the user to the lift number or name, and then the user is not required to press a button once the user is inside the lift.

8.7 LEED Certification

The LEED assessment and certification shown in Fig. 8.17 is owned by the United States Green Building Council (USGBC) [61]. The LEED assessment rating was conducted on a building that complies with certain sustainability-objective criteria requirements as specified by the USGBC. However, LEED certification is an optional rating system in which only certain high-performing buildings can grant certified awards to demonstrate their efforts in creating healthy, livable, and sustainable buildings.

The LEED rating system has many benefits. For example, being more competitive, a sustainable building can lead to market differentiation and, hence, achieve improved financial performance, including lower operational costs, energy savings, and reduced resource consumption. Furthermore, the LEED certificate addresses eight main credit categories, as shown in Fig. 8.17 – sustainable sites, water efficiency, energy, atmosphere, material, resources, and indoor environmental quality.

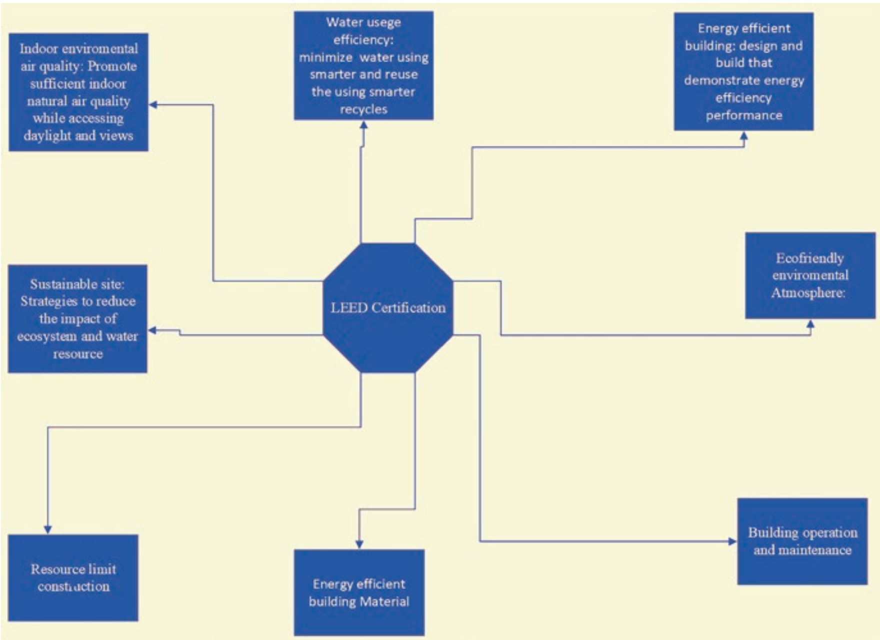

Fig. 8.17 Sustainable building design energy reduction using the LEED certification method

8.8 Sustainable Building Design Energy Optimized Approach

The primary simulation results and the final best alternative design-run simulation package results shown in Table 8.3 demonstrate a significant amount of energy reduction, in particular, the alternative design and the building's solar radiation energy simulation results of fuel and electricity energy consumption. The fuel energy reduction was approximately 50%, while the electricity energy reduction was approximately 30%. These reductions are from the building's solar radiation simulation, which did not include the reduction from the BACS energy control system, IoT, and smart grid energy reductions. The current BACS literature review indicates that an average energy reduction of 30% [52, 62–65] is possible. In this case, the optimum energy reduction is approximately 69.7%. In addition, the primary-run PV cell potential energy efficiency is conceptually increased from the basic 15–40% using an energy efficiency optimization conceptual mechanism techniques as described earlier. Hence, on applying Eq. (8.2), the sustainable building design annual consumption is calculated. The base run is 121,515 kWh, 30% reduction from the BACS is 36,454.5 kWh, and from the alternative design, best reduction is 35,697 kWh. The total reduction is 72,142.5 kWh. Generation of 49,372.5 kWh is from renewable sources in order for the building approximately to be free from carbon footprint emission.

Table 8.3 Sustainable building design energy-simulation achievement results

Primary-run annual usage simulation results		Alternative design-run energy simulation results	
Annual electricity usage	121,515 kWh	Annual electricity energy	85,818 kWh
Annual electric cost ($0.06/kWh)	$12750.9	Annual electricity cost ($0.06/kWh)	$5149.08
Annual fuel energy	177,367 MJ	Annual fuel energy	86,095 MJ
Annual fuel cost ($0.01/MJ)		Annual fuel cost ($0.01/MJ)	$860.95
Lifecycle electric energy	3,645,447 kW	Lifecycle electric energy	2,574,539 kW
Lifecycle fuel energy	5,321,007 MJ	Lifecycle fuel energy	2,582,851 MJ
Annual CO_2 emissions (onsite fuel)	8.8 mg	Annual CO_2 emissions (onsite fuel)	4.3 mg
Total potential solar panel cell annual energy 5–15% efficiency range	8336 kWh	Solar panel cell optimized/boosted efficiency (40%)	11670.4 kWh
Annual potential renewable wind energy	0 kWh	Annual wind turbine potential energy	0 kWh

8.9 Conclusion

The main goal of sustainable building design using renewable energy is to conserve natural resources by seeking environmentally friendly alternative sources of energy to reduce current pollution. Sustainable building design development is the practice of developing land and construction design models in a manner that minimizes the impact on the environment by creating energy-efficient models of self-sufficiency. Hence, building projects that are currently rooted in environmental sustainability should involve replanting, preserving wetlands, and protecting natural surrounding areas from resource harvesting. Thus, in this chapter, considerable attempts were made to approach/achieve the objective of sustainable building design with renewable energy sources.

1. We modeled conceptual buildings and conducted a building solar radiation energy simulation. We obtained and initially analyzed the basic primary-run simulation results.
2. Based on the initial analysis, we conducted further analysis on an alternative design of solar building radiation using automatically selected energy-efficient building material/element packages.

Similarly, based on further alternative design, we conducted building solar radiation energy analysis using manually selected energy-efficient building material/element packages. In addition, we developed a sustainable building design with renewable mathematical equations model.

Furthermore, an efficiency optimization of wind turbine and solar panels were attempted. The optimization used mathematical equations and conceptual simulations. The mathematically optimized basic potential energy of the wind turbine considered the three main proven techniques of Cp, TSR, and OTC. Solar panel cells' basic efficiency was optimized using the concept of the conceptual sunlight intensity tracking method. IoT, smart grid integration, and building energy reduction objectives for the environment-preserving rating certification system are among the considered items.

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Chapter 9
Thermal Energy Storage (TES) for Sustainable Buildings: Addressing the Current Energetic Situation in the EU with TES-Enhanced Buildings

Francesco Valentini, Giulia Fredi, and Andrea Dorigato

Abstract In the last century, global primary energy consumption and related CO_2 emissions increased 10 times, and they are still on the rise. The environmental sustainability and the limitation of the energy consumption of buildings are of substantial importance in reducing greenhouse gas emissions and mitigating the consequences of climate change. The main problem of the next years will be the necessity to find a compromise between energy demand and available energy resources. Europe, despite the lower emissions compared to other regions, will face very hard challenges due to (i) the extreme rise of energy prices that occurred in 2022 and (ii) the necessity to cut CO_2 emissions and energy consumption to reach the targets of the European Green Deal for 2050. The technologies and systems able to store thermal energy allow the accumulation of energy when available (e.g., thermal energy from sun) in order to use it when and where necessary, with a consequent reduction of CO_2 emissions. The use of insulating materials with TES capability may result in the compensation of energy absorption peaks caused by air conditioning or by space heating with a consequent reduction of energy consumption and related CO_2 emissions. The present study, starting from some considerations regarding the energetic problem, greenhouse gas emissions in EU, and used energy source, presents the available energy storage technologies with particular attention to thermal energy storage. Different applications and available commercial technologies are analyzed.

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9.1 The Energetic Problem

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

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

Similarly, as reported in Fig. 9.2, also CO_2 emissions increased 10 times in the last century and around 75% of them are related to energy consumption, mainly due to the combustion of coal and oil [3].

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

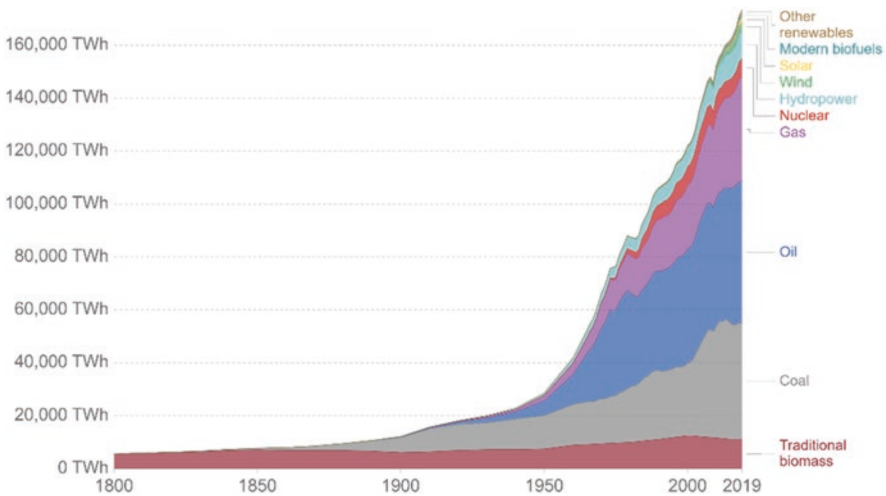

Fig. 9.1 Global primary energy consumption by source [3]

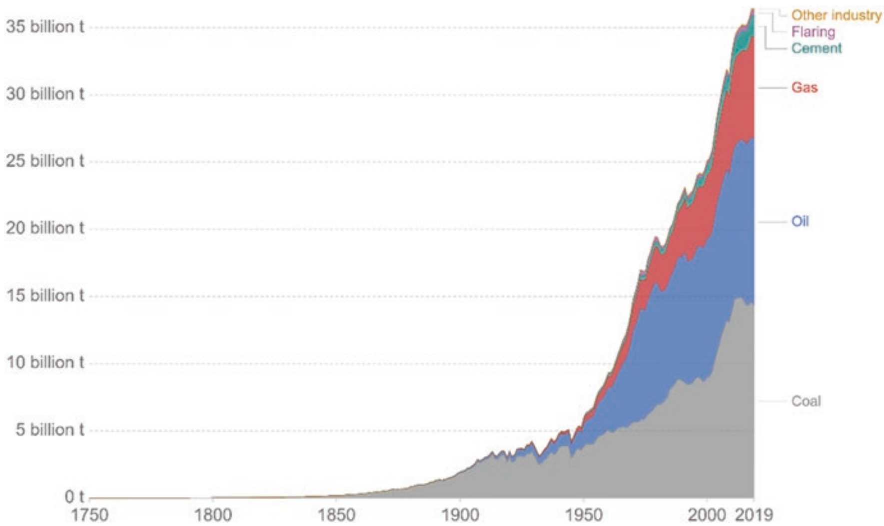

Fig. 9.2 CO_2 emissions by fuel type [3]

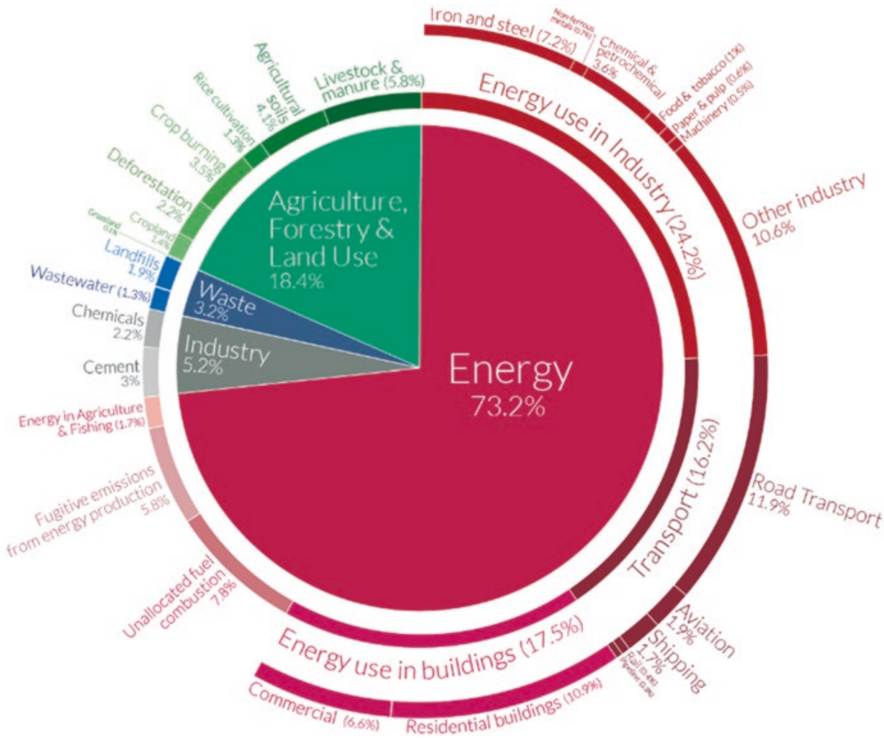

Fig. 9.3 Global greenhouse gas emissions by sector [5]

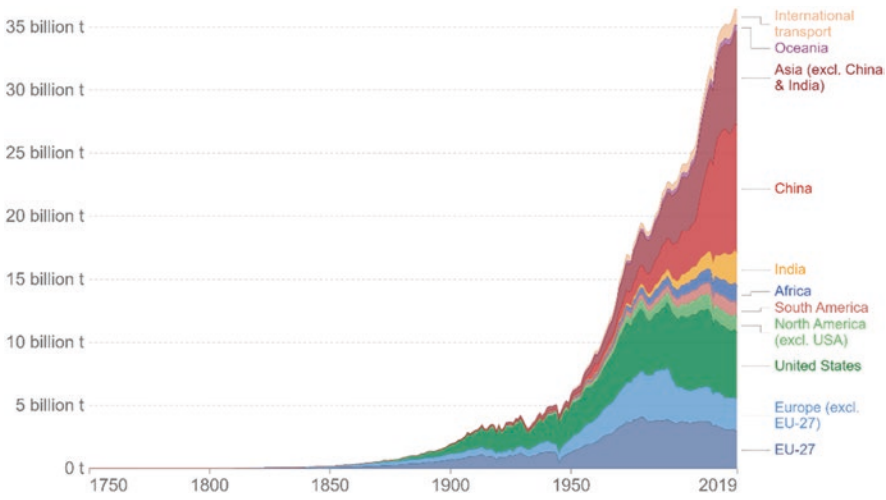

Fig. 9.4 CO_2 emissions by region [5]

From Fig. 9.4, it is evident that the distribution of CO_2 emissions in the twentieth century was dominated by Europe and United States, causing around 90% of global CO_2 emissions in 1990. Starting from 1950, the situation changed significantly: emerging countries, mainly in Asia, caused a strong rise in CO_2 emissions that is still continuing nowadays, although the contribution of other countries has stabilized (United States) or reduced (EU) starting from 1990 [5].

9.2 The Situation in the EU

9.2.1 Greenhouse Gas Emissions

Comparing the CO_2 emission per kilowatt-hour of different countries in 2018, it results that the EU has lower values (270 g CO_2/kWh) than the United States (500 g CO_2/kWh), China (600 g CO_2/kWh), India, and Australia (700 g CO_2/kWh). In 2019, the reduction of CO_2 emissions in the EU was the largest worldwide (235 g CO_2/kWh compared with 270 g CO_2/kWh in 2018) [7–9].

In 2018, the greenhouse gas emissions in the EU were reduced by 23% in 1990, even though the EU population grew by 7%. Hence, the EU was able to reach the targeted reductions of CO_2 emissions in 2020 (−20% with respect to 1990) [10, 11]. Despite this, according to projections of the European Environmental Agency (EEA) (Fig. 9.5), the reduction by 2030 would be around 30% considering the existing legislation or 36% in case of extraordinary measures, below the target of −40% [12]. According to data from the EEA, the EU average annual reduction in greenhouse gas has been equal to 46 Mt. CO_2eq between 1990 and 2017, while it should

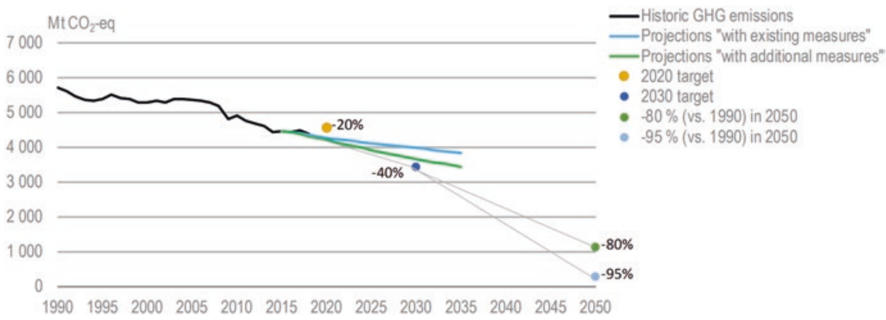

Fig. 9.5 Greenhouse gas emissions in the EU from 1990 to 2018 and projections for 2030 and 2050 [7, 12]

be around 100 Mt. CO_2eq in order to reach the 2030 target and around 114–157 Mt. CO_2eq to achieve the 2050 target (−90% CO_2 emissions) [12, 13]. Moreover, scenarios proposed by the European Commission indicate that, between 2030 and 2050, the primary energy consumption should decrease by around 4–14 Mtoe per year [14].

In 2017, greenhouse gas emissions were caused mainly by oil (42%, 66% of which was due to transports), followed by coal (29%) and by gas (28%). By sector, CO_2 emissions were caused mainly by heat and power generation (35%) and transport (25%), followed by energy use in residential and service buildings (17%), industry (8%), agriculture, forestry and fishing (10%), and waste management (3%) [7, 11, 15]. The Land Use, Land-Use Change and Forestry (LULUCF) sector contributed to a net removal of around 5% of GHG emissions [11].

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

9.2.1.1 Power and Heat Generation

Power and heat generation caused, in 2017, around 35% of the total CO_2 emissions, and the residential sector alone contributed 17%. In the EU residential sector, in 2018, about 64% of the total energy consumption was used for space heating, 15% for domestic hot water, 14% for lighting and appliances, 6% for cooking, and 1% for space cooling [17].

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

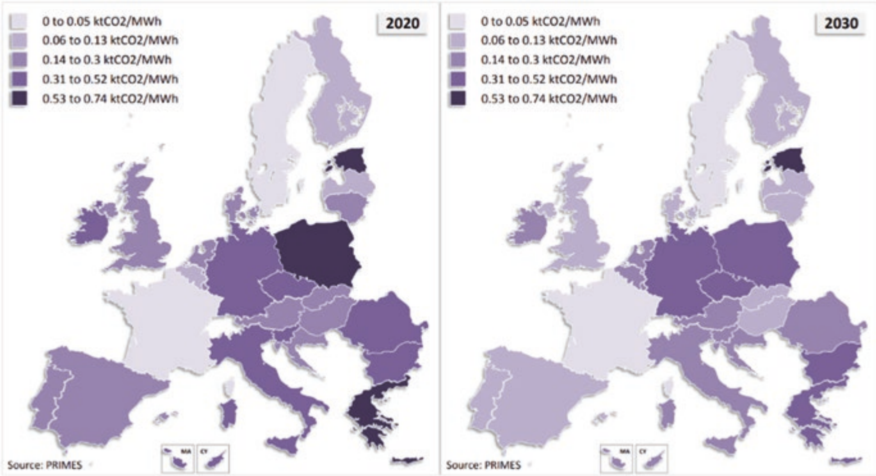

Fig. 9.6 Carbon intensity of power generation in the EU for 2020 and 2030 [16]

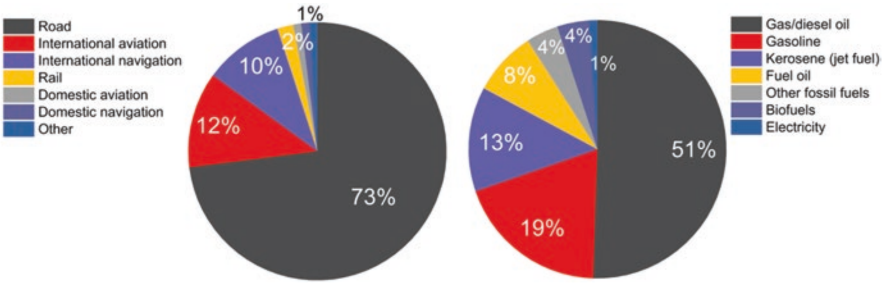

Fig. 9.7 Energy consumption in the transport sector by type (left) and fuel (right) [23, 24]

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

9.2.1.2 Transport Sector

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

In the transport sector, the EU legislation on CO_2 emission limits is the most stringent worldwide, and great efforts should be made by companies in order to reach the imposed target of −37.5% in 2030 compared to 2021 levels for cars (95 g CO_2/km in 2021), −31% in 2030 compared to 2021 levels for vans (147 g CO_2/km in 2021), and −30% in 2030 compared to 2021 levels for heavy-duty vehicles. However, part of these efforts could be fruitless due to the increase in sales of low-efficiency vehicles such as sport utility vehicles (SUVs) [9, 12, 14, 25–27]. The amount of SUVs sold in the EU increased from 7% to more than 30% of new register vehicles in the last 10 years: this trend is favored by carmakers that try to maximize sales of SUVs, which provide higher profits than low-emission economy cars [19]. Moreover, by 2030, zero- and low-emission vehicles (ZLEV) must account for 35% (cars) and 30% (vans) of sales in the EU, but the potential benefits of this regulation could partly be vanished because plug-in hybrid cars, under pressure from car-manufacturing member states, have been comprised within the ZLEV category [19]. To reach the target imposed by the European Green Deal (−90% of greenhouse gas by 2050), it is estimated that around 75% of road transportations should be performed by train [25].

The domestic aviation sector in the EU contributes less than 0.5% of total GHG emission, but international aviation from and to the EU contributes to 3% of total emissions, which doubled between 1990 and 2017. The EU Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) requires airlines to reset the growth of CO_2 emissions starting from 2020 [12, 28].

9.2.1.3 Industry

The European industrial sector accounted, in 2017, for 12.6% of CO_2 emissions, with a reduction of only 0.3% compared to 2013, and, despite this, no specific targets for energy efficiency or use of renewable resources are present [7]. The Industrial Emissions Directive (2010/75/EU) sets emission limits based on the best available techniques (BAT). The permissions, according to the directive, are based on an integrated approach that considers emissions to air, water and land, waste production, use of raw materials, energy consumption, noise, and restoration of the site upon closure [16, 29].

In the case of particular industries like large combustion plants, waste incinerators, and solvent-using activities, limitations have also been imposed for specific pollutants, such as fluorinated gases; in particular, by 2030, fluorinated greenhouse gas emissions should be reduced by 2–3% compared to 2014 levels, below a limit of 1.5 Gt CO_2eq [30]. As alternatives to the common hydrofluorocarbon (HFC) gases for refrigeration, iso-butane is the most widely used for domestic fridges and freezers, while propane is the most diffused for air-conditioning and commercial refrigerators [16].

9.2.1.4 Agriculture

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

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

Concerning emissions from land use and forestry protection, the LULUCF regulation requires that the GHG emissions from a land use category are completely compensated by an equivalent CO_2 removal from another category (such as forestry). Moreover, the conversion of forests to other land uses (deforestation) or the increase of the cropland surfaces should be paralleled with an increase in the forest surface (afforestation) in other sites, thereby equilibrating the CO_2 balance [12, 32, 33]. In 2012, the LULUCF sector contributed with a net carbon sink of approx. 258 Mt. CO_2eq but, by 2030, a decline of around 32% is expected. The two main reasons are the aging of EU forests, with a consequent reduction of carbon sequestration, and an increase in forest harvest, due to the higher demand for wood for material uses and energy production and due to a decrease of forest increment (from 751 million m^3 in 2005 to 725 million m^3 in 2030) [12].

9.2.2 *Energy Consumption*

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

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

9.2.2.1 Oil

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

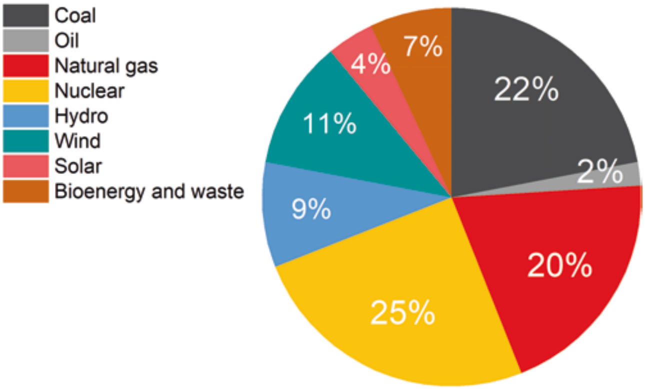

Fig. 9.8 EU electricity production sources in 2017 [7, 35]

9.2.2.2 Natural Gas

Gas is the second largest energy source in the EU, with a consumption of 487 billion m^3 in 2017, 29% higher than in 1990. It is mainly used for power and heat generation, residential heating, and industrial processes; the projections for 2030 see a decrease in gas use for residential heating but an increase for power generation [7, 36].

9.2.2.3 Coal

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

9.2.2.4 Nuclear Energy

Regarding nuclear energy, the EU has the largest number of nuclear power plants operating worldwide, but it is entering a critical stage due to the approaching to the end of the planned lifetime. The EEA expects, by 2050, a decrease of the installed capacity of around 25 GW, with respect to the 125 GW installed in 2017, with a consequent decrease in the contribution to electricity production from 25% in 2017 to 15% in 2050 [7, 28, 36]. The majority of nuclear reactors in the EU were built between 1970 and 1980: by 2015, 91 plants were decommissioned and the decommissioning of other 89 reactors is planned before 2030. To limit the fall of nuclear energy production, the European Commission estimates that investments of around 50 billion € are required for the lifetime extension of existing plants and 450 billion € for the construction of new plants [28]. At the moment, only a few countries are building new plants (Finland, France, Hungary, Slovakia, and the United Kingdom), while France planned a 50% reduction by 2035, Germany the complete decommissioning by 2022, and Belgium by 2025 [37].

9.2.3 The Building Sector in the EU

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

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

A scenario proposed by the Buildings Performance Institute Europe (BPIE) estimates that, to achieve the EU's target of emission neutrality by 2050, a decrease of 22% of the final energy demand for heating and cooling will be required by 2030 with a consequent necessity of a building renovation rate of around 4.4%, higher than the 3% required in the period 2020–2050. This value demonstrates that the postponement of the required measures necessary to reach the targets implies stronger efforts in the future. Moreover, by 2030, a reduction in floor space per capita of around 6% is expected, reaching a value of 44.8 m^2/person [46]. The Energy Efficiency Financial Institution Group estimated that, starting from 2020, annual investments of around 100 billion € are required for building renovations [47].

The Energy Performance of Buildings Directive of 2010 and revised in 2018 (2018/844/EU) established energy efficiency targets for new buildings, energy performance certificates (EPC), and verification methods. Energy performance certificates were introduced in order to increase the transparency of building's energy performance, to improve the demand for buildings with low-emission classes, and to improve the indexing of building's performances [48]. Furthermore, the directive required that, starting from the end of 2020, all new buildings must be nearly zero-energy buildings (nZEB), in which the nearly zero amount of energy required should be mainly satisfied by renewable energy resources. The directive did not provide a precise definition of nZEB, leaving the EU member states the possibility to define it [32, 38, 47, 49–51].

The regulations imposed by member states established, in some cases, a minimum percentage of energy that should be covered by RES and, in other cases, extremely low levels of primary energy (between 20 and 90 kWh/m^2/year) that, practically, can be reached only using RES [52]. Studies carried out in 17 EU countries, evidenced that nZEB requires 15–25 kWh/m^2/year for heating in cold-climate regions and 8–10 kWh/m^2/year in temperate-climate regions [53].

In Italy, RES should cover at least 50% of energy consumption for heating, cooling, and hot water, and the transmittance levels of envelope, roof, and windows should be lower than reference values depending on different climatic areas [52]. In France, the primary energy consumption of residential buildings must be lower than 50 kWh/m^2/year [53]. Moreover, by 2025, all buildings with a primary energy consumption higher than 330 kWh/m^2 (F, G efficiency classes) must be renovated to reach a performance comparable to new buildings, and by 2050, all buildings should be in class A or B [47]. In Germany, three types of house efficiency have been defined (KfW40, KfW50, KfW70), considering the fact that the annual primary energy consumption should be 40, 50, 70% lower compared to a corresponding reference building. Moreover, the minimum share of RES is 15% while using solar heating and 50% while using biomass and geothermal energy [54]. The European Passive House standard states a limit for heating energy use lower than 15 kWh/m^2/year (120 kWh/m^2/year considering heating, cooling, hot water, and electricity), which can be reached by reducing heat losses to 45 kWh/m^2/year, with 15 kWh/m^2 covered by solar heating, 15 by internal heat gains and the remaining part by active heating [55].

It is estimated that a deep retrofitting of buildings located in the EU and the United States could allow a reduction of 33% and 50%, respectively, of energy consumption by 2050 [55, 56]. From an economical point of view, the retrofitting of buildings according to the passive-house standard is quite convenient: the cost for the renovation of a traditional residential building is estimated in the order of 500–600 €/m^2 and the incremental cost of a new passive house is around 8% of the cost of a standard house. If amortized over 25 years at 4% interest and divided by the saved energy, the cost of the saved energy would be around 0.06 €/kWh, equal to the cost of natural gas in the EU in the first half of 2021 and much lower with respect to the cost of natural gas in 2022 [45, 52, 57].

9.2.4 Energy Prices and Road to 2050

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

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

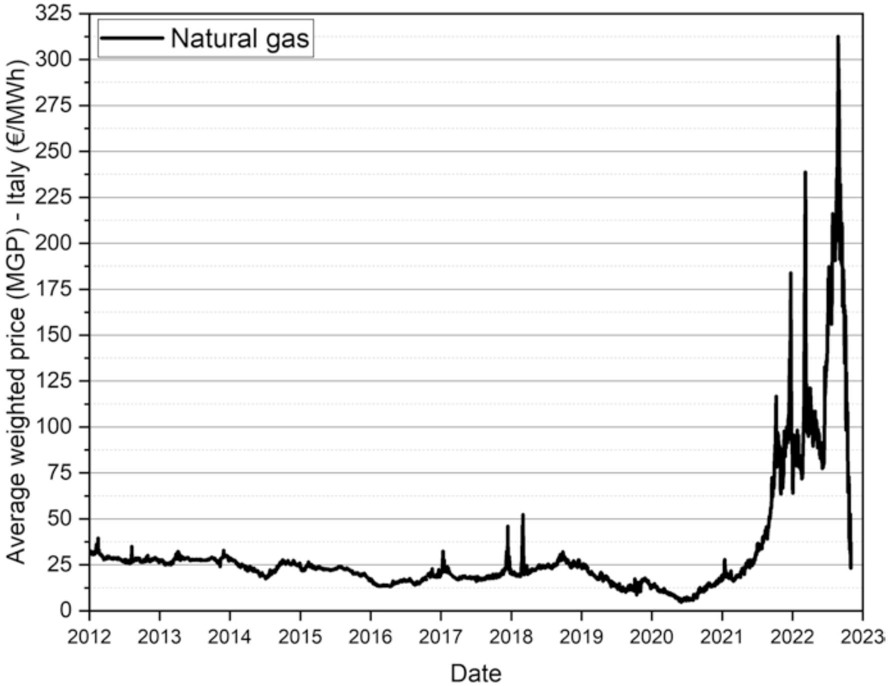

Fig. 9.9 Average weighted price of natural gas (MGP) in Italy from 01/01/2012 to 31/10/2022 [58]

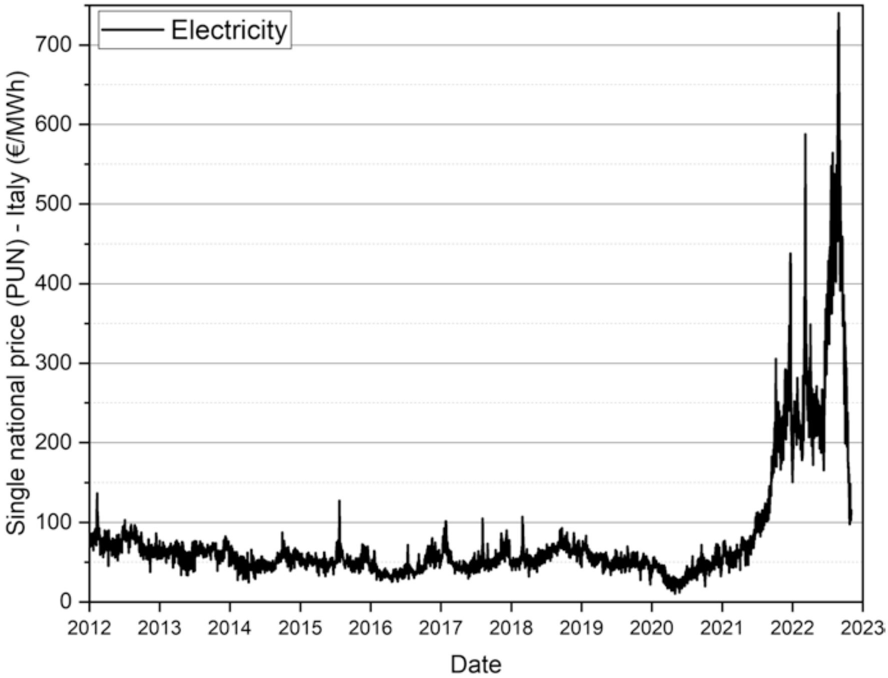

Fig. 9.10 Single national price (PUN) of electricity in Italy from 01/01/2012 to 31/10/2022 [59]

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

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

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

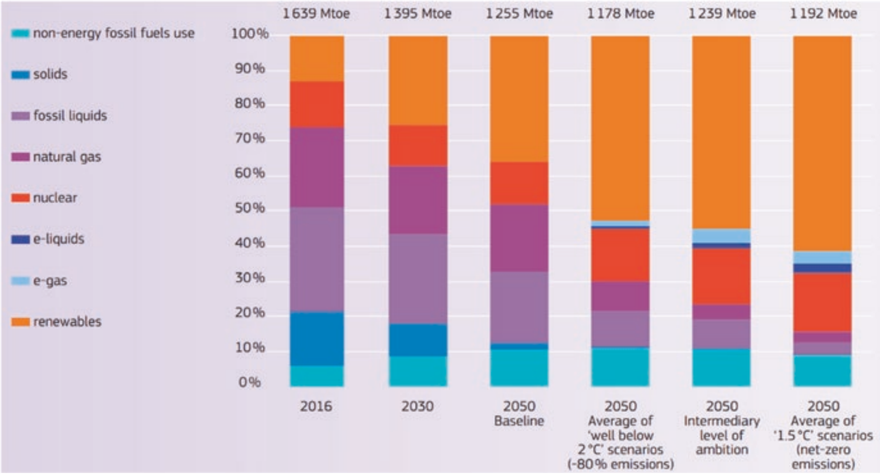

Fig. 9.11 Gross inland consumption of energy in the EU [35]

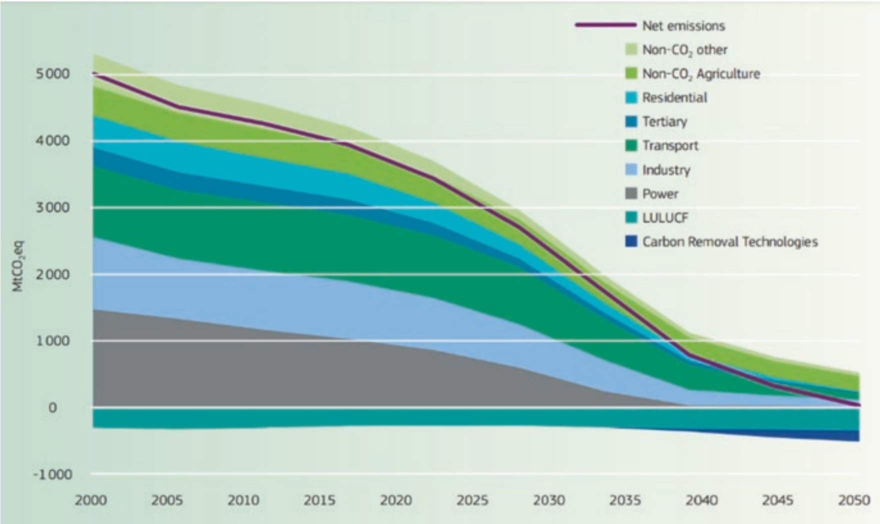

Fig. 9.12 GHG emissions in EU by sector with projection up to 2050 [35]

9.3 Energy Storage Technologies

The need for the reduction of CO_2 emissions and the increasing awareness of the limits of non-renewable energy resources has stimulated the demand for renewable energies [65, 66]. Solar energy is the largest energy source on Earth since the energy that Earth receives from the sun is around 10,000 times higher than the total energy demand. Several technologies are used to convert solar energy into other energy sources, in particular [67–69]:

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

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

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

oxidation of metals with water and liberation of hydrogen, and (iv) complex compounds ($[AlH_4]^-$ or $[BH_4]^-$) [76, 77].

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

9.4 Thermal Energy Storage for Building Applications

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

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

9.4.1 Sensible Heat Storage

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

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

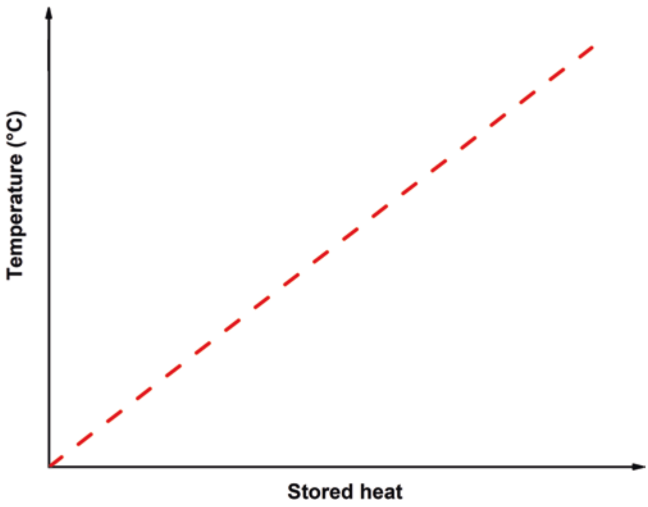

Fig. 9.13 SHS behavior during temperature change

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

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

using water as SHS medium, able to satisfy at least 50% of the annual heat energy demand of buildings using solar energy [83]. In Sweden, a house with a living space of 240 m^2 was equipped with a solar collector area of 50 m^2 [53] connected to a 200,000 liters storage tank. The solar system provides a power of around 35–40 kW, able to heat water during the summer period up to 90 °C. The heat pump of the heating systems is supplied with hot water that is able to cover almost the entire annual energy demand of the building [84]. During the summer period, hot water from solar collectors is charged into the top of the water tank. The stored thermal energy is then recovered by removing the hot water from the upper part of the tank, which is replaced by cold water entering the lower part. The efficiency of the energy storage process strongly depends on the thermal stratification occurring within the tank due to the density difference between hot water, accumulated at the top, and cold water, accumulated at the bottom. The thermal stratification is influenced by several factors, such as the tank geometry, the design of the inlet and outlet valves, and the operating conditions. The highest the stratification, the highest the hot water volume and the highest the efficiency of the system [66].

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

3000 m^2, composed of 31 apartments and 1 office [85]. The considered solutions were:

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

They observed that solution D (followed by B) is the best one in terms of costs, both for cold and hot climates. In terms of CO_2 emissions, solutions B and D are equivalent in the case of cold climates, while solution B is much better in the case of hot climates due to the larger quantity of electricity fed into the grid. It was estimated that solution D, with respect to solution A, in the case of cold climates, allows a reduction of costs and CO_2 emissions of around 60% [85].

9.4.2 Latent Heat Storage

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

9.4.2.1 Phase Change Materials

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

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

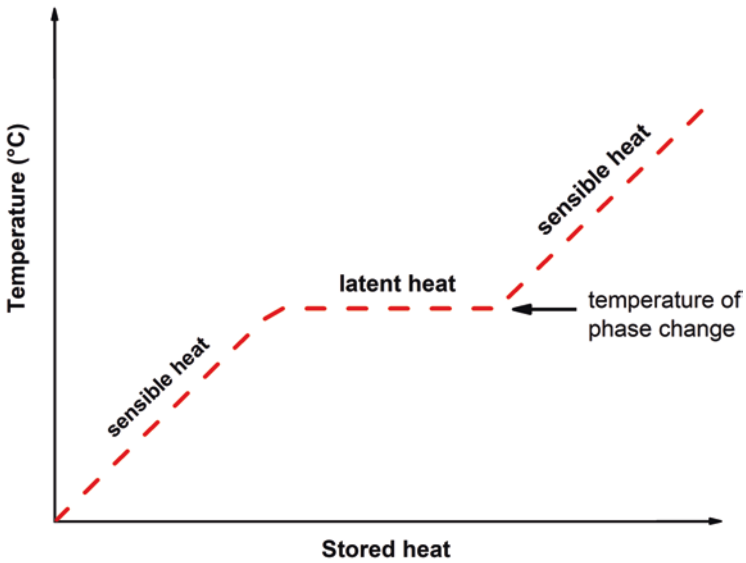

Fig. 9.14 LHS behavior during temperature change

Table 9.2 Properties of some PCMs [86–91]

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

[a]Properties referred to most common alloys (gallium, bismuth, and aluminum)
[b]Price taken from manufacturers according to quotations available to the author

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

Saturated fatty acids are bio-based organic PCMs such as capric acid [$CH_3(CH_2)_8$ COOH], lauric acid [$CH_3(CH_2)_{10}COOH$], myristic acid [$CH_3(CH_2)_{12}COOH$], palmitic acid [$CH_3(CH_2)_{14}COOH$], and stearic acid [$CH_3(CH_2)_{16}COOH$] [97, 98]. Fatty alcohols can be synthesized from the triglycerides (fatty acid triesters), and the resulting methyl esters are then hydrogenated to give fatty alcohols. Various vegetable oils and animal fats are traditional sources of fatty alcohols [99].

Polyethylene glycol (PEG) is a polymer with the chemical formula $H\text{-}(O\text{-}CH_2\text{-}CH_2)_n\text{-}OH$, widely studied due to its high melting enthalpy, congruent melting, non-toxicity, hydrophilicity, and biodegradability. The phase change properties of PEG depend on the molecular weight that ranges from 400 Da (melting point around 4 °C) to 10^6 Da (melting point around 70 °C) [86, 100–102].

Salt hydrates are mixtures of salts and water forming a crystalline solid. The solid–liquid phase change of salt hydrates is a dehydration/hydration of the salt that decomposes into an anhydrous salt and water. The main problem related to salt hydrates is the incongruent melting due to the segregation of the anhydrous salt at the bottom of the container and the consequent hindrance of the hydration process. Examples of salt hydrates are $CaCl_2 \cdot 12H_2O$, $LiNO_3 \cdot 2H_2O$, $FeCl_3 \cdot 6H_2O$, $Ca(NO_3) \cdot 4H_2O$, $Ca(NO_3)_2 \cdot 3H_2O$, $Al(NO_3)_2 \cdot 9H_2O$, $MgCl_2 \cdot 6H_2O$, and many others [92].

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

Eutectic mixtures are PCMs constituted by two or more components able to melt and freeze congruently without segregation. Their properties can be therefore adjusted for specific applications. Examples of eutectic mixtures are triethylolethane + water + urea (melting point at 13.4 °C, latent heat of 160 J/g), $CH_3COONa \cdot 3H_2O$ + NH_2CONH_2 (melting point at 52 °C, latent heat of 125 J/g), $Mg(NO_3)_3 \cdot 6H_2O$ + NH_4NO_3 (melting point at 59 °C, latent heat of 132 J/g), $Mg(NO_3)_3 \cdot 6H_2O$ + $MgCl_2 \cdot 6H_2O$ and $Mg(NO_3)_2 \cdot 6H_2O$ + $MgBr_2 \cdot 6H_2O$ (melting point at 66 °C, latent heat of 168 J/g) [92].

9.4.2.1.1 Applications

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

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

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

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

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

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

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

In the case of building applications, commercial products are present on the market with the name of *heat battery*, which store solar energy in a tank filled with a PCM with a melting point of 58 °C. The system, available with storage capacities from 3.5 to 14 kWh, can be used both for the production of hot water and heat thanks to the integration of an electric heater that works in the case of necessity [113]. Similar products, but with storage capacities from 25 to 50 kWh, are also available and can be designed for cooling or heating applications, depending on the geographical area of the building. The storage tanks range from 700 to 1500 kg of PCM [114].

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

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

9.4.2.2 Encapsulation and Shape Stabilization

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

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

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

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

9.4.3 Thermochemical Heat Storage

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

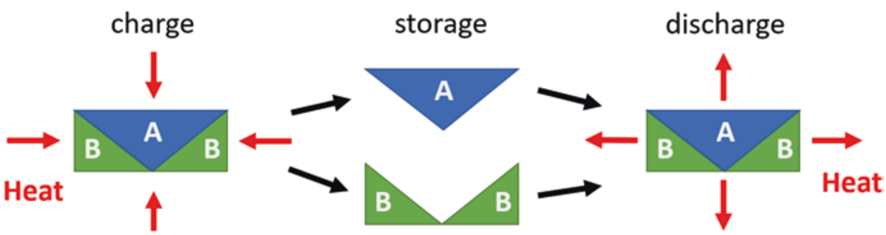

Fig. 9.15 Thermochemical heat storage process

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

Material	Density [g/cm^3]	Theoretical energy storage [kJ/kg]	Cost [€/kg]
$MgSO_4 \cdot 7H_2O/MgSO_4 \cdot 0.1H_2O$	~1.33	2500	~8.7
$MgCl_2$	~1.56	794	0.18
$Na_2S \cdot 5H_2O/Na_2S \cdot 1/2H_2O$	~0.93	2900	~0.6
$CaCl_2$	~1.84	836	0.3
Zeolites 13X	~0.74	535	~2.5
Microporous silica gel	~0.71	127	~18

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

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

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

Another application was based on the use of 400 kg of $SrBr_2$ in a modular system with a power of around 1.5 kW. The system was tested for several months and a strong influence of the working parameters (moisture content of inlet air, temperature, pressure) on the reactor performance was reported by Michel et al. [148].

Mauran et al. tested a chemical heat pump based on $SrBr_2$ with expanded natural graphite as support material. The system contained 1 m^3 of THS material and a power of around 2.5 kW. Different working conditions were tested in order to optimize the system and the positive effect of having a high ratio of reagent volume over the reactor volume was pointed out [149].

9.5 Conclusions and Future Perspectives

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

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

Thermal energy storage (TES) is a very promising technology since the energy that Earth receives from the sun is around 10,000 times higher than the total energy demand. TES may allow the accumulation of heat during the hot season to satisfy the heat demand during the entire cold season. Moreover, the use of insulating materials with TES capability may result in the compensation of energy absorption peaks caused by air conditioning or by space heating with a consequent reduction of energy consumption and related CO_2 emissions. Commercial technologies based on sensible-heat TES, consisting of solar collectors to heat-up water and of a storage system, allow satisfying at least 50% of the annual energy demand of buildings using solar energy. Similarly, the latent-heat TES can be used in PCM-based solar collectors (the so-called heat batteries) to store thermal energy from the sun with a significant volume reduction of the storing system compared to the sensible-heat TES. Latent-heat TES can also be used for the production of insulating panels to increase the storage capacity of the walls allowing the reduction of the energy demand of the investigated buildings by approx. 30%.

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Chapter 10
Introduction and Literature Review of the Application of Hydronic-Based Radiant Cooling Systems in Sustainable Buildings

Deok-Oh Woo and Lars Junghans

Abstract Hydronic-based radiant cooling systems have been widely utilized for their energy efficiency and offering more thermal comfort for occupants when compared to conventional convection-based cooling systems. However, the potential risk of developing condensation on the surface keeps thermo-active building systems (TABS) from being applied in buildings located in warm and humid climate regions. This chapter presents a model predictive control (MPC)-based condensation prevention approach that allows the prevention of surface condensation during the cooling periods when the TABS is in operation. Based on future conditions predicted by the dynamic models, the MPC-based condensation prevention framework adjusts the surface temperature for the TABS in ways that guarantee occupant thermal comfort and energy efficiency without the development of surface condensation.

10.1 Introduction

To accomplish the energy-efficient heating or cooling technologies in buildings, occupants' comfort should not be compromised with minimum energy input to the systems. Based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 55 [1], thermal comfort for a person is defined as *a condition of mind that expresses satisfaction with the thermal*

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environment. Generally, there are six comfort parameters that are widely accepted for determining the indoor thermal comfort for occupants: (1) air temperature, (2) mean radiant temperature, (3) air velocity, (4) vapor pressure in ambient air, (5) activity level, and (6) thermal resistance of clothing.

Among these parameters, air temperature, mean radiant temperature, air velocity, and partial vapor pressure in ambient air can be relatively easily controlled with heating or cooling technologies. However, in many cases, heating or cooling technologies are operated based on ambient air conditions only, disregarding the impacts of indoor surface radiant temperature [2]. When we disregard the impact of indoor surface radiant temperature on thermal comfort, occupants may experience discomfort conditions like radiant asymmetry [3]. People are likely to be more sensitive to asymmetry caused by an overhead warm surface than a cold surface. This leads to facts that: (1) both air temperature and indoor surface radiant temperature should be considered altogether to provide better occupants' thermal comfort, and (2) there is energy savings potential of utilizing surface radiant cooling systems on the ceiling side.

Over the past few decades, a number of cooling technologies have been examined to save buildings' cooling energy. One of the most promising strategies is to flow cold water directly through the construction layer and use these cold surfaces as a radiant cooling device to reduce the cooling load for multi-story buildings [4]. The radiant cooling system refers to using cooled shells or construction layers to remove sensible indoor heat by thermal radiation. The radiant cooling systems can be classified into non-hydronic-based systems (or air-based systems) and hydronic-based systems based on what medium they utilize. Among these two systems, the hydronic-based radiant cooling system is considered more energy-efficient because of its less transport energy input than the non-hydronic-based system. This is because, given the same volume, water has much more thermal capacity to deliver heat energy than air, leading to significant transport energy savings for hydronic-based systems than air-based systems [5].

Figure 10.1 shows a schematic comparison between forced air-based cooling systems and hydronic-based radiant cooling systems. Hydronic-based radiant cooling systems have the following advantages compared to conventional forced air-based cooling systems. First, the relatively high heat capacity of water brings the hydronic-based radiant cooling system to have a smaller distribution system size, such as piping. In general, 10-mm radius water pipes are installed within or adjacent to the radiant cooling systems at intervals of 150–200 mm [6]. On the contrary, the forced air-based systems take a larger volume of system ductwork in order to deliver the same amount of thermal energy. This small space required for a hydronic-based radiant cooling distribution system can bring greater flexibility in the architectural design practice. Therefore, many designers and planners adopted hydronic-based radiant cooling systems in many multi-story building projects to bring more freedom to the design decision process [6].

Second, the radiant cooling systems can lead to significant energy savings by isolating the control for cooling (thermal comfort control) and ventilation (indoor air quality control) [7]. In the forced air-based cooling systems, the total amount of

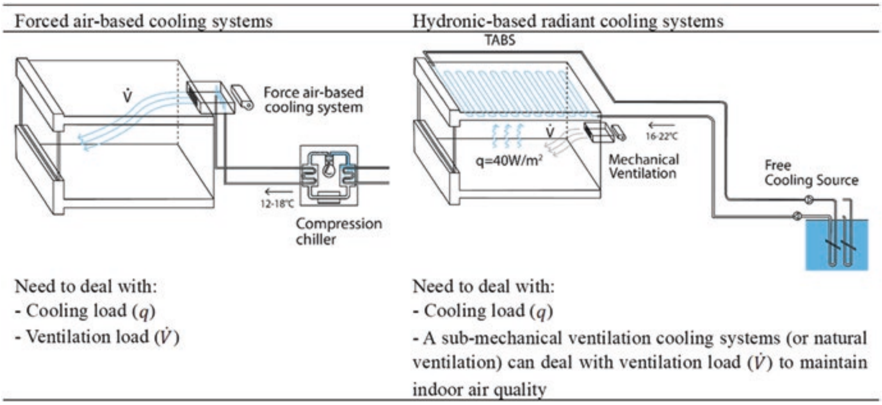


Fig. 10.1 Comparison between air-based cooling systems and hydronic-based radiant cooling systems

air conditioning is decided considering both cooling load and ventilation demand. However, the calculated supply air amount derived from the cooling demand and ventilation demand is rarely equal [6]; this discrepancy can lead to a redundant energy input for air conditioning and fan energy of the forced air-based cooling systems. Potentially, it is true that some amount of power for air conditioning can be reduced by recirculating the conditioned air within the air-based cooling systems. Still, this air recirculation strategy is not applicable for multi-story buildings with a large occupant density because most of the returned air needs to be replaced or mixed with the outdoor air to keep an acceptable indoor air quality [5].

In contrast, the radiant cooling systems allow a precise control for both cooling and ventilation by separating each other. In general, the radiant cooling systems are coupled with a sub-mechanical ventilation cooling system, such as dedicated outdoor air system (DOAS) [6]; the most of sensible cooling load is dealt with the radiant cooling systems while the rest of the cooling load and ventilation load is controlled by the sub-mechanical ventilation cooling systems. This separation in cooling and ventilation functions within the system will allow more accurate control for cooling demand and ventilation demand, thus enabling overall energy savings [5].

Third, when these radiant cooling systems are combined with the sub-mechanical ventilation cooling systems, a higher level of thermal comfort can be provided to the occupants. As mentioned above, six parameters impact human thermal comfort [8]: (1) air temperature, (2) mean radiant temperature, (3) air velocity, (4) vapor pressure in ambient air, (5) activity level, and (6) thermal resistance of clothing. Besides two personal factors (activity level and thermal resistance of clothing), the other four elements can be controlled by the cooling system to achieve a higher thermal comfort level. Conventional forced air-based cooling systems only can deal with three of these factors, ignoring the radiant temperature. Disregarding the impact of radiant temperature on thermal comfort may result in occupants' uncomfortable conditions, such as cold draft or radiant asymmetry. For example, when lightly clothed occupants are working in front of the desk under moderate indoor airspeed (<0.2 m/s), they tend to exchange more of their sensible heat through radiation than convection [6]. Therefore, when the radiant cooling systems are coupled with the sub-mechanical ventilation cooling systems, they can deal with the sensible and latent cooling load and control the radiant surface temperature, thus creating truly comfortable indoor environments for the occupants [5].

Fourth, hydronic-based radiant cooling systems can be operated more energy-efficiently than conventional forced air-based cooling systems because of their effective ways of exchanging heat through the surface radiant cooling effect [6]. Because heat exchange through radiation is more dominant than convection under the same cooling energy input [6], a feed water temperature for radiant cooling systems can be much closer to set point or room air temperature than a supply air temperature for the forced air-based system to bring the similar cooling effect to the occupants. For example, when the major source of cooling is from the vapor compression refrigeration cycle, by having the supply water temperature (from the evaporator side) close to the temperature of the condenser side where waste heat is emitted, the coefficient of performance (COP) for the chillers or heat pumps can be increased significantly [9]. In addition to that, when this condenser side is connected to a free heat sink such as a ground source loop or a cooling tower, which can be cooled down by nighttime colder outdoor air temperature, the COP for the chillers can be increased tremendously [5].

Typically, three types of hydronic-based radiant cooling systems have been identified (Fig. 10.2): radiant cooling panels, embedded surface cooling systems, and thermo-active building systems (TABSs) or thermo-active components [10]. The radiant cooling panels are composed of suspended metal panels that produce cold surfaces to exchange indoor heat by radiation. The cold surface temperature can be generated by water pipes laid on the metal panels. The embedded surface cooling system exchanges heat through the embedded water pipes within gypsum board layers, but it is insulated from the building construction layer. The thermo-active building systems (TABSs) or thermo-active components, on the other hand, flow chilled water directly through the water pipes embedded in construction layers for providing radiant cooling effect to occupants [11].

Among these three types of hydronic-based radiant cooling systems, the TABS can only exploit the thermal storage effect significantly better over the other systems by cooling down the construction layers (e.g., concrete slab) directly. The construction layers with massive material of TABS are usually pre-cooled with nighttime cooling sources (e.g., outdoor air or groundwater sources nearby) a few hours ahead

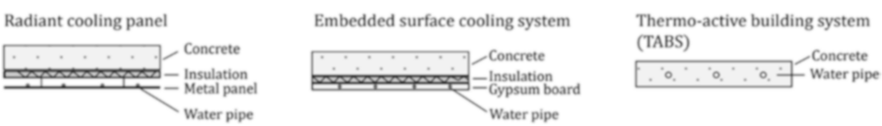


Fig. 10.2 Three types of hydronic-based radiant cooling systems

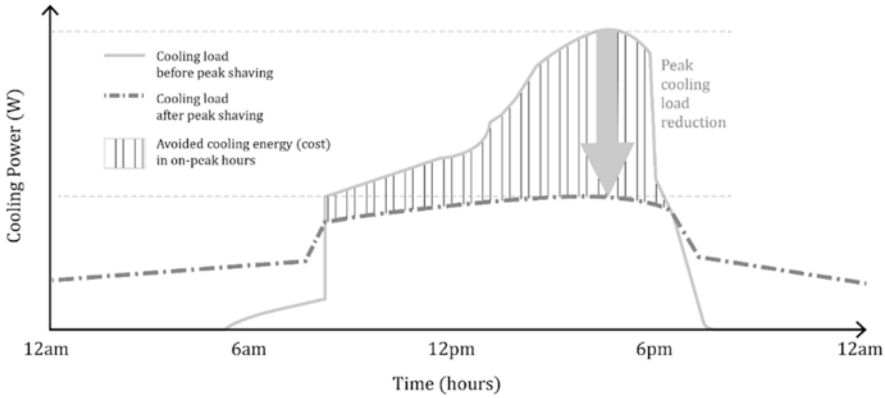


Fig. 10.3 Peak shaving with TABS

of occupancy to cope with rapidly increasing cooling load for incoming daytime hours. Later, this heat stored within the heavy construction layers of TABS during the daytime can be kept beyond the time of occupancy and is then cooled down by the nighttime free cooling sources (outdoor air or ground sources nearby) or can be cooled down during the less expensive operational cost period (Fig. 10.3). Therefore, both the peak cooling load and the operating cost for cooling can be reduced overall [12].

Besides the thermal storage effect of TABS, the low first cost for TABS is another intriguing advantage [9]. Because TABS only requires the installation of pipes or tubes inside the concrete layers, initial installation costs for new construction buildings are considered more cost-effective than the upfront cost for conventional forced air-based cooling systems (Fig. 10.4).

When utilizing the TABS in cooling mode, the following should be considered. First, the installation of TABS on the load-bearing structural systems should be avoided [7]. The TABS should be installed in less load-bearing areas because hollow pipes or tubes do not have enough load-bearing capability. Second, designers or engineers should take acoustic issues into consideration. Installing noise buffers underneath the TABS can reduce the potential noise problems that can be caused by the sound of flowing water through the embedded water pipes or tubes [5].

10.2 Thermo-Active Building Systems in Buildings

By the beginning of this century, thermo-active building systems (TABSs) are gaining more technological momentum and attention because of the significant cost-saving potential and providing high occupant thermal satisfaction level. Thus, the TABS has been widely utilized for cooling especially in multi-story buildings in central Europe (Switzerland, Germany, Austria, etc.) and started to spread out to North America and Asia partly [9].

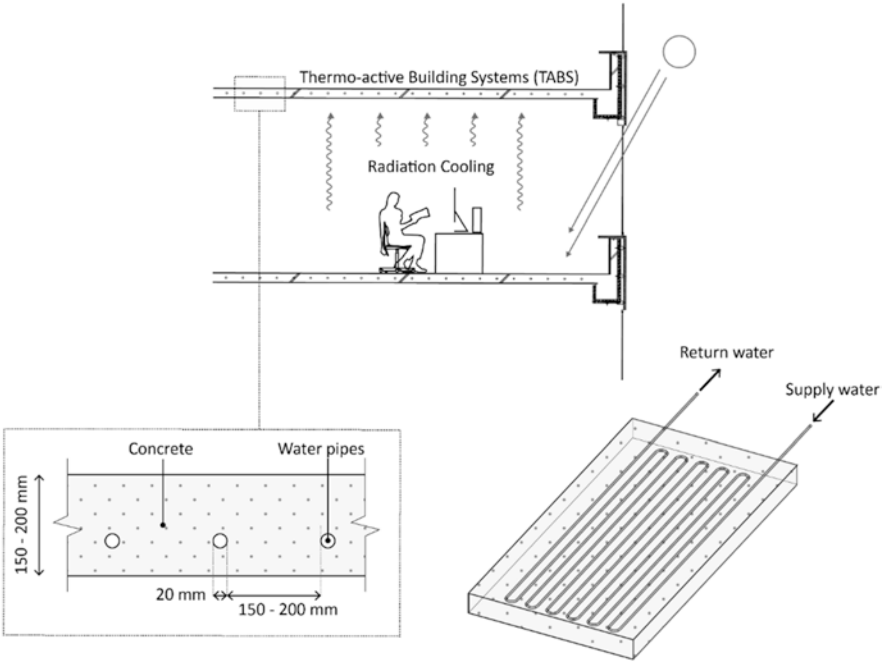


Fig. 10.4 Configuration diagram of the water pipe-embedded TABS and its operation on the ceiling

Starting from the 1990s, many practitioners and architects in Europe adopted TABS as the major cooling system for their projects. In Germany, the TABS is also one of the most widely used cooling systems for multi-story buildings. The Zollverein School of Management and Design, located in Essen, is a good precedent that resolved its design challenge by integrating TABS. The building was designed by the renowned Japanese architectural firm SANAA. This project's main challenge was to achieve the passive house standard for the building envelopes. To achieve this strict passive house standard, thick wall construction and a significant amount of insulation were required, which was quite not a favorable design condition for the team because indoor spaces would be compromised, and first cost for insulation would increase. Instead of having a massive amount of insulation materials, the engineers suggested integrating TABS with a free source of heating and cooling. For the heating purpose, the engineers designed the system to be able to pump up reused heated water from the 1000-m-deep mine shafts; in cooling mode, the cooling tower produced cold water by exchanging heat with cold nighttime outdoor air temperature. By using the free source of heating and cooling for the TABS, the thickness of building envelopes could remain at regular thickness as the designer initially wanted. Compared to the forced air-based HVAC systems, a significant amount of heating and cooling energy savings was achieved thanks to the

TABS. According to [13], the installation cost of TABS for heating and cooling systems was one-third of conventional forced air-based systems [5].

As the energy and cost savings potential of the TABS has been proven throughout many projects in central Europe, newly built building projects in North America started to adopt the TABS as a major cooling system. The Fred Kaiser building at the University of British Columbia, located in Vancouver, is a multi-story building that integrated the TABS for both heating and cooling. A cooling tower at the rooftop produces cold water from the nighttime cold outdoor temperature; the produced cold water is then distributed to each room for the purpose of cooling. The building could save more than 50% of energy compared to Canadian building code, thanks to the TABS [13].

10.3 Thermo-Active Building Systems' Challenge: Surface Condensation

As discussed earlier, thermo-active building systems (TABSs) have been successfully utilized in buildings in central Europe and partly in North America for their energy efficiency as well as providing higher levels of thermal comfort for occupants. Although the TABS has proven to be a promising cooling technology and has been widely utilized in Central Europe and partly in North America, building industries in rest regions still hesitate to accept the TABS for cooling, especially in warm and humid climatic regions [6]. This is because the radiant cooling systems, including the TABS, do not have the capability to handle moisture content in the air. Generally, this moisture content or latent load can only be controlled by dehumidifier or sub-mechanical cooling systems, such as a dedicated outdoor air system (DOAS). Therefore, in the worst case scenario, surface condensation can occur when TABS is utilized in areas with humid summer seasons. The green shaded areas in Fig. 10.5 indicate the climatic regions where TABSs have been widely used; the red highlighted regions in Fig. 10.5 represent the climatic regions with a high risk of developing surface condensation while TABS is in operation. These red-shaded areas can also be classified as "Group A: Tropical climates" under the Koppen climate classification with warm and humid summer seasons [5].

Because of this potential risk of occurring surface condensation, radiant cooling systems, including the TABS, are not recommended in the regions with warm and humid summer (red shaded areas in Fig. 10.5). For example, Crown Hall in Chicago requires an automated dehumidification system or dedicated outdoor air system (DOAS) in addition to the radiant cooling panels to prevent surface condensation. Without the dehumidification process, a great amount of moisture coming from Lake Michigan would encounter the cooling panels' cold surface, leading to surface condensation development. As shown in Table 10.1, most of the buildings that adopted TABS are located in climatic regions with less humid summer; the rest are located in areas with warm and often humid summer seasons [5].

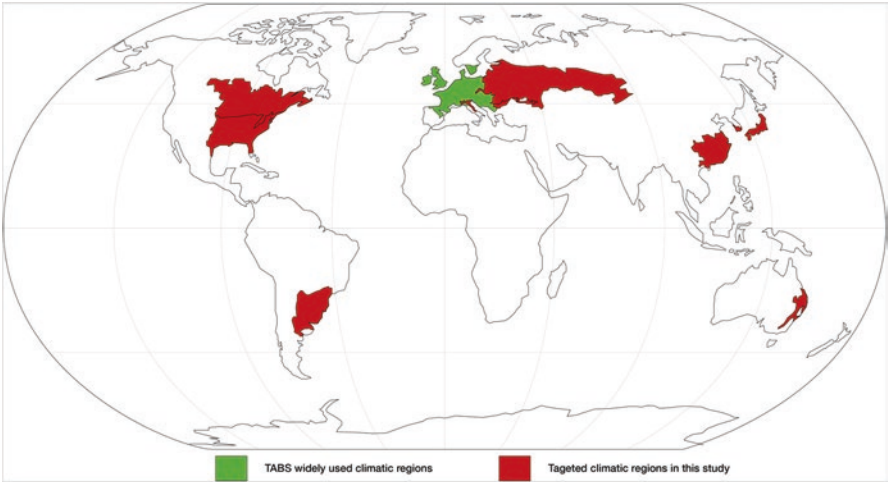


Fig. 10.5 TABS condensation safe climatic regions vs. TABS condensation high-risk regions

When the surface condensation sneaks into internal building construction layers and this interstitial moisture cannot escape from the building construction layers and accumulates, moisture starts to collect and cause moisture-related problems, including corrosion of the building fabric, deterioration of insulation, etc. [14]. Mold is the most critical of these problems (Fig. 10.6). Based on [15], under ideal conditions (optimal temperature and level of humidity), it takes 24–48 hours for mold to germinate and grow [16]. Suppose this mold growth continues for a certain period. In that case, the building construction layers will decay, or in some cases, the mold can extend to interior surfaces, which can lead to occupants' health problems, such as allergic rhinitis. Due to these condensation-driven problems, the potential risk of developing surface condensation keeps thermo-active building systems (TABSs) from being widely adopted in buildings situated in partly warm and humid climate regions [5].

In summary, thermo-active buildings systems (TABSs) are a promising cooling technology in reducing energy demand and providing better thermal comfort for occupants; however, the potential risk of occurring surface condensation on the TABS surface prevents the system to be adopted widely under partly warm and humid climatic regions. Without resolving these surface condensation risks on the TABS, designers and planners will hesitate to adopt the TABS as a primary cooling system for their projects.

Table 10.1 List of TABS-applied buildings with climatic regions

	Project	Location	Climate classification (Koppen Geiger)	Condition in summer
1	Charles Hostler Student Recreation Center	Beirut, Lebanon	Csa, Mediterranean climate	Dry
2	Dolce Vita Tejo	Lisbon, Portugal	Csa, Mediterranean climate	Dry
3	IDOM Company Headquarters	Madrid, Spain	Csa, Mediterranean climate	Dry
4	Fred Kaiser Building	Vancouver, Canada	Csb, Mediterranean climate	Warm and dry
5	Euromed Clinic	Furth, Germany	Cfb, Oceanic climate	Mild
6	Semmelweis Medical University	Budapest, Hungary	Cfb, Oceanic climate	Mild
7	Zollverein School	Essen, German	Cfb, Oceanic climate	Mild
8	Südwestmetall Office Building	Heilbronn, Germany	Cfb, Oceanic climate	Mild
9	Dauerhaft Wandelbar	Stuttgart, Germany	Cfb, Oceanic climate	Mild
10	Wohnhaus	Basel, Switzerland	Cfb, Oceanic climate	Mild
11	Middelfart Savings Bank	Middelfart, Denmark	Cfb, Oceanic climate	Mild
12	Opera House in Copenhagen	Copenhagen, Denmark	Cfb, Oceanic climate	Mild
13	BMW World	Munich, Germany	Cfb, Oceanic climate	Mild
14	Balanced Office Building	Aachen, Germany	Cfb, Oceanic climate	Mild
15	Viborg Town Hall	Viborg, Denmark	Cfb, Oceanic climate	Mild
16	Klarchek Information Commons	Chicago, Illinois, USA	Dfa, Humid continental climate	Warm and often humid
17	Crown Hall	Chicago, Illinois, USA	Dfa, Humid continental climate	Warm and often humid
18	Cooper Union New York	Manhattan, New York, USA	Dfa, Humid continental climate	Warm and often humid
19	Kripalu Housing Tower	Stockbridge, Massachusetts, USA	Dfb, Humid continental climate	Warm and often humid
20	The Terrence Donnelly Center	Toronto, Canada	Dfb, Humid continental climate	Warm and often humid
21	Dockland Offices	Hamburg, Germany	Dfb, Humid continental climate	Warm and often humid
22	Berliner Bogen Offices	Hamburg, Germany	Dfb, Humid continental climate	Warm and often humid
23	Mercedes World	Berlin, Germany	Dfb, Humid continental climate	Warm and often humid
24	Linked Hybrid	Beijing, China	Dwa, Humid continental climate	Hot and often humid

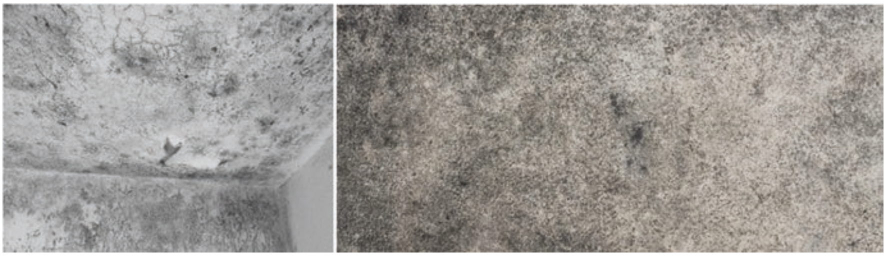


Fig. 10.6 The condensation occurrence and the resultant mold growth on the concrete surfaces

10.3.1 Moisture Movement in Building Construction Layers

While controlling heat transfer through the building envelopes has been the major concern for reducing building cooling and heating energy demand over the past few decades, a moisture-driven problem within the building construction layers has relatively less been considered [17]. The source of this problem is that as designers target increased insulation of the building envelope to achieve higher thermal resistance, there will be an increased temperature differential between the inner and outer portions of the walls; depending on the climate, the inner portion of the wall may get warmer but, at the same time, the outer part will get much colder, or vice versa [18]. Temperature differences in these walls affect the flow of moisture in the wall, a moisture transport process in both vapor and liquid phases, which can lead to interstitial condensation. Thus, special care and attention are required when designers select material and construction layers in envelope systems.

There are mainly four moisture movement mechanisms where the surface condensation development can damage building construction layers: (1) liquid flow by gravity or an air pressure difference, (2) capillary suction through porous materials, (3) air movement, and (4) vapor diffusion. Any moisture-related problem is a consequence of one or a combination of the above-mentioned four mechanisms. The liquid flow is responsible for moving moisture into the building construction layers from the outdoor caused by gravity or an air pressure differential. Capillary suction is a combined effect of the pore size in building construction layers and condensation existence next to it. If the pore size in the construction layers is too small, like concrete material, capillary suction can occur. The moisture can also penetrate the construction layers with air movement. When a crack or gap exists in the construction layers, the infiltration can bring moisture into the layers, which can cause damage to the construction material eventually. Vapor diffusion is the moisture movement in the vapor state through construction layers. This process is driven by a function of the vapor permeabilities of materials and the vapor pressure differential posed across the construction layers. During the vapor diffusion process, when the partial vapor pressure reaches the saturation level, moisture starts to condense within the construction layers [5].

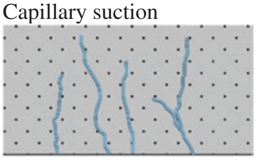
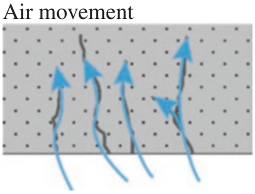
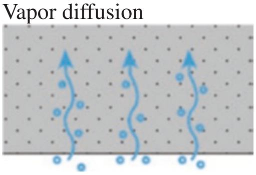
Considering TABS is generally installed on the ceiling side of indoors, the mechanism of liquid flow caused by gravity or an air pressure difference can be disregarded for surface condensation problems of the TABS. Therefore, capillary suction through porous materials, air movement, and vapor diffusion are the three mechanisms of moisture movement that need to be controlled to prevent surface condensation while the TABS is in operation (Table 10.2).

Capillary suction brings moisture into porous materials mainly. If the pore size in a material is small enough (e.g., concrete, silty clay, etc.), the capillary suction occurs. Capillary suction never occurs in material without pores (e.g., glass, steel, plastics, etc.) [5].

In general, capillary suction can be controlled by blocking off the capillary moisture or selecting relatively large pore size of the building construction materials. Capillary suction can also be prevented by sealing the connections between materials using caulking joints or providing the links wide enough not to cause capillary effect [5].

Air movement mechanisms can transport moisture into building construction layers both from the conditioned indoor space and the exterior. Following three conditions should be satisfied to let moisture into the building construction layers with an air movement mechanism: (1) moist air should exist, (2) a gap or an opening exists in the building construction layers, and (3) an air pressure difference occurs across space in the building construction layers [5].

Table 10.2 Three mechanisms of moisture movement while TABS operation

Moisture transfer pathways	Description
Capillary suction 	Capillary suction is a combined effect of the pore size in building construction layers and condensation existence nearby. If the pore size in the construction layers is small, like concrete material, the capillary suction effect can be significant.
Air movement 	The moisture can also penetrate the construction layers via air movement. When a crack or gap exists in the construction layers, the air can bring moisture deep into the layers, which can cause severe damage to the construction material.
Vapor diffusion 	Vapor diffusion is the movement of moisture in the vapor state through construction layers.

Even if the moisture enters the building construction layers, it does not necessarily deposit along with the building construction layers; the air movement's velocity should be slow enough for the moist air to be cooled down to the dew point temperature, which in turn leads to the surface condensation development. Otherwise, the fast-flowing moist air can be maintained above the dew point. Making the building envelope airtight is one of the most effective strategies to deal with moisture transfer through the air movement mechanism [5].

Vapor diffusion is the moisture movement process in the vapor state through materials. As far as the vapor pressure difference exists between indoors and outdoors, vapor diffusion occurs. In a cold climate where a building is mainly heated, vapor diffusion typically moves moisture from the indoor conditioned room into building construction layers. In contrast, in warm weather, the vapor diffusion naturally moves moisture from the exterior into the building construction layers [5].

Considering these three potential moisture transfer pathways together, the total amount of moisture transferred from the indoor space or the exterior into the building construction layers can be computed, thus enabling the prediction in the surface condensation occurrence while TABS is in operation. With this information, the potential risk of developing surface condensation can be estimated and controlled to prevent the construction material's damage [5].

10.3.2 Dynamic Modeling of Heat and Moisture Transfer in Building Construction Layers

Fourier's law is a basis for the heat transfer model, while Fick's law and Darcy's law are used for the moisture transfer model and liquid flow model, respectively [19].

Fourier's law (for heat transfer):

$$\dot{q} = -k\frac{\partial T}{\partial x} \tag{10.1}$$

where $\dot{q}$ is the heat flux, k is the thermal conductivity of the material, T is temperature, and x is the length of the material.

Fick's law (for vapor diffusion):

$$\dot{m}_{\mathrm{v}} = -\mu\frac{\partial P_{\mathrm{v}}}{\partial x} \tag{10.2}$$

where $\dot{m}_{\mathrm{v}}$ is the mass flux for vapor, μ is the vapor permeability, and P_{v} is the water vapor pressure.

Darcy's law:

$$\dot{m}_{\mathrm{l}} = K\frac{\partial P_{\mathrm{l}}}{\partial x} \tag{10.3}$$

where $\dot{m}_l$ is the mass flux for liquid water, K is the hydraulic conductivity, and P_l is the capillary pressure.

The overall moisture balance is given by

$$\frac{\partial}{\partial x}\left(\mu \frac{\partial P_v}{\partial x}\right) - \frac{\partial}{\partial x}\left(K \frac{\partial P_l}{\partial x}\right) = \rho \frac{\partial w}{\partial t} \tag{10.4}$$

Because there is no energy generation in the system, the significant energy flows are heat conductivity and enthalpy flow via liquid water transfer and vapor transfer. Thus, the mass and energy conservations are obtained by using Fick's law, Darcy's law, and Fourier's law:

$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + h(T)\frac{\partial}{\partial x}\left(\mu \frac{\partial P_v}{\partial x}\right) = \frac{\partial T}{\partial t}\rho\left(C_{p,d} + wC_{p,l}\right) \tag{10.5}$$

Equations (10.4) and (10.5) are the governing equations; they need to be solved to predict heat and moisture transfer in building construction layers. For a numerical solution, vapor diffusion and capillary transfer equations need to be decoupled and are given as

$$\frac{\partial}{\partial x}\left(\mu \frac{\partial P_v}{\partial x}\right) = -\frac{\partial \dot{m}_v}{\partial x} = \rho \frac{\partial w_v}{\partial t} \tag{10.6.a}$$

$$\frac{\partial}{\partial x}\left(K \frac{\partial P_l}{\partial x}\right) = -\frac{\partial \dot{m}_l}{\partial x} = \rho \frac{\partial w_l}{\partial t} \tag{10.6.b}$$

$$w = w_v + w_l \tag{10.6.c}$$

$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + h(T)\frac{\partial}{\partial x}\left(\mu \frac{\partial P_v}{\partial x}\right) = \rho\left(C_{p,d} + wC_{p,l}\right)\frac{\partial T}{\partial t} \tag{10.6.d}$$

The last step for dynamic modeling of building construction layers is identifying a correlation between the surface temperature of the concrete layer and the supply water temperature for the TABS. The surface temperature for concrete materials can be calculated from a supply water temperature using Eqs. (10.7) and (10.8) [19]. When the thickness of the slab is two L, and its initial temperature of T_1 is cooled with the fluid temperature of T_∞, a numerical solution is available for the temperature T at a location and time t [20].

$$Y = Y_0 f\left(b_1 n\right) \tag{10.7}$$

where

$$Y = \frac{T - T_\infty}{T_1 - T_\infty}$$

$$Y_0 = \frac{T_0 - T_\infty}{T_1 - T_\infty} = c_1 \exp\left(-b_1{}^2 F_o\right)$$

$n = x/L$, x= a distance from the midplane of the slab of thickness $2L$ cooled on both sides,

b_1, c_1= the coefficients that are functions of the Biot number, $F_o = at/L^2$, $a= k/\rho C_{p.}$

$$f\left(b_1 n\right) = \cos\left(b_1 n\right) \qquad c_1 = \frac{4\sin\left(b_1\right)}{2b_1 + \sin\left(2b_1\right)} \tag{10.8}$$

Therefore, if we set $x = L$ and T=T_{sf}, we can calculate the surface temperature of the TABS concerning the fluid temperature.

10.3.3 Building Construction Condensation Prediction Models

Since the 1930s, numerous studies have explored ways to model heat and moisture (hygrothermal) transfer in building construction layers. Rodgers [21] was the very first to research vapor pressure as a driving potential for moisture transfer. In the study, Rogers presented the vapor pressure curves method, which shows the relative partial vapor pressure level across building construction layers. Rowley et al. [22, 23] then refined the existing work into the prevailing theory of vapor diffusion models by adopting heat conduction principles. Vos and Coleman [24] further developed the models by attesting the combined effect of vapor diffusion and capillary suction on moisture transfer. Later, Künzel and Grosskinsky [25] identified air transport as an additional driving potential for moisture transfer. The Luikov model [26] and the Philip and de Vries model [27] are the most widely used hygrothermal transfer models; these adopt the temperature and the moisture content as driving potentials. However, taking the moisture content as the moisture transfer potential sometimes makes the models challenging because the moisture content level is not always continuous across the building construction layers [28]. Therefore, Y. Liu et al. [29] proposed the constant relative humidity instead of the moisture content as the driving potential for moisture transfer to deal with this problem. With these modifications, the researchers have developed the hygrothermal transfer models in a way that incorporates the three hygrothermal pathways in building construction layers while simplifying the solution for the models by adopting continuous parameters. The results provided by the models predict short-term condensation with reasonable accuracy in building construction layers.

Despite their usefulness, these models are not directly applicable for controlling the surface condensation of TABS for two reasons. First, a short-term condensation prediction from the existing model is insufficient for dealing with dynamic indoor condition changes. Indoor conditions do not remain stable but fluctuate according to daily weather changes [30]. Because of this dynamic indoor condition change, the risk of surface condensation sometimes can increase rapidly, which in turn can lead to a sudden development of surface condensation, even though the model has calculated the ongoing risk. Second, the model's short-term condensation estimation can sometimes cause severe prediction errors for buildings with heavy construction materials like concrete. The hygrothermal transfer rate of building construction layers is delayed due to the construction materials' high heat capacity; this time delay can sometimes last up to almost half a day. Because of less accurate condensation prediction caused by the slow and gradual hygrothermal transfer in heavy construction materials, direct application of these models can be inadequate for enabling a system to control surface condensation.

Thus, given the dynamic daily fluctuation in indoor conditions and the time delay in the hygrothermal response of heavy concrete materials, an estimation that anticipates the surface condensation at least a few hours ahead is required for more accurate surface condensation control. With a few hours-ahead assessment, both the indoor condition changes and the time delay in the hygrothermal transfer can be considered altogether in advance, providing a more accurate condensation prediction for the system to make a better decision.

10.3.4 Model Predictive Control-Based Condensation Prediction

A promising approach for surface condensation control is model predictive control (MPC) among rigid control approaches. In contrast to other rule-based controllers, such as two-position or modulating controls, MPC determines the input signal for the system not based on just the current states but also on the impact the actions will have on the future conditions (Fig. 10.7). Because MPC considers both current states and future states, it is suitable for anticipatory surface condensation control capable of dealing with dynamic indoor condition changes and the time delay in hygrothermal transfer in advance [14].

The classical objective function utilized by the MPC is given as [31]

$$J(t_k) = \sum_{i=N_1}^{N_y} \mathbf{w}_y(i)\left[\hat{y}(t_k+i) - y_{\text{set}}(t_k+i)\right]^2 + \sum_{i=N_1}^{N_u} \mathbf{w}_u(i)\left[u(t_k+i) - u(t_k+i-1)\right]^2 \tag{10.9}$$

where

t_k = control time-step
y_{set} = set point, $\hat{y}$ = predicted output
u = command effort

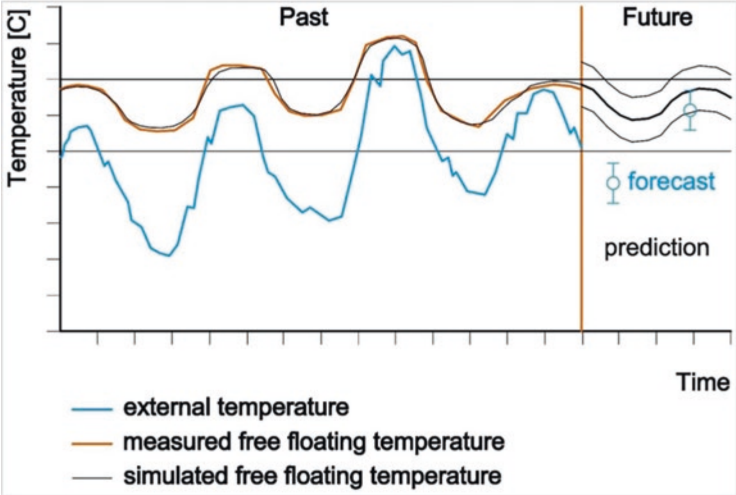


Fig. 10.7 Conceptual diagram of model predictive control for temperature

N_y = the prediction horizon where the output error
$\hat{y} - y_{set}$ is minimized
N_u = the control horizon where the effort increment is minimized
ω_y = weighting factor for prediction error
ω_u = weighting factor for command effort

An initial application of the MPC started in the late 1970s in the process industries in chemical plants and oil refineries [32]. Since then, the MPC has been adopted in autoclave composite processing, wastewater treatment, automotive industry, etc. In autoclave composite processing, the MPC is assumed to define an optimal input to determine a bagging procedure and a cure cycle that assures cost efficiency [33]. For the wastewater treatment process, input parameters of aeration rate, dilution rate, and recycled ratio are adjusted to achieve a specific concentration level of dissolved oxygen by repeatedly rejecting the water's substrate concentration [33].

Recently, MPC has been studied widely in the built environment because of significant time and cost reduction in data processing. The majority of MPC research is primarily focused on HVAC system control [34–37], building thermal behavior predictions [38, 39], or indoor thermal comfort control [40–42]. However, there are few studies in which MPC was applied to control the surface condensation on building construction layers.

The basic framework of MPC for HVAC systems is shown in Fig. 10.8. It is a closed-loop cycle consisting of a dynamic model and optimizer [43]. The dynamic model simulates several potential future states using adjustments in the control inputs. The best control input that minimizes an objective function without penalizing the constraints is found using the optimizer [44]. When the best control input is determined, it is fed back into the HVAC system operation. This process is repeated for every control horizon [11].

The MPC objective function that ensures thermal comfort with minimum cooling energy is [31]

$$minimize:\ J(t_k) = \sum_{i=1}^{N_u} u(t_k + i) \quad \text{Objective function}$$

$$\text{subject to}:\ 0 \le u(t_k + i) \le u_{\max}, \quad i = 1 \ldots N_u \quad \text{Constraints} \tag{10.10}$$

$$\hat{y}(t_k + i | t_k) \le y_{\max}(t_k + i),\ i = 1 \ldots N_y$$

where t_k = control time-steps, N_u = the number of steps in the future horizon, $u(t)$ = system inputs, $u_{\max}$ = the maximum cooling system input, $\hat{y}(t)$ = system outputs, and $y_{max}(t)$ = upper indoor temperature threshold for thermal comfort.

After dynamic model predicts several potential future states, MPC determines the best control scenario under the objective function and the constraints [45]. At every control time-step, the control problem for MPC is formulated and solved to meet the objective without violating the control horizon's restrictions. When the best control input is determined under the control horizon, the best control input is fed back into the system operation and moves forward to the next control time-step (Fig. 10.9).

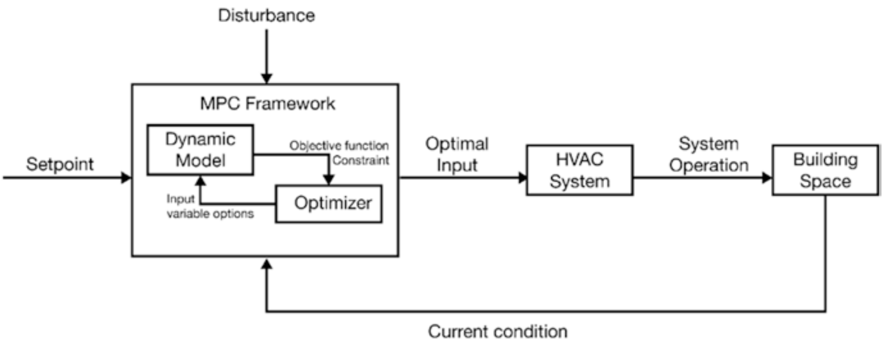


Fig. 10.8 The basic framework of model predictive control for HVAC systems

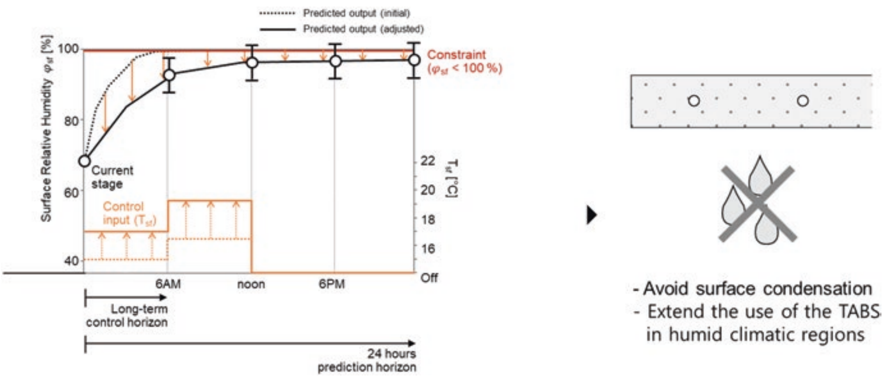


Fig. 10.9 Surface condensation control with MPC

10.4 Conclusions

Hydronic-based radiant cooling systems have been widely used for their energy efficiency and providing better thermal comfort for occupants when compared to conventional convection-based cooling systems. However, due to the potential risk of developing condensation on the surface prevents hydronic-based radiant cooling systems, including thermo-active building systems (TABS), from being applied in buildings located in warm and humid climate regions [14].

Throughout this chapter, a framework to prevent surface condensation while TABS is in operation was introduced. Because the MPC-based surface condensation prevention framework can continually control the surface condensation risk when the TABS is in operation, potential damage to the building construction layers can be avoided. Avoidance of this damage in building envelopes will extend the repair cycle for each building construction layer, which in turn can lead to overall maintenance cost savings for buildings [14].

The MPC-based surface condensation control can also resolve mold growth-driven health problems like allergic rhinitis. With several hours ahead of surface condensation prediction by the MPC framework, the potential risk of failing to detect surface condensation can be eliminated, which will contribute to the prevention of mold growth in building construction layers [14].

Additionally, MPC-based surface condensation prevention will broaden the adoption of the TABS even in warm and humid climate regions. Given the growing demand for the TABS [46], the MPC clearly satisfies an important need of building industry. By controlling the potential risk of surface condensation development, it can extend the use of the TABS to areas in which climate conditions have made them infeasible [14].

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Chapter 11
Performance Effectiveness of Daylight Modifiers for Optimizing Daylighting in University Buildings

Gillian Anschutz-Ceja and Morteza Nazari-Heris

Abstract Daylighting is a crucial factor for the comfort of humans. Insufficient daylighting can make residents feel more disoriented, anxious, and uneasy, while excessive daylighting can result in glare and severe heat gain. This chapter studies the effectiveness of daylight modifiers: dynamic glass, metal overhangs, and perforated panels on optimizing daylighting, glare probability, and solar heat gain with a focus on university buildings. Due to the building's excessive natural light, this study focuses on the A. Alfred Taubman Engineering, Architecture, and Life Sciences Complex, which is home to the Marburger STEM Center at Lawrence Technological University. The majority of the building's façade is made up of enormous curtain walls, which the inhabitants claim cause them to feel uncomfortably warm and endure substantial glare. Through the evaluation of several daylighting options and a cost analysis, this study seeks to identify the most effective remedy for occupant discomfort. In this study, dynamic glass, post-construction overhangs, and perforated paneling were all considered daylight modification techniques. To find the best option, the cost and performance of each system are compared. There are recommendations for the best solution based on the performance of each modifier for glare likelihood, daylight autonomy, solar heat gain, and cost, as well as the significance of each parameter.

11.1 Introduction

Human comfort is a very important facet of building design. Providing adequate daylighting while also providing a comfortable environment for the building occupants is a common issue encountered by lighting designers. Often providing a large curtain wall, although aesthetically pleasing, can cause significant glare and heat

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gain issue. Providing a large amount of glazing allows for more solar radiation, "thermal comfort of building occupants will be affected by variations in solar radiation throughout the building," and it is also "the main cause of a non-uniform indoor thermal environment" [13]. Since curtain walls are a very popular design element, a lot of buildings need a solution to provide adequate comfort to their occupants. With the increasing popularity of daylight integration, it is important to recognize that it needs to be done properly to implement an optimal environment for the building's occupants. Cost savings is a major benefit to daylighting, and "energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and the potential for smaller heating, ventilating and air-conditioning (HVAC) plants" [14].

When considering daylighting in existing buildings, it is important to design the building such that a reasonable amount of natural light enters the building. Doing a full daylighting and heat gain analysis on a building takes a great amount of time and effort from the designer, so it is often overlooked or not within the budget for the building design firm. This later creates issues for buildings that have a large amount of glazing on their perimeter walls with the occupants feeling discomfort due to glare or heat. Considering the fee, it would cost to have daylight analysis performed during the design stages of a building project, an after-market fix would be a good solution. There are a few different options for daylight modifiers that allow occupants to see out while still preventing harsh glare from entering the buildings, but there is not a guide or an easy way to select what would work for the building. By performing analyses on an existing building and determining the impact different daylight modifiers have on the solar heat gain, daylight autonomy, and perceptible glare, the different methods can be compared both in design and cost to give an idea of what would work for similar buildings.

Although daylighting is a very efficient way to light buildings while connecting the occupants to the outdoor environment, considerations need to be made about human comfort during the design process. The most important factors to consider are glare, daylight autonomy, and thermal comfort. When too much glazing is provided on the east and west facades, the potential of glare is more prominent. The optimal building orientation for natural daylighting is north as it provides more indirect, even lighting within the space. Classrooms that receive "high daylight intensity with low glare, added with high quality artificial light source improves the visual comfort, which improves the learning space environment," directly impacting the performance and psychology of the students [19].

Daylight autonomy uses the percentage of daylight available annually to determine if a space will receive sufficient daylighting, given a minimum threshold based on space type [11]. Thermal comfort is not always considered when designing spaces with a lot of glazing, although there is significant heat gain and loss through the glass. By implementing a daylight controlling technique, the space could potentially be more comfortable for the occupants. Occupant behavior is significantly impacted by providing adequate daylighting. In a study performed by Rensselaer Polytechnic Institute, it was found that behavior patterns for people in an office setting near windows versus in a windowless space were significantly different. It was found that people in offices with windows spent more time working on the computer and less time talking to others, whether in person or on the phone, than those in windowless offices [10]. Having the ability to investigate nature has proven to be effective in reducing stress and anxiety while improving attention and mood. Studies performed in 1979, 1981, and 1986 found that individuals recovering from psychophysiological stress that were exposed to natural settings had a quicker recovery than those who did not have exposure to nature. The group that was exposed to nature also had lower muscle tension, skin conductance, and blood pressure than their counterparts [9].

The effect of daylighting on student productivity has been studied to find the benefits and challenges of natural light in the classroom. Daylighting has such a large impact on student productivity because health and mental functions are dependent on circadian rhythm. The intensity and duration of light exposure influences the circadian rhythm. Not enough daylight can cause students to be less productive since their mental functions are not acting at as high of levels as they are intended during the day due to lack of daylight exposure [15]. Although daylighting has a very positive effect on students, it is important to prevent providing too much daylighting to avoid glare and thermal discomfort. Glare reduces vision and causes eye strain, causing students to be uncomfortable and less productive. Reduced vision can also lead to more errors in work and potential hazards that would have been visible in proper daylighting conditions [2]. Glare is most problematic when the professor is required to write and solve problems on a whiteboard or blackboard since the glare on the surface lowers the contrast, preventing students from being able to follow along. Glare on desk surfaces causes low visibility for reading and writing tasks, causing students to be distracted and a lapse in concentration. Long-term effects of glare in the classroom can include visual fatigue and migraine as well as negatively impact the students' ability to learn and the teachers' ability to teach [26].

As mentioned previously in this section, there are various methods utilized for glare/daylight control. Some typical methods are perforated panels, dynamic glass, and overhangs, as summarized in Table 11.1.

11.2 Literature Review

Daylighting is a widely researched topic that affects everyone. The benefits and harms of daylighting are very important to understand when designing buildings. With the increased popularity of curtain walls and the use of a lot of windows, it is very easy to allow too much daylighting into the space, causing discomfort for the occupants. There are different daylight modifiers on the market that can be utilized to reduce the glare experienced by the occupants and reduce thermal discomfort.

Table 11.1 Comparison of glare control methods in buildings

Method	Cost	Features	Applications	Pros and cons	Reference
Perforated panels	$5–10/ sq. ft.	Metal sheet with holes punched in it to allow light to filter through	Commercial, industrial, and large-scale residential	**Pros:** Aesthetic appeal, energy efficient, dampens noise, durable, lightweight **Cons:** More expensive for small projects, can rust over time	[4] [21]
Dynamic glass	$50–150/ sq. ft.	Wi-fi connected glass that adjusts automatically based on photo sensors or manual override	Commercial and residential	**Pros:** Versatile, energy efficient, protects from sunlight, sound isolation, environmentally friendly, security, cost efficient over time, increases market value, aesthetic appeal, low cost of maintenance **Cons:** High up-front costs, requires electricity to operate, difficult to install, hard to find	[12] [23]
Fixed metal overhangs	$9–25/ sq. ft.	Strong, long lasting, fixed position, preventing light to directly enter window	Commercial, industrial, and residential	**Pros:** Energy efficient, protects from sunlight, cost effective, environmentally friendly, aesthetic appeal, low cost of maintenance, 20-year lifespan **Cons:** Can rust, blocks view, not adjustable	[20] [27]

11.2.1 Daylighting Utilization

Daylight harvesting and maximizing the usage of daylighting should be used to increase the energy efficiency of a building. In modern building design, light, bright finishes are used to increase reflectance to reduce the lighting power density in buildings. Typical surface reflectances for walls, floors, and ceilings are 50–70%, 20–40%, and 60–80%, respectively. It was found that off-white tiles have a 70% reflectance while white tiles have a 85% reflectance, causing a significant increase in surface reflectance with a small color change. This study selected an office building in Sri Lanka and modeled it in a design-build software and simulated four different scenarios: (1) current situation, (2) added sunshade of 1.5 m for each window, (3) three different window film types for windows, and (4) best combined options from previous scenarios [3]. The investigated scenarios of this reference can be summarized as follows:

- In simulating scenario 1, it was important to recognize that the building currently utilized vertical blinds to manipulate sunlight in most spaces. For the majority of the day, the occupants kept the vertical blinds closed. For the entire year, the building consumed 67,742 kWh of energy for lighting, 60,896 kWh of energy for air conditioning, and had a total annual energy consumption of 128,638 kWh. By removing the vertical blinds, the annual solar gain from the perimeter windows increased by 286,144 kWh, the electricity consumption for lighting reduced by 51,001 kWh, and the electricity consumption for air conditioning increased by 7626 kWh.
- Scenario 2 involved removing the existing blinds and adding 1.5 m overhangs to the windows. When compared with the existing building without any form of daylighting control, the annual solar heat gain reduced by 10.5%, while the lighting electricity consumption did not change, and the air conditioning electricity consumption increased by 0.23% per year.
- Three window film types were used for scenario 3, including: 3M prestige 70, 3M prestige 50, and 3M prestige 40. The highest solar heat gain reduction was found using 3M prestige 40 and the lowest using 3M prestige 70, with a reduction of 74% and 39%, respectively. When both lighting and air conditioning energy consumption was considered, the 3M prestige 70 was the most effective, reducing energy consumption by 39%. For visual comfort, the 3M prestige 40 film was found to be optimal as it has a lower transmissible visibility than the 3M prestige 70 film.
- Scenario 4 combined the optimal window film found from scenario 3 (3M prestige 40) with the 1.5 m overhangs, resulting in both a reduced energy consumption and solar heat gain. After running daylighting simulations on all four scenarios, the study found that scenario 4 reduced the daylighting factor to a comfortable level for the occupants near the exterior windows.

11.2.2 Dynamic Glass

Daylighting is important to connect occupants to outside nature and to reduce the need for electric lighting. Heat and glare are often uncomfortable side effects of daylighting. Electrochromic glass can provide control of the amount of daylight entering a space as well as solar heat gain through local control or automatically based on various sensors on the building. This allows solar heat gain to be reduced during summer and increased during winter while constantly maximizing daylight admission, resulting in reduced cooling and electrical lighting loads [24]. During building design, it is important to consider the amount of perimeter glass on the building as well as the orientation of the building. The long sides of the building should be facing north and south, with the glazing primarily located on these facades to minimize solar gains, but this is not always possible [24]. The higher the glass is located on the facade, the deeper daylight penetration can get within the building. Utilizing "split-glazing" can help optimize the daylighting for the occupants:

comfort. The lower section of the glazing should be able to be controlled while the upper section of the glazing causes less glare so can be left uncontrolled [24]. When compared with the ASHRAE 90.1 (2010), a building that utilizes electrochromic glazing with a 50% window-to-wall ratio has equivalent energy performance to the 20–30% window area with conventional glazing. At Ball State University, Dehority Hall has a fully glazed roof that utilized a standard low-e glass with a 50% frit pattern but was found to be very uncomfortable by occupants due to glare and heat gain. The glazing was then replaced with electrochromic glass and was examined a year later, and the space was found to be more comfortable both visually and thermally to its occupants [24].

Tinting glass is a common method of daylight control to prevent reducing the transmissible visibility of the light entering space. Glass tinting is usually performed by adding small amounts of metal oxides to the glass composition (Coat and tinted). This method of daylight modification is fixed, not allowing adjustments depending on the time of day. Dynamic glass is very similar to tinted glass, but it allows the transmissible visibility to automatically adjust based on the amount of light entering the space or via manual override. Dynamic glass utilizes multiple layers of ceramic material that is coated on thin glass panes. When tinting the dynamic glass, an electric charge makes lithium ions transfer between the ceramic layers. When the polarity is reversed, the glass switches to clear (The science behind). Two main benefits of electrochromic glass are that it lowers the peak loads and reduces glare. By lowering the peak loads, the HVAC equipment can be smaller and more cost-effective, in some cases making it an option to use a green ventilation system. By reducing glare, the occupants become more comfortable, and the cost of electric lighting reduces. Since occupants are typically in control of the amount of daylight entering the space via manual blinds, the electric light is required to be on or at a higher output more often [24].

11.2.3 Visual Comfort and Energy Efficiency

The daylight factor is a very important aspect of daylighting as it expresses the efficiency of a room as a natural lighting system. The daylight factor is calculated by dividing the internal horizontal illuminance at work plane height by the external horizontal illuminance measured during an overcast time [16]. This paper studied a classroom in Malaysia since the weather does not significantly change from season to season. The classroom studied is in a preschool at the University of Malaya, with a window-to-wall ratio of 28% on the north-, east-, and south-facing facades. In its existing condition, the windows on the north and east facades were covered with a frosted window film, and the south facing wall was completely obstructed using a curtain. The study found that the curtains blocking the southern facade significantly reduced the daylight factor as well as the illuminance level on the desks. The uniformity ratio did not meet the MS1525 requirement but did meet the BREEAM requirement. When compared with the uncovered windows, the lighting level dropped to

52–88% depending on the proximity to the window, the uniformity ratio was also reduced by 10%. Without the frosted window film and the curtains, the room is well-lit. With the amount of daylight entering the classroom, electric light would not be required during typical operating hours. With the window coverings in place, the daily energy consumption from lighting for the classroom is 1.2 kWh.

11.2.4 Perforated Panels

Perforated metal panels are often used as a method to block daylight where glare is an issue. In this study, six different metal screens were selected to test the visible and solar angular transmittance performance. All screens had about a 40% openness factor; the main difference between them was the pattern of perforations in the panels [17]. To test each sample, a 300-watt tungsten halogen lamp was mounted on a holder with a rotational arm to adjust the angle of incidence. The detection system utilized three different array spectrometers and detectors. Once the data were collected, the thermal losses for each type of mesh were simulated using TRNSYS. The summer cooling and winter heating loads were performed for a typical office. The study found that the openness of the metal panels was not an adequate measure of their performance. For the generic mesh sample, the results do not vary much for the east or west orientation. However, for the northern and southern elevations, the solar transmittance greatly varies, hitting a minimum during summer and reaching its maximum during winter. When using a low-g glass, the cooling load was higher than that of a clear glass with a perforated metal shading system, with the difference reaching as much as 40%. The study also found that the incidence of solar reflectance on the metal wire coating is stronger during the summer months than in the winter months.

11.2.5 A Summary of the Literature

Many concepts regarding different daylight modifiers as well as the effect of providing adequate daylighting on the building occupants regarding human comfort and efficiency have previously been discussed. The literature regarding these various studies is reviewed and outlined in Table 11.2.

11.3 Analytical Procedure

The A. Alfred Taubman Engineering, Architecture, and Life Sciences Complex Home of the Marburger STEM Center (Taubman Building) on the Lawrence Technological University campus has a curtain wall facing south-west that causes the occupants to feel uncomfortably warm. This problem could be mitigated by using a number of daylight-controlling techniques using dynamic glass, extruded exterior shades, or perforated metal screens. The purpose of this chapter is to analyze different solutions to control daylighting to optimize daylight autonomy, daily glare probability, and heat gain while considering the cost of each solution. This issue is very common with the rising popularity of curtain walls and inadequate design consideration. Using this analytical experiment, future building occupants suffering from discomfort due to glare and heat gain, a quick solution will be selectable with an idea of the cost that would impact the owner.

Figure 11.1 shows the simplified flowchart of the proposed model for optimizing daylighting in university buildings.

As shown, the first step is to select the daylight modifiers to be used. Then, the floorplan is to be modeled in AutoCAD. Once the floorplan is complete, it is then imported into Rhino and a 3D building is created. Each modifier must then be modeled on the existing building. Climate studio is then used to run simulations for Daylight Availability, Annual Glare, and Radiation. The data from these simulations is then exported to Microsoft Excel. The data are then analyzed and compared to recommend the optimal modifier.

To examine the performance of daylight modifiers, the Taubman Building on Lawrence Technological University's campus was analyzed. The building plans were retrieved as PDFs and imported into AutoCAD to model the floorplan of each level of the Taubman Building. These floorplans were then imported into Rhino and each level's walls were extruded to create three-dimensional figures. These levels were then stacked on top of each other to get a full model of the Taubman Building. Once the base building was modeled, the file was duplicated to create a model for each of the daylight modifiers to be applied individually.

By using the Climate Studio plug-in for Rhino, the areas with glare were determined from the base model. The building was broken into spaces based on the areas that have exterior glazing; this is important for analysis. The areas were broken up and labeled as indicated in Figs. 11.2 and 11.3.

The perforated panels were modeled for each of the large curtain walls. These perforated panels were designed to have ¾-inch diameter holes with a spacing of 2-1/4-inches on center, as shown in Fig. 11.4. This translates to the panel being about 65% open. The perforated panels were placed 8 in. away from the exterior walls of the building to create a shading system that still allows a decent amount of visibility out of the building.

The overhangs were placed above each of the curtain wall segments. They protrude 3-feet from the building and are 1-foot tall. These will allow for the sun to be partially shaded from entering the building, preventing harsh direct light in the eyes of the building occupants. The overhangs also very minimally impact the view out of the building as the only area obstructed would only be visible while very close to the glass.

The dynamic glass was very similar to modeling the standard glass that is already in the building. Utilizing the climate studio plug-in, selecting a true dynamic glass is not an option; rather, they provide the four standard tint levels of View dynamic

Table 11.2 Literature summary of daylighting modifiers in buildings

Method(s)	Standpoint of analysis	Application type	Pros	Cons	Reference
Perforated panels	Illuminance, perforation ratios	Residential	Reduced peak heat gain in space by 50–70% Reduced illuminance to a comfortable level	Non-uniform light entering space	[1]
Dynamic glass	Environmental satisfaction, perceived health, perceived productivity, and emotional responses in building occupants	Office	38% of occupants experienced fewer headaches, thermal stress, distraction, tired eyes, drowsiness, visual discomfort, and glare annoyance About 26.4% of occupants felt more relaxed and satisfied with their view to the outdoors 24.4% more alert and 17.2% more productive than those with manual blinds Positive emotional responses were reported as 30% greater for those with offices using dynamic glass and 22% lower negative responses than those with manual blinds	Only 17 workers were examined and considered accurate for t-tests; not adequate size sample when divided into groups based on age, gender, and location Lacked a control group to remain in offices with manual blinds. The number of closed offices was also adjusted so the size of new workstations may have also affected the response of the occupants	[6].

(continued)

Table 11.2 (continued)

Method(s)	Standpoint of analysis	Application type	Pros	Cons	Reference
Perforated panels, overhangs	Useful daylight illuminance, daily glare probability, energy performance, and visual comfort	School	Exterior overhangs are optimal for all façade orientations External overhangs reduced total annual energy use intensity by 4.5–18.8% The lighting quality inside the nearest window was improved by 25–37% for the overhangs The visual comfort with the external overhangs was improved by more than 30% The solar irradiance was reduced by at least 27% for the classrooms with overhangs	Perforated panels were only the optimal solution for the façade receiving intense sunlight (east-west) Perforated shading panels regardless of patterns have close to no impact on visual comfort and energy performance	[28]
Dynamic glass	Human comfort, daylighting, glare	Offices	Occupants near windows with dynamic glass were more productive and satisfied Providing personal controls alleviates negative perceptions Finding a balance between efficiency and perceived happiness is important	Occupants toward the center of the building did not receive enough natural light Satisfaction differed depending on the distance from windows In one instance, occupants reported feeling gloomy due to the dynamic glass shading	[7]

(continued)

Table 11.2 (continued)

Method(s)	Standpoint of analysis	Application type	Pros	Cons	Reference
Overhangs	Transmittance value	Commercial	Overhangs provide shading from harsh light entering the space	Overhangs significantly impact the amount of dirt build-up on the window by sheltering it from the rain The reduced transmittance due to dirt creates an unsightly environment for its occupants	[25]
Perforated panels	Irradiance, energy performance	Commercial	Perforated panels enhanced the daylit area by 112% The panels reduced the overlit areas by 53% Heating energy was decreased by 75% Cooling energy was decreased by 50% Solar energy density was lowered by 57% Total annual energy use was reduced by 45%	Lighting energy increased to 53% to supplement dimmer spaces	[5]
Dynamic glass		Commercial	When using dynamic glass, the annual energy across three different climate zones decreased by 4–23.4% Annual energy use across the three climate zones decreased by 1.2–5.8%	Optimal results cannot be standardized as the location will impact the optimal control conditions	[18]

(continued)

Table 11.2 (continued)

Method(s)	Standpoint of analysis	Application type	Pros	Cons	Reference
Overhangs	Light level, light distribution, quality of light	Classroom	Overhangs are very cheap to add and install on an existing building When comparing light levels in a classroom without external overhangs versus with, there was a 15–17% reduction	The improvements were not as large as that of pricier daylight modifiers	[22]

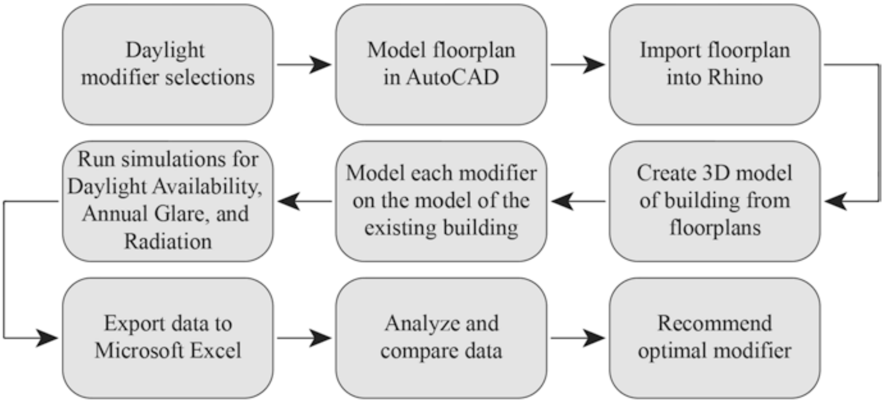

Fig. 11.1 The flowchart of the proposed framework for optimizing daylighting in university buildings

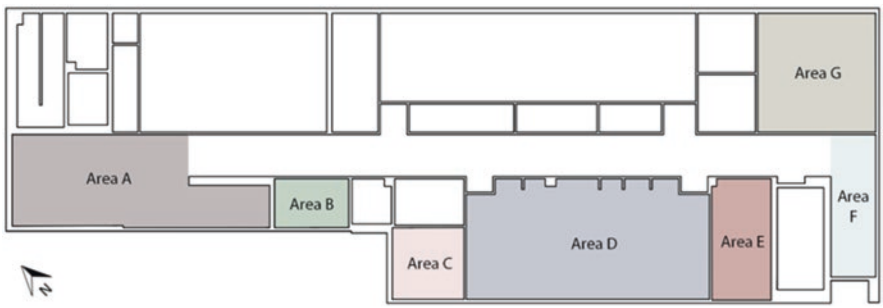

Fig. 11.2 First-floor analysis areas

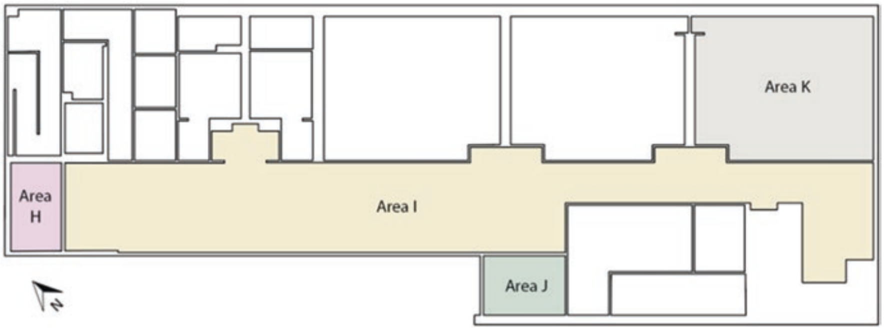

Fig. 11.3 Second-floor analysis areas

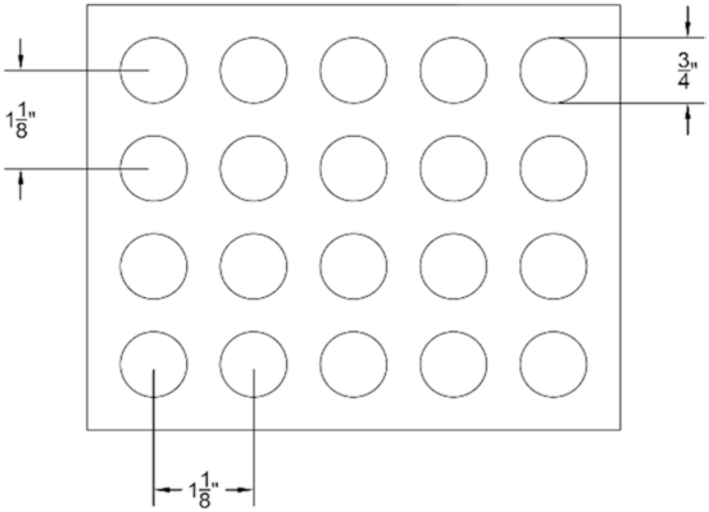

Fig. 11.4 Example of the perforated panel

glass. Since four tint levels were available to select, four iterations of this modifier were created, one with each tint level. This allows the optimal data from each simulation to be combined to create an accurate representation of what automatically tinting dynamic glass would provide for the occupants.

Each daylighting solution would be subjected to a simulation on June 21, September 23, December 21, and March 20 in 2023 representing the summer solstice, fall equinox, winter solstice, and vernal equinox, respectively. This will ensure that the heat gains and daylighting will be optimal for all seasons throughout the year. In this book chapter, we have reported the detailed results of September 23 and March 20 in 2023. Once each simulation is performed, a cost analysis of implementing each solution into an existing one will be performed to determine a reasonable solution for existing buildings. A method of "good," better," and "best" will be utilized to suggest to the industry for solutions that may be implemented once a building experiences issues.

11.4 Simulation Results

Using the Climate Studio plug-in for Rhino, three simulations were run for the original building with and without daylight modifiers. After modeling the Taubman Building, shown in Fig. 11.5, each variation underwent three simulations: Daylight Availability, Glare Probability, and Radiation Map. Once the simulations were complete, the data from each was downloaded into excel and generated graphs to display the results. After preliminary analysis, it was determined that areas A, B, C, D, and E on the first floor act similarly, so area D will be used in further analyses to represent these spaces. Areas F and G also very similarly receive daylight; thus, area F will represent these areas in future analyses. On the second floor, areas H, I, and J receive a similar amount of daylighting, so area J will represent these spaces in further analysis, and area K does not act similarly to other areas, so it will be analyzed on its own.

11.4.1 No Daylight Modifier

To create a baseline for the results for the daylight modifiers, the current state of the building was first examined. The hourly illuminance for March 20, 2023, is displayed in graphs in Fig. 11.6. The daylight autonomy for March 20, 2023, based on operating hours 5:30 am to 7:30 pm is 73.33% for areas D and F and 80% for areas J and K meaning that there is 73.33% of usable daylight for areas D and F and 80% of usable daylight for areas J and K during the vernal equinox. Although for all spaces, this is most of the operating hours, it is not necessarily optimal for the occupants. The daily sunlight exposure is 26.7%, 60%, 60%, and 66.7% for areas D, F, J, and K, respectively. This translates to the percentage of floor area receiving

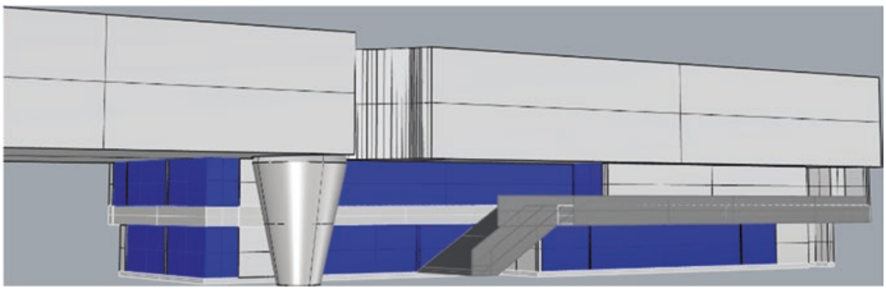

Fig. 11.5 Rhino model of the Taubman Building

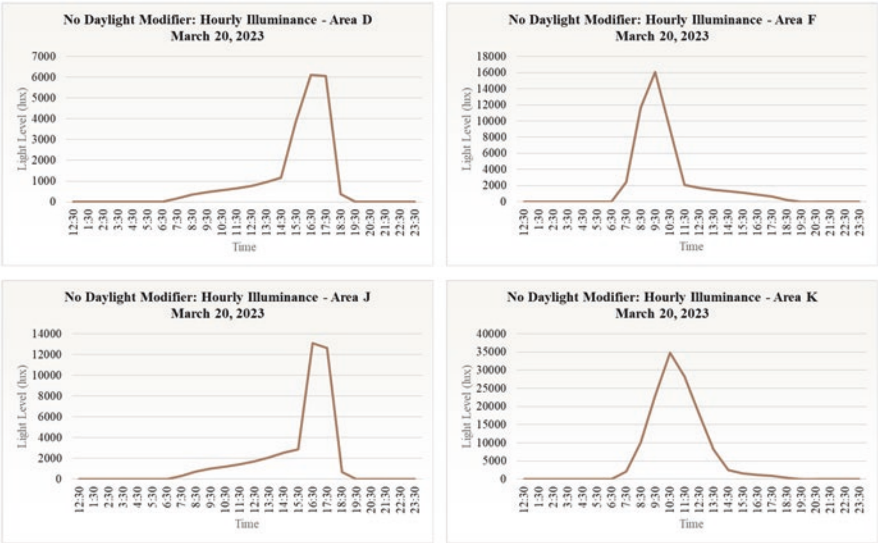

Fig. 11.6 No daylight modifier: hourly illuminance for March 20, 2023

intense daylight (i.e., 1000 lux). When compared with the acceptable value of 10%, this value is extremely high. The percentage of the day that the amount of daylight entering the space is within the target values of 300 lux to 500 lux is only 20% (3 h), 3.8% (34 min), 6.7% (1 h), and 6.7% (1 h) for areas D, F, J, and K, respectively. This means that for most of the operating hours, the daylight is at an unacceptable level.

The hourly illuminance for September 23, 2023, is displayed in graphs in Fig. 11.7. The daylight autonomy for September 23, 2023, based on operating hours 5:30 am to 7:30 pm is 66.7% for area D and 73.3% for areas F, J, and K. Most of the operating hours are still exceeding the 300-lux threshold, but the daily sunlight exposure is still high. The sunlight exposure for area A is 40%, for areas F and J, it is 60%, and for area J, the sunlight exposure is 66.7%, all of which exceed the acceptable limit of 10%. This means that almost the entire time that the minimum lighting threshold is met during the operating hours, the space is receiving an uncomfortable level of intense sunlight. Thus, only 6.7% (1 h), 2.6% (24 min), 6.7% (1 h), and 1.8% (16 min) of operating time, the amount of daylight entering the space is within the target values of 300 lux to 500 lux for areas D, F, J, and K, respectively.

The worst-case illuminance occurs at different times of the year depending on space. The maximum light level for areas D and J is reached on December 21 at 2:30 pm. The maximum light levels are 8892 lux and 19,552 lux for areas D and J, respectively. The maximum illuminance for areas F and K is reached on March 20. Area F experienced a maximum light level 16,062 lux at 9:30 am and area K reached its maximum of 34,759 lux at 10:30 am. Each area during its worst-case illuminance is displayed in Fig. 11.8.

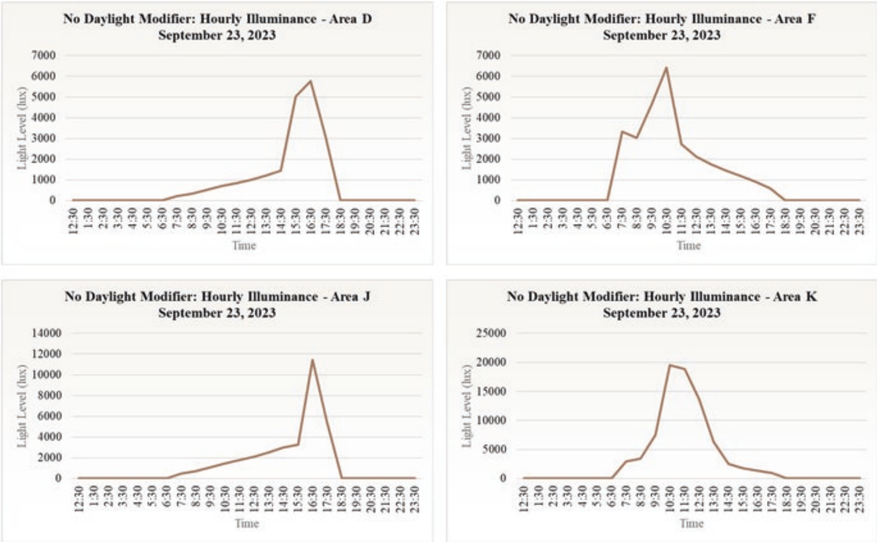

Fig. 11.7 No daylight modifier: hourly illuminance for September 23, 2023

11.4.2 Dynamic Glass

Dynamic glass was selected as a daylight modifier to utilize its ability to automatically adjust tint depending on the amount of light entering the space. Figures 11.9 and 11.10 display the hourly illuminance on two of the key dates selected to represent the summer solstice, fall equinox, winter solstice, and vernal equinox. The hourly illuminance with dynamic glass for March 20, 2023, is displayed in graphs in Fig. 11.9. The daylight autonomy for March 20, 2023, is 80% in areas J and K and 73.3% in areas D and F based on operating hours 5:30 am to 7:30. This means that during the vernal equinox, areas J and K receive 80% of usable light and areas D and F receive 73.3% of usable light naturally. Although for the current state the daylight autonomy was very similar, the daily sunlight exposure is significantly less, indicating that the light is not overpowering within space. The daily sunlight exposure is 0% for areas D, F, and K, meaning that the floor area never receives intense daylight. Area J has 53% sun exposure, which is significantly higher than the acceptable 10%. The percentage of the day that the amount of daylight entering space is within the target values of 300 lux to 500 lux is only 6.67% (1 h) for area J although the other areas performed significantly better. Areas D and F received light levels between 300 lux and 500 lux for 73.3% (11 h) while area K received light within this limit for 66.7% (10 h) of the day. This means that for the majority of the operating hours, the daylight is at an unacceptable level for all areas except area J.

The hourly illuminance with dynamic glass for September 23, 2023, is displayed in graphs in Fig. 11.10. The daylight autonomy during September 23, 2023, is 66.7% in area D and 73.3% in areas F, J, and K based on operating hours 5:30 am

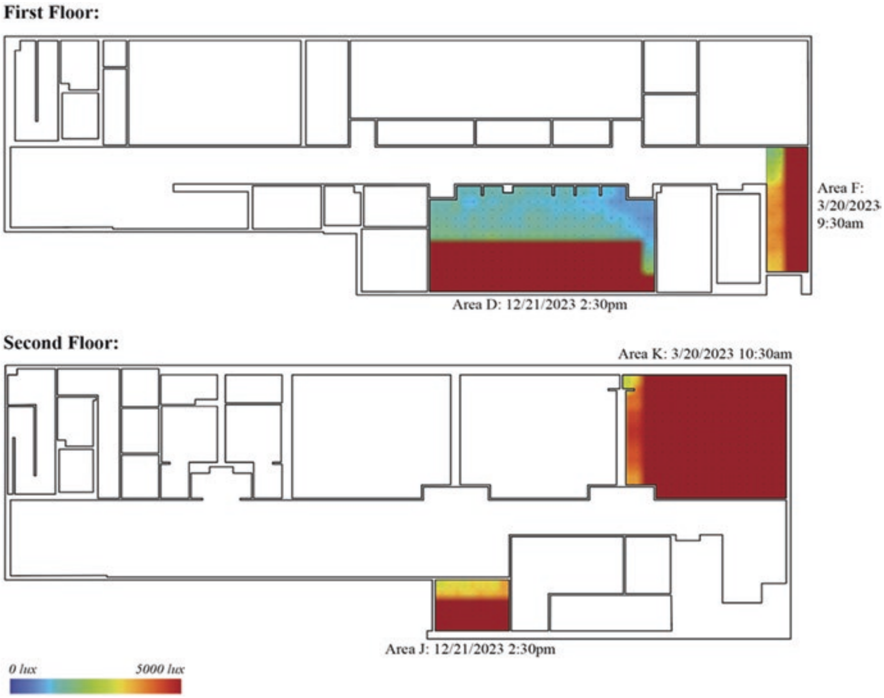

Fig. 11.8 No daylight modifier: worst-case illuminance per space

to 7:30 am, translating to the amount of usable light in the space. Again, areas D, F, and K never receive intense daylight since the daily sunlight exposure is 0% for these spaces while the sun exposure for area J is unacceptable at 53.3%. A light level of 300 lux to 500 lux enters area D 66.7% (10 h) of the day, areas F and K 73.3% (11 h) of the day, and for area J, 6.7% (1 h). For most of the day, all areas except J receive optimal daylighting.

In order to accurately compare the effect of the modifier on the amount of daylight in each space. On December 21 at 2:30 pm, the light level for area D was 437 lux and for area J was 19,397 lux. On March 20, at 9:30 am, area F reached 439 lux and at 10:30 am, area K reached 642 lux. The illuminance during each of these times is displayed in Fig. 11.11.

11.4.3 Overhangs

Overhangs are a more typical, cost-effective daylight modifier that was examined to determine its impact on daylighting in the Taubman Building. The hourly illuminance on each of the key dates selected to represent the summer solstice, fall equinox, winter solstice, and vernal equinox is displayed in Figs. 11.12 and 11.13. The

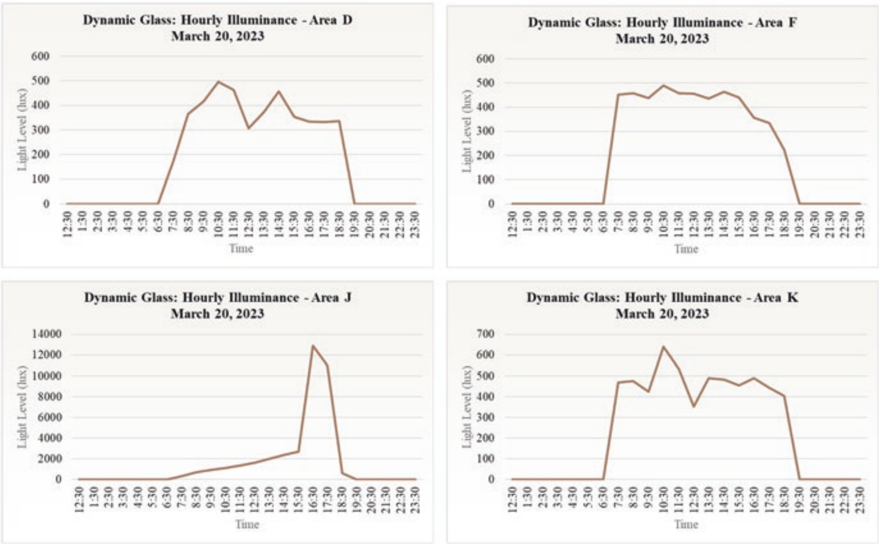

Fig. 11.9 Dynamic glass: hourly illuminance for March 20, 2023

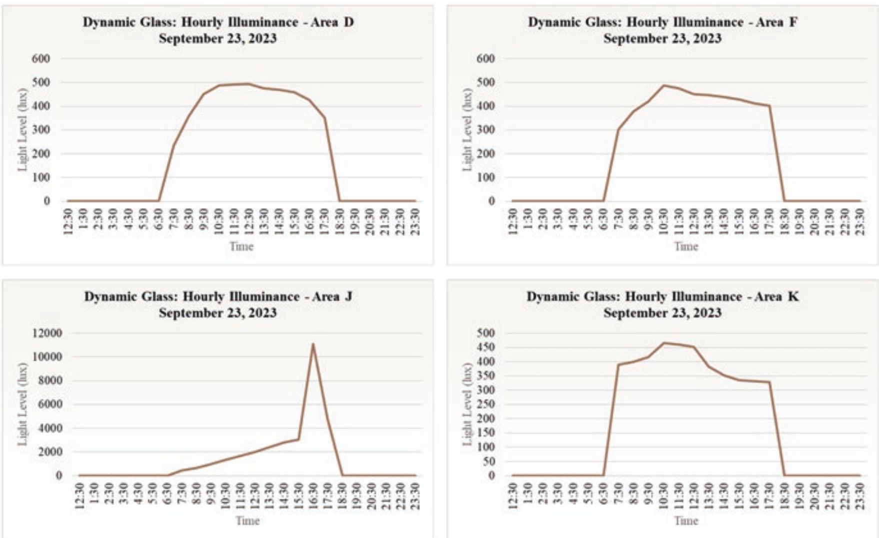

Fig. 11.10 Dynamic glass: hourly illuminance for September 23, 2023

hourly illuminance with overhangs for March 20, 2023, is displayed in graphs in Fig. 11.12. The daylight autonomy for March 20, 2023, is 80% for areas J and K while areas D and F have a daylight autonomy of 73.3% based on operating hours 5:30 am to 7:30 pm. Although most of the operating hours have a very high daylight autonomy, the sun exposure for each space is still fairly high. The sun exposure is

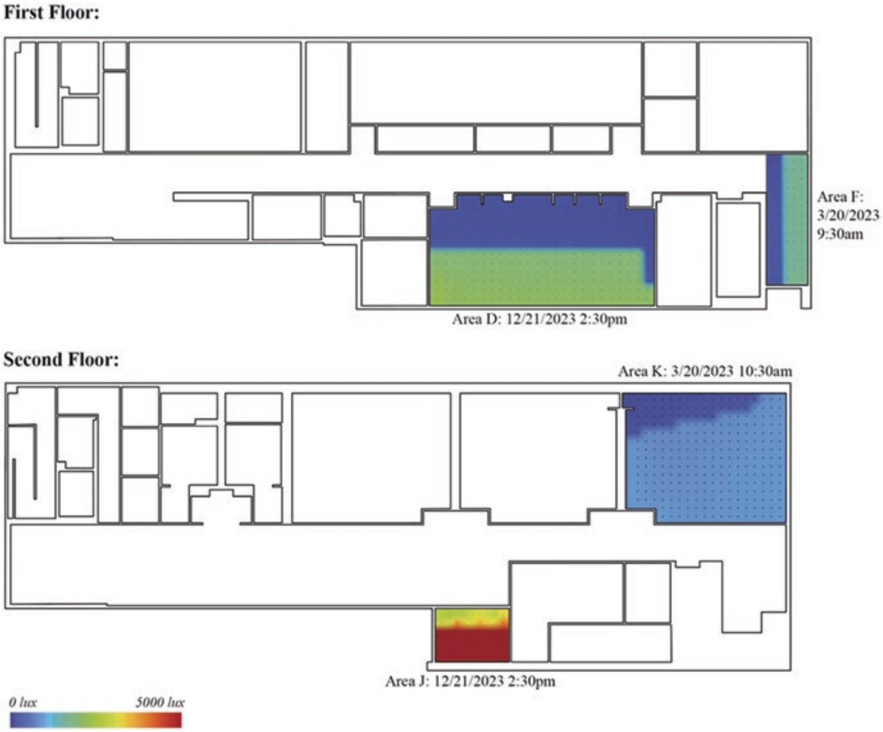

Fig. 11.11 Dynamic glass: worst-case illuminance per space

26.7% for area D, 60% for area F, 53.3% for area J, and 66.7% for area K. This corresponds to the amount of floor area that receives intense daylight throughout the day. The amount of daylight entering the space within 300 lux to 500 lux is 20% (3 h) for area D, 4% (36 min) for area F, and 6.7% (1 h) for areas J and K, spending most of the operating hours outside of the desired range.

The hourly illuminance with overhangs for September 23, 2023, is displayed in Fig. 11.13. The daylight autonomy on September 23, 2023, is 66.7% for area D and 73.3% for areas F, J, and K based on operating hours 5:30 am to 7:30 pm. These values indicate that during the fall equinox, area D receives 66.7% of usable daylight while areas F, J, and K receive 73.3% of usable daylight. The sunlight exposure in area D is 33.3%, in area K is 66.7%, and in areas F and J is 60%, all areas experiencing intense sunlight exposure. The amount of daylight entering the space between 300 lux to 500 lux occurs for 6.7% (1 h), 2.8% (25 min), 6.7% (1 h), and 1.9% (17 min) for areas D, F, J, and K, respectively.

For an accurate comparison of the amount of daylight in the space, each modifier was analyzed based on the worst-case illuminance of the unmodified building. At 2:30 pm on December 21, 2023, the light level for area D was 8870 lux and 19,504 lux for area J. At 9:30 am on March 20, 2023, area F reached 15,971 lux and at 10:30 am, area K reached 31,347 lux. The illuminance during each of these times is displayed in Fig. 11.14.

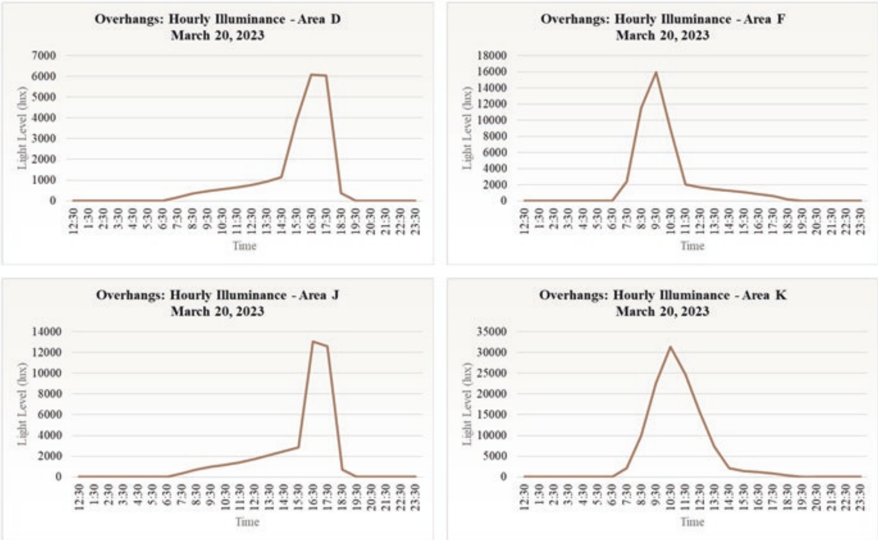

Fig. 11.12 Overhangs: hourly illuminance for March 20, 2023

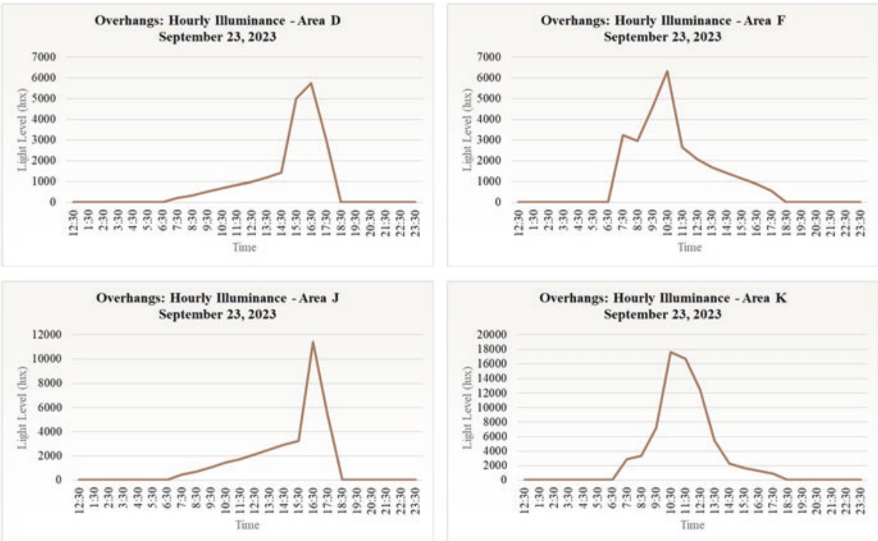

Fig. 11.13 Overhangs: hourly illuminance for September 23, 2023

11.4.4 Perforated Panels

Perforated panels were the last daylight modifier examined. To determine its impact on the daylighting in the Taubman Building, the hourly illuminance was determined for March 20, June 21, September 23, and December 21, and results for two of them are displayed in Figs. 11.15 and 11.16. The authors have reported the detailed results of September 23 and March 20 in 2023 in this book chapter. The hourly illuminance with overhangs for March 20, 2023, is displayed in Fig. 11.15. The daylight autonomy for March 20, 2023, is 73.3% in areas D and F and 80% in areas J and K based on operating hours 5:30 am to 7:30 pm, meaning that during the vernal equinox, areas J and K receive 80% of usable light and areas D and F receive 73.3% of usable light naturally. The daily sunlight exposure is 33.3% for areas D, 66.7% for area K, and 60% for areas F and J meaning that all areas receive intense daylight, exceeding the accepted threshold of 10%. The percentage of the day that the amount of daylight entering the space is within the target values of 300 lux to 500 lux is 13.3% (2 h), 3.4% (31 min), 6.7% (1 h), and 6.7% (1 h) for areas D, F, J, and K, respectively.

The hourly illuminance with overhangs for September 23, 2023, is displayed in graphs in Fig. 11.16. Based on the operating hours 5:30 am to 7:30 pm, the daylight

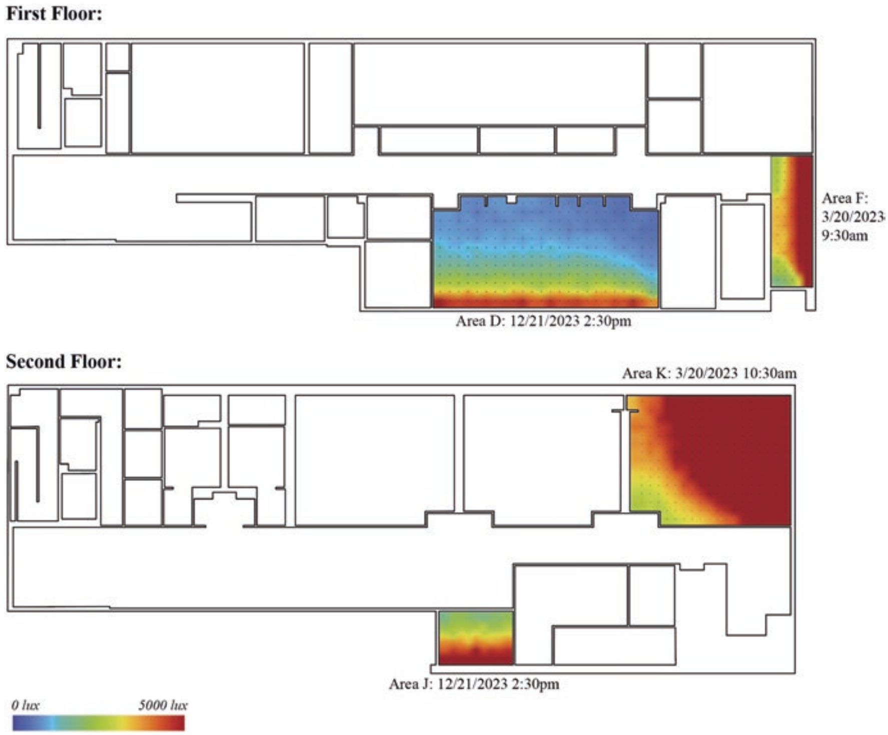

Fig. 11.14 Overhangs: worst-case illuminance per space

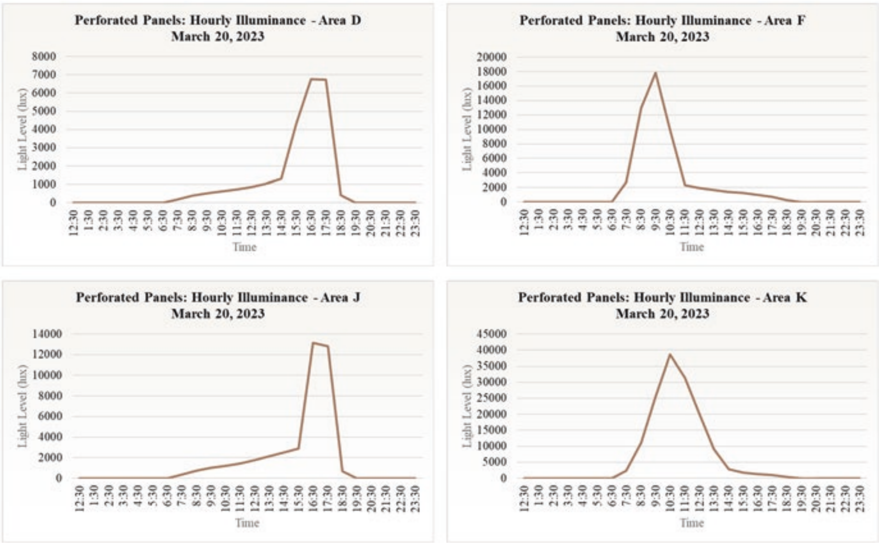

Fig. 11.15 Perforated panels: hourly illuminance for March 20, 2023

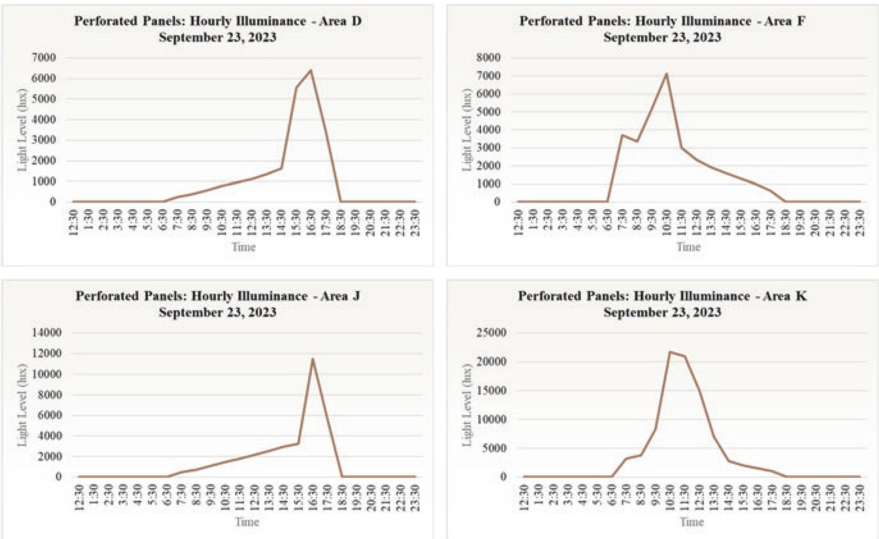

Fig. 11.16 Perforated panels: hourly illuminance for September 23, 2023

autonomy for September 23, 2023, is 66.7% in area D and 73.3% in areas F, J, and K. This means that during the fall equinox, area D receives 66.7% of usable daylight and areas F, J, and K receive 73.3% of usable daylight. The daily sun exposure is 40%, 66.7%, 60%, and 73.3% in areas D, F, J, and K, respectively. These percentages indicate that all areas receive intense daylight. The percentage of the day that

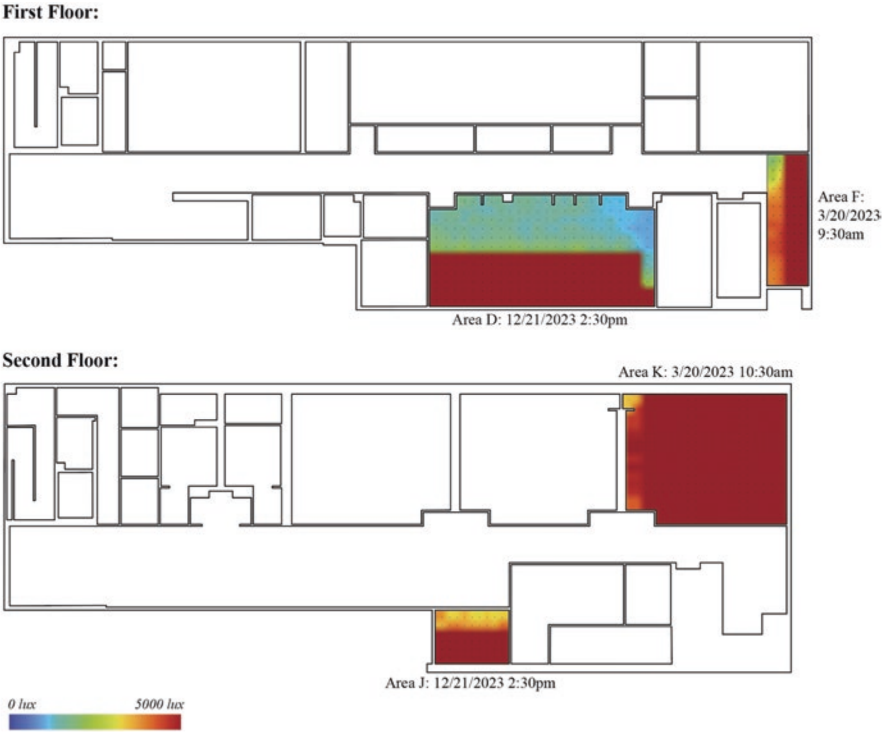

Fig. 11.17 Perforated panels: worst-case illuminance per space

the amount of daylight entering the space is within the target values of 300 lux to 500 lux is 6.7% (1 h), 2.4% (22 min), 6.7% (1 h), and 1.7% (15 min) for areas D, F, J, and K, respectively.

To accurately compare the amount of daylight in the space, each modifier was analyzed based on the worst-case illuminance of the unmodified building. At 2:30 pm on December 21, 2023, the light level for area D was 9877 lux and 19,539 lux for area J. At 9:30 am on March 20, 2023, area F reached 17,858 lux and at 10:30 am, area K reached 25,506 lux. The illuminance during each of these times is displayed in Fig. 11.17.

11.5 Results and Analysis of Glare Probability

Glare can be very distracting for the occupants, so it is important to reduce the possibility of glare within the area. Imperceptible glare is any glare probability less than 35%, while perceptible glare is considered any glare probability of 35–40%. Glare probabilities from 40% to 45% are considered disturbing, and anything over 45% is considered intolerable glare [8]. The glare probability for each variation of daylight modifier was analyzed during March 20, June 21, September 23, and December 21 of 2023 to represent the vernal equinox, summer solstice, fall equinox, and winter solstice, respectively. In this book chapter, we have reported the detailed results of September 23 and March 20 in 2023.

11.5.1 No Daylight Modifier

To create a baseline for the results for the daylight modifiers, the current state of the building was first examined. The hourly glare probability on each of the key dates is displayed in Figs. 11.18 and 11.19. During March 20, 2023, the hourly glare probability was analyzed for each of the four areas selected during the typical operating hours of 5:30 am to 7:30 pm. In area D, the glare is imperceptible for 13 h of the typical operating time, perceptible for the other 1 h, and disturbing for 1 h. Area F has imperceptible glare for 8 h of the day, perceptible for 2 h of the day, disturbing for 1 h, and intolerable for 2 h. Area J has imperceptible glare for 9 h of the day, perceptible for 2 h of the day, disturbing for 3 h, and intolerable for 1 h. Area K has imperceptible glare for 8 h of the day, perceptible for 2 h of the day, and intolerable for 5 h.

On December 21, 2023, the hourly glare probability was analyzed for each of the four areas selected during the typical operating hours of 5:30 am to 7:30 pm. Area D has imperceptible glare for 12 h of the day, disturbing glare for 1 h, and intolerable for 2 h. Area F has imperceptible glare for 13 h and perceptible for 2 h. Area J has imperceptible glare for 11 h of the day, disturbing glare for 1 h, and intolerable

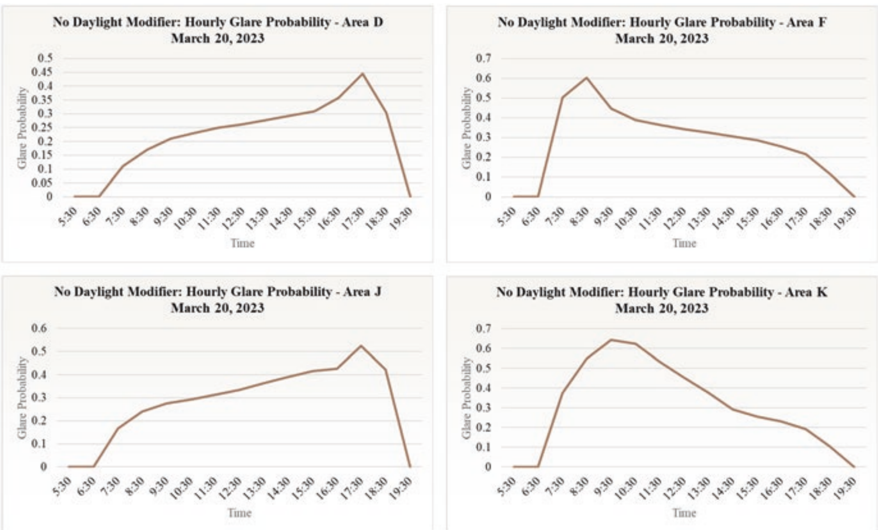

Fig. 11.18 No daylight modifier: hourly glare probability for March 20, 2023

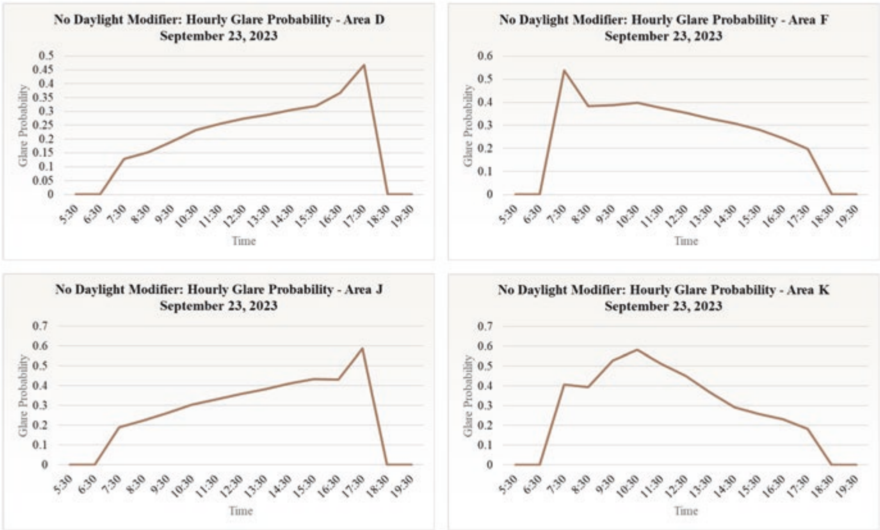

Fig. 11.19 No daylight modifier: hourly glare probability for September 23, 2023

for 3 h. Area K has imperceptible glare for 12 h of the day, perceptible glare for 1 h of the day, and disturbing for 2 h of the day.

The worst-case glare probability occurs at different times of the year depending on space. The maximum glare probability for area D is 55.7% reached on December 21 at 4:30 pm. Area F has a maximum glare probability of 39.8% at 10:30 am on September 23. The maximum glare probability for area J is 61.7% at 3:30 pm on December 21. Lastly, area K reaches a maximum glare probability of 64.3% on March 20 at 9:30 am. Each area during its worst-case glare probability is displayed in Fig. 11.20.

11.5.2 Dynamic Glass

Dynamic glass was utilized to reduce the glare probability for each area. The hourly glare probability on two of the key dates is displayed in Figs. 11.21 and 11.22. During the typical operating hours of 5:30 am to 7:30 pm on March 20, 2023, the hourly glare probability was analyzed for each of the four selected areas. For both areas D and F, the glare is imperceptible for all 15 h of the typical operating time. Area J has imperceptible glare for 10 h of the day, perceptible for 1 h of the day, and disturbing for 4 h. Area K has imperceptible glare for 13 h of the day and disturbing glare for 2 h.

On September 23, 2023, from 5:30 am to 7:30 pm, the hourly glare probability was analyzed for each of the four selected areas. For both areas D and F, the glare is imperceptible for all 15 h of the typical operating time. Area J has imperceptible

Fig. 11.20 No daylight modifier: worst-case glare probability per space

glare for 11 h of the day, perceptible for 2 h of the day, disturbing for 1 h, and intolerable for 1 h. Area K has imperceptible glare for 13 h of the day and disturbing for 2 h.

To accurately analyze the decrease in glare, each space was examined at the time of worst-case glare based on the unmodified state, as displayed in Fig. 11.24. Area D has a glare probability of 28.7% on December 21 at 4:30 pm. On September 23 at 10:30 am, area F has a glare probability of 10.9%. The glare probability for area J is 61.2% at 3:30 pm on December 21. Lastly, on March 20 at 9:30 am, area K reaches a glare probability of 4.8% (Fig. 11.23).

11.5.3 Overhangs

Overhangs are a cheaper alternative that are intended to reduce the glare probability for each area. The hourly glare probability on two of the key dates is displayed in Figs. 11.24 and 11.25. During the typical operating hours of 5:30 am to 7:30 pm on March 20, 2023, the hourly glare probability was analyzed for each of the four selected areas. Area D experiences imperceptible glare for 13 h, perceptible for 1 h,

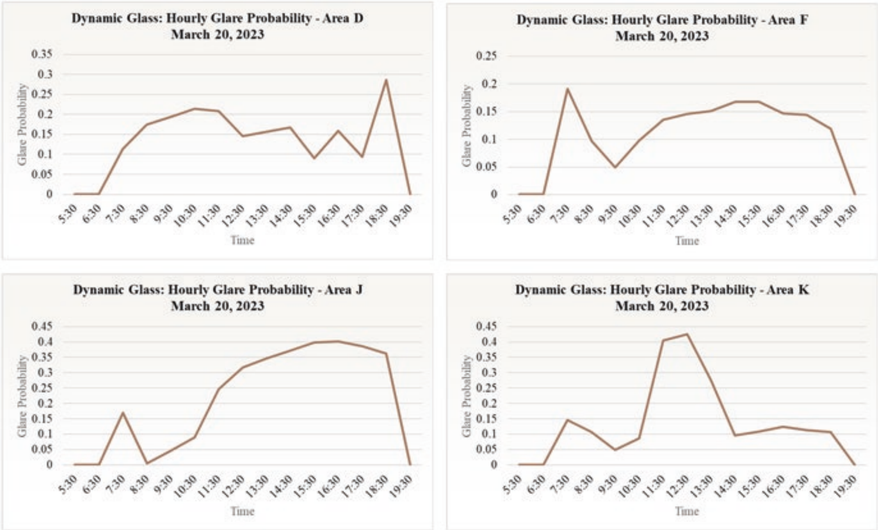

Fig. 11.21 Dynamic glass: hourly glare probability for March 20, 2023

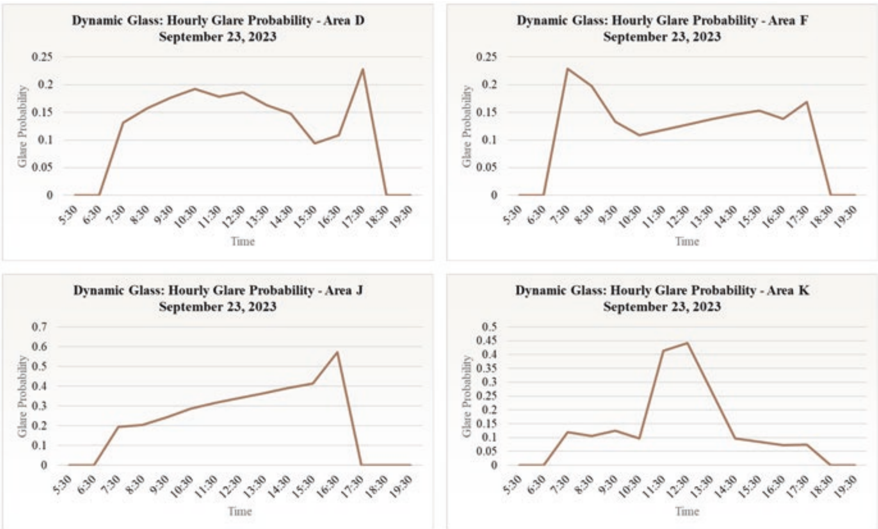

Fig. 11.22 Dynamic glass: hourly glare probability for September 23, 2023

and disturbing for 1 h of the typical operating time. Area F has imperceptible glare for 10 h of the day, perceptible for 2 h of the day, disturbing for 1 h, and intolerable for 2 h. In area J, the glare was imperceptible for 9 h, perceptible for 2 h, disturbing for 3 h, and intolerable for 1 h. Area K has imperceptible glare for 8 h of the day, perceptible glare for 2 h, disturbing glare for 1 h, and intolerable glare for 4 h.

Fig. 11.23 Dynamic glass: worst-case glare probability per space

On September 23, 2023, during the typical operating hours of 5:30 am to 7:30 pm, the hourly glare probability was analyzed for each of the four selected areas. Area D experiences imperceptible glare for 13 h, perceptible glare for 1 h, and intolerable glare for 1 h of the typical operating time. Area F has imperceptible glare for 9 h of the day, perceptible glare for 5 h of the day, and intolerable glare for 1 h. In area J, the glare is imperceptible for 9 h, perceptible for 2 h, disturbing for 3 h, and intolerable for 1 h. Area K has imperceptible glare for 8 h of the day, perceptible glare for 2 h, disturbing glare for 2 h, and intolerable glare for 3 h.

Each space was examined at the time of worst-case glare based on the unmodified state, as displayed in Fig. 11.26 in order to accurately compare the effect of overhangs on the daily glare probability. Area D has a glare probability of 55.4% on December 21 at 4:30 pm. On September 23 at 10:30 am, area F has a glare probability of 39.4%. The glare probability for area J is 61.9% at 3:30 pm on December 21. Lastly, on March 20 at 9:30 am, area K reaches a glare probability of 63.4%. The worst-case glare probability per space for overhangs is shown in Fig. 11.26.

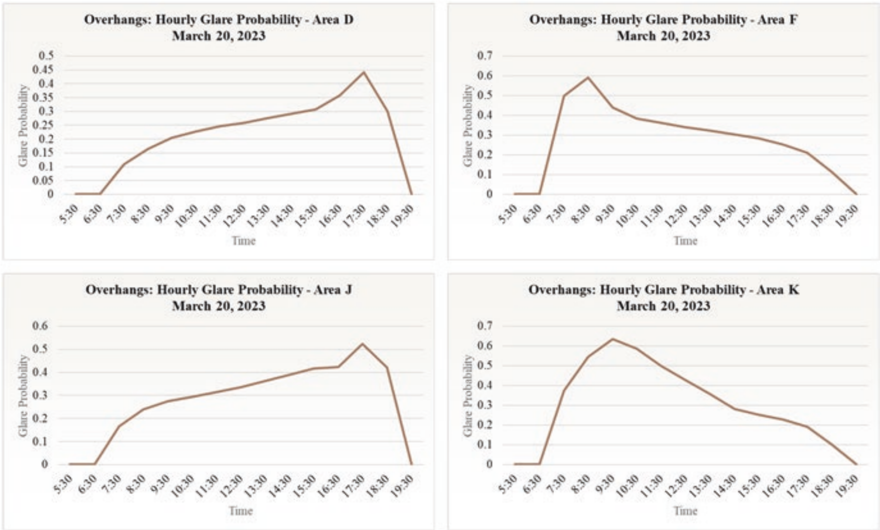

Fig. 11.24 Overhangs: hourly glare probability for March 20, 2023

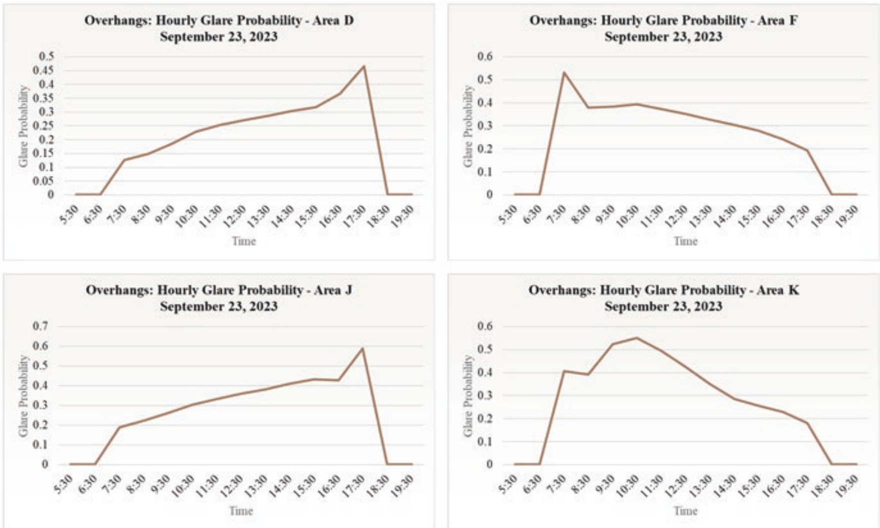

Fig. 11.25 Overhangs: hourly glare probability for September 23, 2023

11.5.4 Perforated Panels

Perforated panels are a commonly used daylight modifier used to reduce the glare probability. They were applied to the model of the Taubman Building and analyzed for areas D, F, J, and K. The hourly glare probability on two of these key dates is

Fig. 11.26 Overhangs: worst-case glare probability per space

displayed in Figs. 11.27 and 11.28. On March 20, 2023, during the typical operating hours of 5:30 am to 7:30 pm, the hourly glare probability was analyzed for each of the four selected areas. Area D has imperceptible glare for 13 h, perceptible for 1 h, and disturbing for 1 h of the typical operating time. Area F has imperceptible glare for 9 h of the day, perceptible for 2 h of the day, disturbing for 1 h, and intolerable for 3 h. In area J, the glare was imperceptible for 9 h, perceptible for 2 h, disturbing for 3 h, and intolerable for 1 h. Area K has imperceptible glare for 8 h of the day, perceptible glare for 2 h, and intolerable glare for 5 h.

On September 23, 2023, during the typical operating hours of 5:30 am to 7:30 pm, the hourly glare probability was analyzed for each of the four selected areas. Area D has imperceptible glare for 13 h, perceptible for 1 h, and intolerable for 1 h of the typical operating time. Area F has imperceptible glare for 9 h of the day, perceptible for 2 h of the day, disturbing for 3 h, and intolerable for 1 h. In area J, the glare was imperceptible for 9 h, perceptible for 1 h, disturbing for 3 h, and intolerable for 1 h. Area K has imperceptible glare for 8 h of the day, perceptible glare for 1 h, disturbing glare for 2 h, and intolerable glare for 4 h.

Areas D, F, J, and K were examined at the time of worst-case glare based on the unmodified state, as displayed in Fig. 11.29, in order to accurately compare the effect of overhangs on the daily glare probability. Area D has a glare probability of

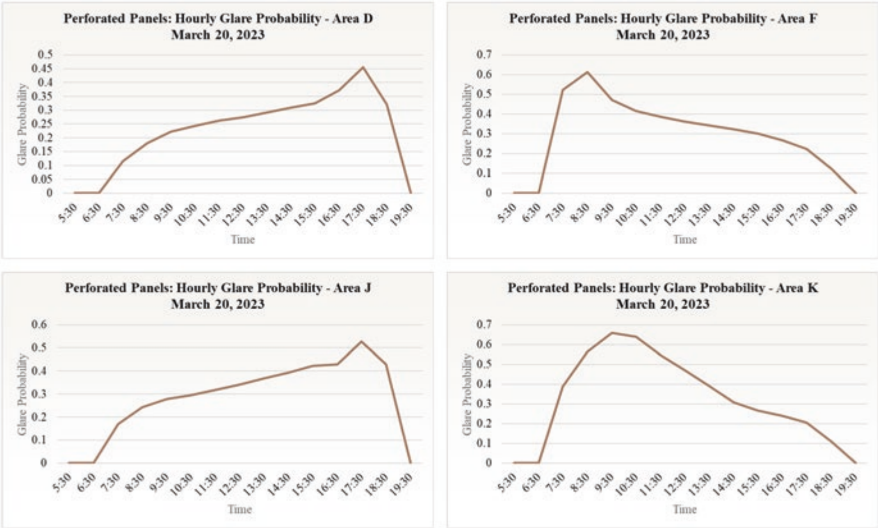

Fig. 11.27 Perforated panels: hourly glare probability for March 20, 2023

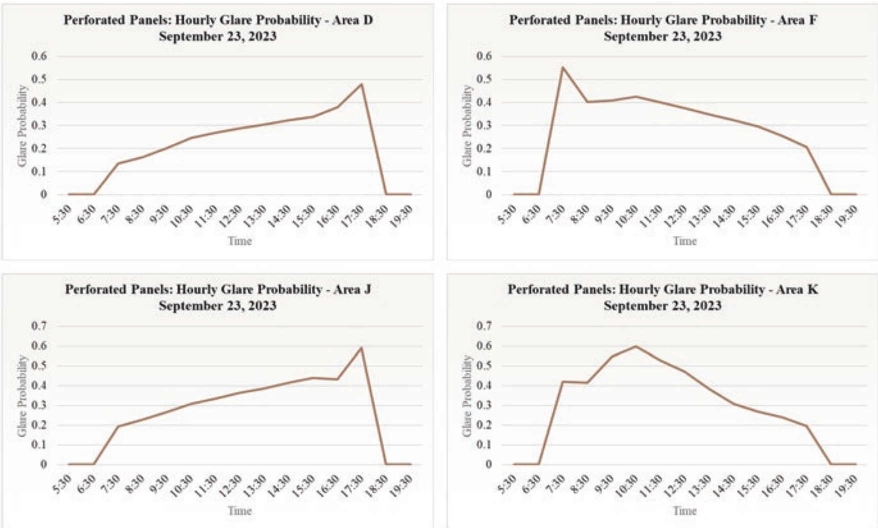

Fig. 11.28 Perforated panels: hourly glare probability for September 23, 2023

56.8% on December 21 at 4:30 pm. On September 23 at 10:30 am, area F has a glare probability of 42.5%. The glare probability for area J is 62.1% at 3:30 pm on December 21. Lastly, on March 20 at 9:30 am, area K reaches a glare probability of 66.0%.

Fig. 11.29 Perforated panels: worst-case glare probability per space

11.6 Comparison and Analysis of the Modifiers

As discussed in Table 11.1, the cost per square foot of each daylight modifier is as follows: $5–$10 for perforated panels, $50–100 for dynamic glass, and $9–$25 for metal overhangs depending on the manufacturer. The costs to implement each option are calculated based on the required material needed for modification of the Taubman Building, as shown in Table 11.3.

The dynamic glass is the most expensive option, with an average cost of $333,450. The next most expensive modifier is perforated panels with an average cost of $33,345. Lastly, the most cost-effective option uses overhangs, with an average cost of $19,397.

It is important to consider that there are many factors that contribute to the selection of the optimal daylight modifier, including performance in light levels within the building, glare probability, solar heat gain, and cost. Table 11.4 outlines the best options depending on the concern. Each modifier is ranked on a scale from 1 to 3, with one being the best solution and 3 being the worst solution for the concern specified in the top row of the table.

Table 11.3 Modifier cost comparison

Modifier	Surface area needed (ft^2)	Cost ($\$/ft^2$)		Total cost (\$)	
		Low end	High end	Low end	High end
Dynamic glass	4446	50	100	222,300	444,600
Overhangs	1141	9	25	10,269	28,525
Perforated panels	1556	5	10	22,230	44,460

Table 11.4 Modifier overall comparison

Modifier	Concern			
	Optimal light level	Glare reduction	Solar heat gain reduction	Cost
Dynamic glass	1	1	3	3
Overhangs	2	2	1	1
Perforated panels	3	3	2	2

11.7 Conclusions

This study investigated the effectiveness of daylight modifiers: dynamic glass, metal overhangs, and perforated panels on optimizing daylighting, glare probability, and solar heat gain with a focus on Lawrence Technological University's A. Alfred Taubman Engineering, Architecture, and Life Sciences Complex Home of the Marburger STEM building. This analysis was performed using AutoCAD, Rhino, and Climate Studio. The floorplans were first traced in AutoCAD from the provided PDFs of the existing building. These drawings were then imported into Rhino to extrude the wall outlines into three-dimensional floors and stacked on top of each other to get an accurate model of the entire building. Each daylight modifier was then applied to the building, and Climate Studio was used to run simulations for daylight availability, annual glare, and radiation. The data were extracted from each simulation and examined to determine the optimal daylight modifier for the building.

Each modifier has its benefits, but as far as performance goes, the use of dynamic glass is the most effective option. It can automatically adjust the tint to the optimal transmissible visibility to optimize the amount of light entering the space via remote light sensors located throughout the building. The perforated panels reduced the solar heat gain but only compromised the natural light levels within the building at these times. The perforated panels overall worsen the daylighting in the building, which may be due to the light reflecting off of it as it is a metallic surface. Overhangs do help the solar heat gain as well, but as far as daylight autonomy and glare probability, they do not make a significant impact.

The implementation of dynamic glass would be the most effective daylight modifier for the Taubman Building at Lawrence Technological University based on performance. With that said, it is important to consider that there are many factors that contribute to this suggestion and could affect an owner's decision to implement the daylight modifier.

Dynamic glass is the most effective for optimizing the light level entering the building and reducing the glare to an acceptable level. It is less effective in the reduction of heat gain since its purpose is to allow in as much light as necessary to achieve the target light level within the space. With this considered, it does effectively reduce the solar heat gain to a more acceptable level but does not reduce it as much as the alternatives. Dynamic glass is also the most expensive option, which is not always within budget for the project.

Overhangs are the second-best option of those analyzed in the project for both optimizing the light level and for reducing the glare in the space. In many spaces, the light level in the space was not modified adequately to provide the target levels for most operating hours, but in some instances, it did bring the light level closer to the target. The glare per space with overhangs was reduced in some areas, but not significantly. Overhangs, however, were the most effective in reducing solar heat gain, outperforming both dynamic glass and perforated panels. They are also cost-effective, being the most affordable option.

Perforated panels were the worst-performing daylight modifier examined in this project in terms of optimizing the light level and reducing glare. In the case that the light level or glare was changed from the current state, it was worsened to bring the light level further from the desired target and increase the glare in the space. However, the perforated panels were effective in reducing solar heat gain, yet not as effective as overhangs. Perforated panels, although not effective for all concerns, is more affordable than dynamic glass.

As newer daylight control methods are found and existing methods are improved upon, the best practice will change to suit the newest technology. It is important to recognize that advances in engineering in daylighting are always progressing and evolving. The industry will continue to find better methods and find ways to optimize the parameters that go into daylighting design. As newer products become more available, their prices will decrease and become more available for lower-budget projects. Here are some future study topics, which can use the results of the current study for controlling the daylighting of university buildings:

- The obtained results for an optimal daylighting option for the A. Alfred Taubman Engineering, Architecture, and Life Sciences Complex are helpful to perform experimental research to verify its effectiveness. This can entail implementing the solution in a specific area of the building and observing how it affects energy usage and occupant comfort.
- The future work can focus on examining occupant behavior to the daylighting system by analyzing how occupant behavior affects daylighting and thermal comfort. This could entail conducting surveys or observational studies to see how users interact with space and how their actions impact how well the various daylighting systems work.
- Daylighting is only one component of a building's design; it is crucial to consider it as future work can focus on integrating the proposed model with other building systems, such as building mechanical/electrical systems.

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Chapter 12
Emotional Response to Different Lighting Conditions

Dalia Saleem and Morteza Nazari-Heris

Abstract Daylight and artificial light have a considerable and significant impact on humans daily. Daylight provides natural light, which saves energy and benefits the environment. However, daylight can cause harsh glares. Harsh glares come directly from the sun and reflect on surfaces, making the environment difficult to work in. Thus, the harsh response of daylight adds to the importance of artificial lights, making them more important to have once daylight is too harsh or nighttime intervenes. Artificial lights provide individuals with many different types of light. The spectrum chart provides a broad selection of colored lights. Colored lights can have a significant impact on individuals' emotions. This chapter discusses the impact of lights on individuals' emotions. The effects of artificial lighting on human physiological and psychological reactions are examined in this chapter with a focus on how human eyes adjust to light, age-related changes in light sensitivity, comfort levels as determined by a visual lighting spectrum chart, and the body's reaction to artificial lighting. Additionally, the study explores the relationship between memory performance and LED illuminance, color temperature, and melatonin suppression. The chapter also examines how artificial light affects mood, considering a person's cultural background, the weather, and how these factors affect light. Finally, it explores how different light hues are seen by people and how that affects perception. The chapter offers insights into how artificial lighting affects people and emphasizes the significance of lighting design and choice for the best human functioning through a study of numerous studies.

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12.1 Introduction

An investigation into the emotional response to artificial light is critically important in the world of lighting design because humans experience and respond to light differently. Artificial color-changing lights have been commonly used in recent years by different generations. Artificial lights can cause harm to the eyes; thus, it is important for the consumer to understand the effect of artificial lighting under different conditions. Most lighting products and lighting designs are not yet optimized for human health and well-being as these can have an influence on humans' comfort levels. Light stimulates the production of serotonin that regulates humans' sleep and wakefulness. Thus, it is important to understand the variable impact on the emotional response to different types of lighting techniques. Artificial lighting can have a huge impact on humans' melatonin during nighttime, even to the point of disrupting the humans' sleeping pattern. Having dimmed light of one lux ALAN for a couple of nights can affect a human's sleeping pattern. People in general are more sensitive to all kinds of lights at night, including blue light [28].

Having daylight or natural light with artificial light is necessary in a workspace since it increases productivity. In general, it is healthy to have daylight in the working space. However, daylight is not always beneficial in a work environment. Consider harsh sunlight coming in from a window and reflecting on a laptop screen causing harsh glare. Or consider that on a cloudy day it is harder to work when not enough light is entering a space. Thus, it is necessary to have both daylight and artificial light. Daylight has also been proven to have a great impact on human sleeping patterns and can uplift a human's mood in a work environment. Therefore, it is necessary to have windows in a work environment [4].

It is important to utilize daylight and artificial light in buildings as both will draw attention to different surface textures and highlight certain areas such as wall art. Lighting also enhances the way we look at an object by making the object appear extra bright or colorful. There are many ways to add daylight to a building such as skylights, windows, or any opening wherein the rays of the sun can be reflected inside the building. Daylight provides natural light to a building without the need for artificial lighting. Daylight can also be used as an energy-saving feature in buildings [14]. Artificial lighting is a man-made lighting source. Artificial light comes in warm temperature light (2000–3500 K), cool temperature light (4000–8000 K), and colored lights. Artificial light, especially colored lights, can affect a human's stress level. Thus, it is important to understand the meaning behind each color of light to use it most effectively and efficiently [3]. Primary colored light of red, green, and blue can impact human emotion greatly since they are such bold dark colors [34]. According to Xie, the color red can affect humans' anxiety levels, the color green can affect humans' relaxation levels, and the color blue can have an impact on humans as nonstimulating color, so it produces more melatonin to the human body, making it easier for individuals to fall asleep. On the other hand, according to Valdez's case study, the brightness of the colors is deemed to be more pleasant than dimmed colors, such as green and yellow, which are least pleasant. For instance, the color green induced greater dominance than the color red [12]. Artificial lighting can be used to highlight surface features and textures in indoor environments, or it can be added to streets to provide light during nighttime. Artificial lighting can be introduced in many different shades and colors and comes in a variety of types, including fluorescent, LED, and incandescent lights [5]. With both daylight and artificial light, the human eye allows individuals to see light and texture differently to explore the architectural beauty of an object. While daylight has its benefits, it can sometimes be harsh on the eye. With artificial light, individuals can manipulate light by choosing dimmable artificial lights or lights with warmer temperatures to enhance how light affects the individual's experience [5].

12.2 Background

Back in the day, technology was not fully developed, so humans relied on the use of daylight during the day, adding windows to homes to provide a light source. The use of candles and oil-based lamps was established during the 1800s to provide a light source during the nighttime. Eighty years later, scientists started exploring the idea of artificial lights to avoid using candle wax or oil-based lamps to find a better way to provide lights in a way that did not adversely affect human health. The use of candles or oil-based lamps can cause harm to humans, and some candles are toxic to children and animals. With that came the idea of artificial light in warm light temperature that imitates the same shades as candles or lamps [1]. Daylight is important to have in buildings as it increases productivity and heightens mood in general. Windows, open spaces, and sliding doors have been utilized to bring daylight into houses or buildings during the daytime. Unfortunately, candlelight did not provide enough light inside these types of spaces. Moreover, because streets were dark at night, the need for artificial light started to develop more and more [17]. In the mid-1800s, Sir William Herschel initiated an interest in utilizing daylight. Herschel believed most light comes from white light that contains many different wavelength ranges [32]. His experiment began with him placing a prism glass in front of daylight, which allowed him to see all the different shades of the rainbow, causing the wavelength to bend slightly to different angles due to optical refraction. He measured the lighting temperature using a thermometer for each color of the rainbow. Herschel's experiment resulted in his discovery that different shades of light result in different temperatures, and the further away the daylight color, the higher the resultant temperature [32]. Almost a century later, scientists began to show more interest in the rainbow lighting spectrum. Scientists discovered that the visible lighting spectrum varies from different shades of light and temperature. Scientists compressed lighting temperature to be viewed as warm light temperature ranging between 2700 and 3000 K; cool light temperature, ranging between 3000 and 5000 K; and daylight temperature, ranging between 5000 and 6500 K [19]. Thus, lighting was displaced based on its needed environment. The visible lighting spectrum chart contains seven different colors (rainbow) ranging from the color red to the color violet. However, the lighting spectrum chart involves more than just seven colors. There are many more colors that are not visible to the human eye and some that only certain types of human eyes can see. Most human eyes are unable to distinguish the color indigo due to its similarity to the colors blue and violet. Similarly, the color cyan on the lighting spectrum chart can only be detected by a select number of human eyes. Consequently, the visible lighting spectrum varies from different shades of light and temperature. Human eyes can detect visible light wavelengths from 400 to 700 nm with peak sensitivity at 500 nm, with 400 nm being the color violet and 700 nm being the color red [19].

12.3 How Human Eyes Adapt to Light

Human eyes adapt to lighting differently, and their adaptation changes throughout the span of a lifetime. The human eye contains the iris, retina, and pupil. The latter, the pupil, is the part that allows humans to see light. The iris acts as a structure made of miniature muscle that works with the pupil to give humans the ability to see light [2]. Eye color is defined by the iris. In a dim or a dark room, the eye muscle relaxes causing the pupil to dilate, allowing more light to enter the eye. Contrarily, the muscle contracts in a bright room causing the pupil to constrict, thereby minimizing the amount of light entering the eye. Once light enters the eye, it filters through the retina onto light-sensing cells that live in the back part of the eye. These cells are called photoreceptors. Photoreceptors are divided into two types: rods, which are responsible for nighttime vision, so the eye has low resolution, and codes, which are responsible for daylight vision. Codes are fewer in number when compared to rods, and their main responsibility is to provide the human eye with color vision. Both photoreceptors allow the eye to adapt to certain lights based on the environment the eye is in. Some lights can be strong on human eyes, especially if the light hits the eye directly, which leads to photophobia, also known as light sensitivity [31].

12.4 Light Sensitivity Based on Human Eyes and Age Difference

When a light is aimed or focused directly on the human eye, this can cause many problems such as nausea, dry eyes, dilated pupils, migraines, eye infection, sunburned eyes, and more. Having a light directed into one's eyes has the potential of causing a long-lasting eye problem as well as minor issues such as trouble adjusting eye vision back to normal [10]. Studies have shown that a light-toned eye color sometimes experiences light sensitivity differently than a dark-toned one. Light sensitivity also differs based on the age of the person. Younger people, especially children, have strong eye muscles, causing their eyes to handle direct lighting very well with minor sensitivity. With older people, eye muscles tend to be weaker, causing the pupil to decrease. Therefore, less light is visible and can enter the eye, causing the eye to receive only about one-third as much light as other-aged adult persons. Due to eye muscle weakness, older people will have a harder time seeing in a dark room and their eyes are more prone to glare and sensitivity [31].

According to Chellappa, the human eyes preserve artificial light during the day and nighttime. Thus, it is important to understand the target biological mechanisms of each individual eye and how light can affect the eyes. It is important, then, to keep in mind that light can affect people differently based on age and vision. The finding of the research concluded that individuals prefer light in different settings, so it is important for lighting designers to provide different LED lighting settings when designing lights to allow personalized lighting solutions that will improve individuals' health and quality of life [7].

12.5 Comfort Level Based on Visual Lighting Spectrum Chart

The light spectrum chart contains seven different colors: violet, blue, cyan, green, yellow, orange, and red. With artificial lighting industry improvements, scientists noticed that people were feeling different emotional responses with certain types of colored lights. Red light helps increase melatonin, which leads to better sleep at night which can, in turn, improve a person's mental health. Melatonin suppression has been proven over time to decrease with light intensity, so knowing which light to choose during the nighttime is essential. Having a blue light in a room may help reduce anxiety. For many people, blue light can be extremely relaxing, thus leading to improved mood. Also, it is important to understand that lighting temperature affects greatly how the light will look in a room, as shown in Fig. 12.1. For instance, lights that are less than 2000 K in temperature are very similar to candle lights. These types of lights are best used to achieve low light in a room. Lights with a lighting temperature between 2000 and 3000 K have soft glow and appear as yellow light. These lights are recommended for use in living rooms, bedrooms, and outdoor spaces due to their calming effect. Also, 3100–4500 K lights have bright white light, which helps people focus on given tasks. They are best used as task lights in places such as kitchens, vanity rooms, and workspaces. Daylight temperature or blue-white temperature lights range between 4600 and 6500 K and have very bright light. These types of lights are mainly used in workspaces. Lastly, 5600 K and up are bright blue lights that are often used in commercial buildings [19]. It is important to understand the lighting spectrum chart as well as lighting temperature to offer a favorable light type based on client preference. To conclude, humans have high sensitivity to light during the nighttime, so it is recommended to use a minimum of 30 lux during the night to avoid disrupting sleeping habits. Although this result may vary based on individual preferences, it is still important to use 30 lux minimum to

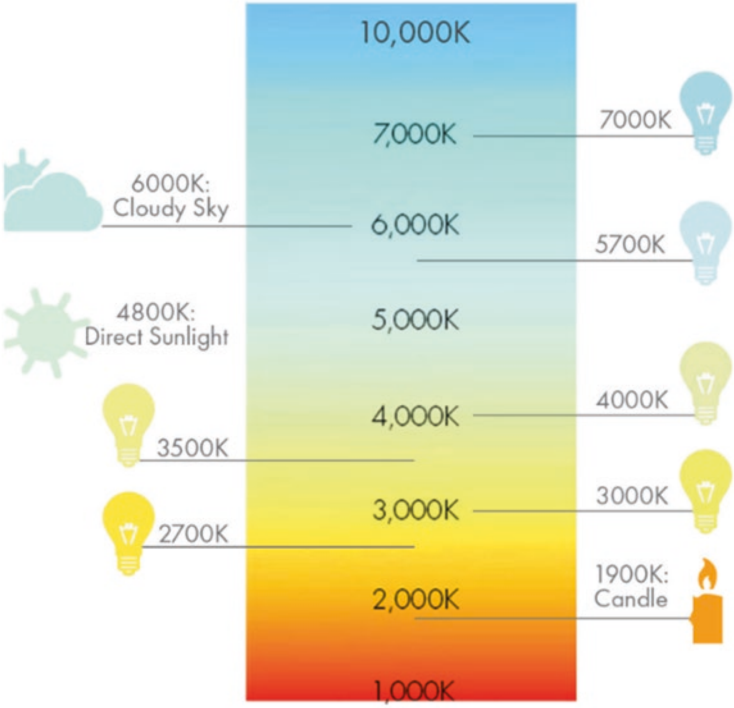

Fig. 12.1 Kelvin color temperature scale chart [19]

help improve individuals' circadian systems to avoid any health issues or diseases that may occur in the future [24].

12.6 Artificial Lighting vs Human Physiological Response

Recent studies have shown that human behavior relative to light differentiates based on a cardiant cycle. Human eye muscles weaken the older the human becomes. Thus, light sensitivity occurs. Spitschan and Nayantara discuss the suprachiasmatic nucleus, also known as SCN, which is the central pacemaker of the circadian system. The retinohypothalamic tract (RTH) sends information about environmental illumination to the SCN. Therefore, humans can distinguish the difference between daytime, nighttime, hormone variation, and changes in body temperature. SNC also affects melatonin production. According to the article, when the human eye gets exposed to light during nighttime, circadian rhythm occurs and inaugurates the human nighttime cycle. Therefore, light has a significant impact on the human eye during nighttime. The article recommends that people avoid any bright light during nighttime to avoid interfering with melatonin in the body, which can then delay or alter the sleep schedule. Based on a recent study done by Phillips et al., "the most sensitive observer was almost 60 times more sensitive than the least sensitive observer." The human body observes light differently due to age, health status, and the amount of caffeine the individual consumes in a day, all of which can affect the sleep cycle.

Recent architectural lighting design studies suggest the importance of light use during the day, as well as the importance of the light comfort level for individuals during nighttime while minimizing the negative effect of light on the eyes. Brown and Wright are a group of international lighting experts who suggest the use of a minimum of 250 lux during daytime, 10 lux during evening, and 1 lux during the nighttime. The Brown and Wright group experiment was created with the use of certain variables such as age, sleep schedule, health, ethnicity, and gender. The results showed significant reduction in melatonin suppression when they used a minimum of 1 lux during nighttime. Using this application, individuals expressed that they felt at ease in going to sleep. It is important to note that it is extremely difficult for laboratories to conduct the same experiment on different individuals to compare results. While the results will vary, they will be similar enough to the ones the Brown and Wright group found in their experiments to give lighting experts some understanding of how light affects and causes melatonin suppression [27].

12.7 How Illuminance Affects Melatonin Suppression

This case examines the level of the light spectrum and its effects on human melatonin. The study involves 16 participants whose ages range between 21 and 50 years, studied during normal bedtime hours while taking into consideration 30 min of commute to the laboratory. The participants were exposed to different types of lights from the spectrum chart for 3 h using a 450–500 nm wavelength, enhancing the power level on a short wavelength to see the melatonin production. The participants were given the Ishihara color vision test, with 14 out of 15 being the most prevalent participation score. Participants were asked to fill out a consent form beforehand and had little to no expectation of what was to happen. The participants were paid at the end of the study. It is important to note that, to get the most accurate results, excluded from the study were people who were pregnant or color blind and those who suffered from migraines, epilepsy, or who drank more than six cups of coffee daily. The participants were exposed to three light conditions on three different days 1 week apart. Participants were also asked to keep track of their daily sleeping schedules. The 16 participants were composed of nine men and seven women. The experiment schedule was divided between 2 months. Eight of the participants were scheduled to do the experiment in September 2016, and the others were scheduled in October 2016 due to work conflicts. Participants were asked to avoid drinking alcohol and coffee on the day of attendance to get the best and most accurate result. In the laboratory, the participants started with 1 h of exposure to high dim light. The light was dimmed gradually for the next 3 h. Use of the restroom was taken into consideration during the experiment. To avoid or minimize the impact of the light in hallways, the participants were required to wear blue-blocking glasses. At the end of the experiment, the participants' saliva samples were sent to the chrono work laboratory for melatonin analysis. The high MEF (450–500 nm wavelength) condition was expected to cause a high melatonin suppression. while the low MEF (400–430 nm wavelength) level was expected to cause less melatonin suppression. Wavelength affects melatonin much more than white light, illustrating the criticality of the illumination level over the wavelength of the spectrum chart. Shorter wavelength (400–430 nm) causes less melatonin suppression. The experimental results showed little to no difference between high and low MEF spectra [26].

12.8 The Correlation of LED Illuminance and Color Temperature on Memory

LED light has been proven over the years to be easy to operate and use in homes, offices, and commercial spaces. LED lights are offered in assorted colors and come with different lighting temperatures. LED lights also use less power than other luminance. LED lights come in many different types such as luminance fixtures, strip lights, cove lights, and pendant lights. Typically, less expensive, LED lights can brighten up a space without the need to use high-voltage power. Most LED lights are dimmable, making them a great tool to use during nighttime to help reduce melatonin suppression. Lee and Kim discuss the importance of lighting on human emotions, melatonin suppression, and memory performance. Memory performance has drawn more interest in current times due to heightened concerns regarding dementia. Recently, lighting experts have shown interest in the relationship between light and its effect on human memory. Lights, in general, can be divided into three different types: color of lights, illuminance of lights, and temperature of lights. Most of the research that has been done regarding the illuminance of lights has shown that there is a human memory improvement while working or studying under a bright light when compared to working or studying in a dimly lit area. However, some studies have shown an improvement in memory retention in a study area that is dimly lit as opposed to one using bright light. Experiments have demonstrated that easily handled tasks proved out well using bright light. On the other hand, difficult tasks showed much more improvement using a dimmable light at 200 lux. Color temperature lighting studies show mixed results [16].

To prove lighting temperature and lighting illuminance effects on the brain, Lee and Kim [13] conducted an experiment with 30 participants, 19 men and 11 women, with an average age of 21.6 years. The experiment was explained in detail to the participants and a pledge was expected from each participant prior to the experiment. The participants were also asked to achieve enough sleep and to avoid drinking alcohol and coffee if possible. The experiment included the use of an automatic LED light on a light sensor, a color lighting temperature sensor, and a light control system to construct an appropriate lighting environment. The power was set at 10–20 W and the automatic lighting device was equipped with 2.4 GHz remotely to control model and pc environments, as shown in Fig. 12.2. The experiment was conducted in a laboratory, and any other lighting source was blocked with the use of light-blocking curtains. The lab temperature was 24 °C, and a humidity level of 50% was provided to meet ASHRAE standards. The tool that was used to measure working memory was the n-block test. The n-block test is mainly used in psychology and cognitive neuroscience to measure a specific part of working memory. The participants were required to adapt to the light environment by staying for 2 min in the dark room and 2 min in the light room. The experiment was conducted for 4 h in the afternoon. The results showed improvement in the working memory for an average number of 53.4 under 1000 lux and 5000 K light conditions. However, using 400 lux and 7000 K, the average number was 42.73, thus showing the lowest results in the working memory, as shown in Fig. 12.3.

Lastly, the study found that working under a bright light can help improve working memory. Therefore, 1000 lux and 5000 K was the best lighting temperature for working memory. In colored temperature, there were inconsistent results varying between 3000, 4000, and 6000 K to improve the working memory based on results from different individuals [16].

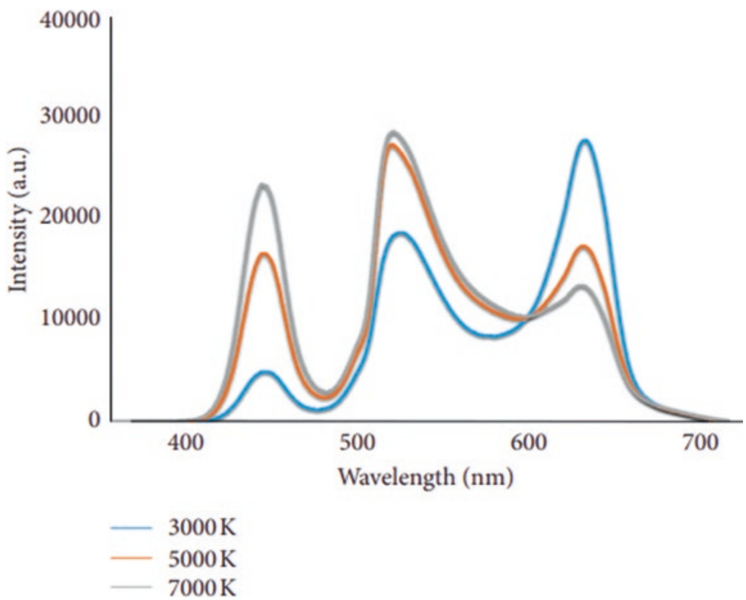

Fig. 12.2 Spectral power distribution [16]

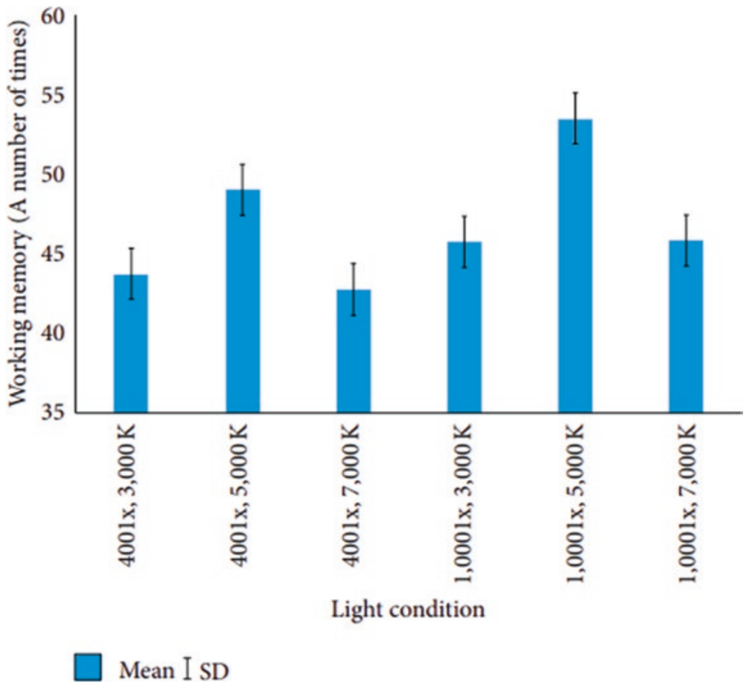

Fig. 12.3 Difference in working memory according to light illuminance and color temperature conditions [16]

Table 12.1 Summary of lighting conditions [21]

Lighting conditions	Color temperature (K)	Average room illuminance (lx)	Desk illuminance (lx)	Uniformity ratio
1	3000	266.67	306.00	0.81
2	3000	807.74	731.25	0.80
3	4000	269.25	321.75	0.70
4	4000	821.00	749.50	0.72

12.9 The Impact of Artificial Light on Human Mood

McCloughan et al. [21] discuss how lighting can affect an individual's mood. The article reviews an experiment using a group of 64 participants (26 females and 38 males), with ages ranging from 24 to 65, using two illuminance levels and two CCT levels, as well as two experimenters to conduct the experiment. The participants were placed into two identical rooms with white walls and ceilings as well as shutter-covered windows. Table 12.1 shows the results based on lighting conditions, color temperature, average room and desk illuminance, and uniformity ratio. The identical rooms also had six TLD surface luminaires with p3 standard prismatic controllers. The participants were able to change the lighting temperature by using lamp ballasts. Mood was assessed for five types: anxiety, depression, hostility, sensation-seeking, and the positive effect. Also, participants were asked to rate the following: brightness, clarity, warmth, attractiveness, comfort, and pleasantness.

At the beginning of the experiment, participants were randomly assigned to experience the two illuminance levels or the two CCT levels without the experimenter's knowledge. The mood assessment experiment was divided into a computer session that lasted 5 min and the rest of the experiments that lasted 35 min. Thus, mood assessment was expected to last approximately 45 min. The mood of participants was assessed using the Multiple Affect Adjective Checklist, also known as MAACL-R, a sensitive indicator device. The resultant data were analyzed using MANOVA and ANOVA on each level individually. The participants were paid for their time at the end of the experiment. The results of the experiment read that males were higher in the negative affect than females, people prefer sensation seeking under low illuminance level, and lastly, hostility was greater under warm temperature CCT. The results of the experiment differentiate between genders [21]. The conclusion was that females had higher positive affect than males as well as higher sensation-seeking than males. Gender difference proved a key factor in the results of this experiment. It is important to note that this experiment was conducted in 1998 using newer technology compared with older technology to prove newer technology accuracy. The purpose of conducting the experiment is to help interior designers better understand individuals' comfort levels with artificial lighting.

Table 12.2 summarizes similar types of case studies that were published within the past 5 years. The experimenter highlighted the objectives, methodology, and conclusions of each reference.

12.10 Cultural Background, Weather, and Their Effect on Light

The way humans preserve light colors and temperature can differ based on the individual's cultural background. The experiment was based in America; thus, the results might be different if the light is exposed to a person from the Middle East, as they often like bold colors that represent their culture and background. Most Middle Eastern people are Islam Arab. And the color of Islam is green as it means happiness and peace; therefore, many Arab people might prefer the color light green over other color lights as it makes them feel at peace. Even though green can be a harsh bold color to look at, some cultures are accustomed to it and would prefer it over other colors. Psychologically, the color light blue means imagination, safety, and protection. Similarly, in the United States, the color blue represents peace, happiness, and patriotism. Therefore, it explains why people feel lulled by the color light blue as it personifies peacefulness [6].

Table 12.2 Literature review table

References	Objective	Methodology	Conclusion	Year
Leccese et al. [15]	Used six classrooms at the university building to assist the indoor comfort light quality Daylight glare was an issue in all the presented classrooms The LQAM method presents a shading system to avoid glaring	LQAM is the deviation of specific lighting parameters to the reference calculations taken from the international technical standards table Using LQAM as a lighting quality assessment method to determine the indoor comfort level Based on the selection of five lighting criteria 470 evaluation questions filled out by different groups of students to determine a comfortable lighting quality in the classrooms	Initially, there was an absence of shading in all the classrooms that were used in the assessment. Once the shading was determined, it was recommended to use shading devices in the classrooms to improve the quality and comfort of the lighting Recommending application of LQAM for educational buildings such as classrooms to help assist with the lighting quality and comfort level when the rooms are being renovated Helpful tool to use for architects, engineers, etc., for pre-renovations to ensure a comfortable lighting quality in the rooms	2020
Liu et al. [20]	Investigating the classroom lighting based on students' perspectives Lighting can have a great impact on student studying To determine the individual's color preference, to improve focus and study impact overall for students in the classrooms	Two experiments were conducted in a classroom located at Wuhan University in China at 6:30 pm One experiment included the use of tubular LED luminaries, and the other experiment used LED panel luminaries 79 college students were divided into three groups and placed in a classroom to determine the emotional aspect of lighting and its effect on them The experimenters were also given Anfimov tests to determine sleep/productivity levels The experiment was conducted in the span of three days and participants were given different tasks in which to perform	Indoor lighting has a significant impact on atmosphere perception and skin preference Paper color was determined to increase reading comfort Increase of visual fatigue was determined after a 2-h study session Indoor lighting decreased the level of visual comfort while reading	2020

(continued)

Table 12.2 (continued)

References	Objective	Methodology	Conclusion	Year
Li et al. [18]	The effect of indoor light and CCT based on emotional perspectives The effect of light therapy and its impact on human eye exposure in the long term	24 participants were required to come into a laboratory for at least two days for the experimental design The experimental design includes a mixed model design that explores the individual and interaction regulation of illuminance to lights and CCT indoor light exposure	During the face judgment (LMM), the low CCT decreased the humans' negative responses to light LMM results show that CCT and illuminance did not have a huge impact on sleepiness and did not affect mood During the facial expressions, the participants felt sad when shown a low soft light and low CCT In general, the mood remained insensitive to illuminance and CCT during the experiment	2021
Vetter [31]	Lighting has an effect on humans biologically. Thus, it is necessary to understand the use of different types of lights to maintain visual performance and visual comfort Understanding color lights and their impact on any drawings/rooms	Summarizes the psychological effect of lights on humans such as the impact on the human sleep cycle, fatigue, alertness, and the regulations of circadian and neurobehavioral functions Due to the improvement of LED light technology over the years, LED light can be deemed to support human health	Lighting can have a great impact on a human sleep schedule; thus, it can impact holding daytime jobs Based on the experiments, it is recommended to have highlights during the day and low-potency light during nighttime	2022
Day et al. [9]	The effect of daylight in buildings and its impact on reducing energy Daylight may have a negative impact on humans if employed poorly, causing eye glare, eye strain, and headaches It is necessary for designers to understand daylight and its effect on human comfort	Three commercial office buildings in the United States were used to conduct an experiment to determine the effect of daylight on humans Each building has different types of shadings such as: Automated blinds Roller shades Electrochromic glazing The report conducts the physical data and the surveys	Building two has an over skylight and received a negative response from the participants due to its electrochromic glazing window designs Participants were highly satisfied with automated blinds and roller shades. Thus, this building received a positive response from participants due to having a higher perceived level of productivity	2019

(continued)

Table 12.2 (continued)

References	Objective	Methodology	Conclusion	Year
Kim et al. [13]	This case study examines the importance of color and its effect on human emotions in a luxury hotel setting A number of customers were asked to stay in a room to determine the impact of colored lights in a luxury setting preference to determine how this aesthetic prescription benefits consumers as well as companies	A luxury hotel room was painted with different types of colors using the SOR model Using SOR model to determine the psychological effect on humans based on specific color choices	Having muted and bright colors gives the appearance of a classic and expensive layout Customers felt pleasure and dominance in matte and bright-colored room The results determined the following: colored lights give off a more classic aesthetic Warm-colored light gives off sophisticated, creative affect	2020
Shishegar et al. [25]	Determining the effectiveness level based on lighting spectrum in older adults Lighting in different home settings and its effect on older adults Determining which light is best to use and its effect during bedtime	Investigation takes place in a living room setting in a house to determine the effect of different lighting color and temperature within 9 days. 21 older adults participated in the experiment Applying direct and indirect lights (500 lux) lights during the time 8:00–12:00 am. One illuminance stayed at one lighting setting, and the other gradually dimmed throughout the day	L2 light conditions (gradually decreasing throughout the day) helped increase sleep duration during nighttime and made the person feel more comfortable in general L1 decreased sleep duration at night, causing disturbance in older humans' sleep	2021

(continued)

Table 12.2 (continued)

References	Objective	Methodology	Conclusion	Year
Müezzinoğlu et al. [22]	A case study was conducted to determine student productivity levels using three lighting strategies To increase individual student productivity levels in the classroom	113 students participated in the case study by answering a questionnaire regarding lighting preference The data were then collected, compared, and analyzed using the SPSS package program	High light temperature space with daylighting received negative feedback from students Room with low light temperature and some daylight received positive feedback from students stating they felt productive Male students felt more productive in the low indoor lighting setting Low color light temperature received positive feedback more than daylight in a space/ room	2021
Li et al. [18]	Light exposure over time has been proven to damage the human eye in the long run Light causes changes in human moods and has a significant effect on the human sleep schedule	The material used in the experimental phase included different lighting temperatures such as: A 2 (CCT level: 2700 K vs 6500 K with 2 illuminances: 100 lux vs. 1000 lux at eye level, within space). Participants were asked to choose between a morning or afternoon session with a minimum of 2 days in between each experiment. The total experimental duration for each participant was 2 days	The results for CCT: 2700 had a positive impact on the participants During the face expression tests, it was determined that most felt comfortable under 2700 K lighting temperature The results for CCT 6500 K received a negative impact on participants. However, participants responded faster to the emotional pictures under 6500 K	2021
Park et al. [23]	The importance of understating ultraviolet (UV) and blue light and their effect on people UV lights are harmful to humans Blue light causes a nerve crush to the optic nerve, so it strains the eyes, causing eye damage	The methodology includes carbon dot films, which imitate a strong UV and blue light absorption Synthesis of carbon dots that included deionized water and acetone that was filled into a container and stirred using a magnetic stirrer for half an hour	Blue Region UV films decreased, and the cool light emission changed to warm white light The fabrication of carbon dot films proved to have a strong absorbance peak as well as a strong blue excitation wavelength; thus, it decreases harsh light to protect the human eyes	2019

In Asian countries such as China, the color red means happiness and good luck. However, in the United States, the color red means stress; some might argue the color red means energy or even anger. To that point, a few people report in the experiment feeling angry can make them feel energized and not stressed. In China, the color green means health. Similarly, in the United States, the color green means hope [6].

In terms of lighting temperature, many European countries use warm temperature light as it is healthier for the eyes than cool temperature light. As the United States has many people from different backgrounds, the light temperature preference differs as well. Some individuals prefer more warm light temperatures, while others prefer more cool light temperatures [29]. Moreover, some individuals prefer a mixture of warm and light temperatures to imitate daylight. On the other side of the spectrum, Middle Eastern countries mainly prefer cool light temperatures, as it has a blue hue, causing an increase in productivity. It is also important to note that some countries in the Middle East, such as Gulf countries, prefer more of cool light temperature as it provides a sense of cooling when the weather is hot in the summer and sun is shining all day [33].

Finally, it is necessary for the readers to understand that different cultural backgrounds can have a great influence on the way humans perceive light. Moreover, the light experiment for this paper was held in the winter season in Michigan [11]. Perhaps, if the experiment was held in the summer, results may have been different. In kind, if the experiment was held at a warmer state, the results may have been different. The experimenter was not able to do the experiment again in the summer or in a warmer climate to compare the results for differences applicable to weather.

12.11 Light Perception to Different Light Colors

The human eyes come in many different shapes and colors. Understanding the human eyes and how they function is necessary as it impacts the way humans preserve lights. Everyone has a unique eye color, although most can be combined in the brown region and the blue region. Some are unique and a mixture of both, such as heterochromia.

The countries with the most brown-eye people are those countries in southwest Asia, such as the Gulf countries. The Gulf countries are known for having people with black eye color, as well. The color of the eye is not actually black; it is dark brown, and the eye has more pigmentation causing the color to appear black rather than dark brown. This permits the theory that Gulf countries prefer cool light temperature due to the heat. Brown eyes or dark eye-colored individuals prefer cool light temperature. Research has shown that light-colored eyes have less pigmentation; thus, they are more sensitive to cool temperature light and harsh sunlight. Moreover, people with light eye shade prefer warm light over cool light temperature. On the other hand, individuals with dark eye shade have more pigmentation, so it is easier for them to adapt to cool temperature lights. Although blue eye color is more sensitive to cool light temperature, their night vision is clearer and stronger than darker shade eyes [8].

Color-changing eyes are known to be rare, though human eyes can change color based on light level and wavelength. The types of clothes the human wear can also have a minor influence on how eyes might change color. Sun exposure can cause the eyes to produce more melatonin. The melatonin causes the eye color to change. Finally, looking at a bright light can also cause eye color to change. Individuals with heterochromia have less pigmentation in the eyes, causing their eyes to be sensitive to blue light. Heterochromia occurs when the irises in the human eyes are different color due to genetics, diabetes, or eye surgeries. Thus, it is recommended for heterochromia individuals to use sunglasses while exposed to sun or bright light and use warm light temperature when in a working environment to avoid harming the eyes [30]. Lastly, human eyes can have an impact on the way humans perceive light. Different colored eyes or color-changing eyes can impact the way humans preserve light. So, light companies and manufacturers should always educate their consumers on light, and how light can impact the human eyes negatively. Although eye color examination was not conducted in the light experiment, it is important to note the eye color importance and how it might change results if the experiment was to be conducted differently.

12.12 Conclusions

Humans are significantly affected by both natural and artificial lighting, with daylight offering the most environmentally friendly and energy-efficient light. However, glaring sunlight can make it challenging to work in some settings, highlighting the significance of artificial lighting. The effects of artificial lighting on human physiological and psychological responses are examined in this chapter, along with age-related variations in light sensitivity, comfort, and the body's reaction to such lighting. The chapter also analyzed the connections between LED brightness, color temperature, and melatonin suppression and memory performance. The chapter examined how mood can be influenced by artificial lighting in connection to diverse cultural contexts and weather, as well as how different light colors are perceived and influence perception. The spectrum chart provides a wide range of colored colors that are available in artificial lighting and have a significant emotional impact on people. Based on several research studies, the chapter emphasized the significance of lighting design and selection for ideal human functioning. The harsh response of sunshine and the negative impacts of artificial lighting on human physiology and psychology, although natural daylight has energy-saving advantages, underscore the significance of carefully planning and choosing artificial lighting for the best results.

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