

Review

Advances in Building Energy Management: A Comprehensive Review

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Abstract

Buildings are a significant contributor to global energy consumption and greenhouse gas emissions, making their efficient management critical for achieving sustainability goals. This review aims to provide a comprehensive synthesis of recent advancements in building energy management, with a focus on emerging technologies, renewable energy integration, energy storage, simulation-based optimization and life-cycle costing (LCC) and carbon assessment (LCA) frameworks. Furthermore, a structured and systematic methodology was employed to select, organize, and analyze the relevant studies. The review highlights promising strategies, such as IoT-based smart energy systems, which have demonstrated up to 30% reductions in energy consumption. Furthermore, the integration of renewable resources such as solar, wind, geothermal, and biomass with thermal and electrical storage supports peak load reduction and improves resilience. Widely adopted simulation platforms (EnergyPlus, TRNSYS, DesignBuilder) enable robust evaluation, while LCC and LCA frameworks provide economic and environmental insights. Despite these advancements, challenges persist in data quality, system interoperability, and the absence of standardized evaluation methodologies.

Keywords: energy management; sustainable development goals; internet of things; digital twin; energy storage; renewable energy



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1. Introduction

In recent times, the idea of buildings that are both decarbonized and exceptionally energy-efficient has risen to considerable importance. Buildings significantly contribute to global energy consumption and greenhouse gas emissions, representing 40% of total energy usage, with projections indicating further growth globally [1,2]. Their operations heavily rely on fossil fuels, resulting in substantial environmental impacts and natural resource depletion [3,4]. Over the past 40 years, energy demand from buildings has risen by 1.8% annually, predominantly driven by developing nations. Demand is anticipated to exceed 4400 Mtoe by 2050 [5]. In the European Union (EU), energy consumption in buildings constitutes roughly 40% of overall energy usage and 36% of CO₂ emissions [6].

In 2022, direct CO₂ emissions from building operations decreased to 3 gigatons, whereas indirect CO₂ emissions increased to nearly 6.8 gigatons. This decline in direct emissions represents a slight year-on-year reduction, contrasting with the trend observed from 2015 to 2021, during which direct emissions grew at an average rate of approximately 1% per annum. Concurrently, indirect emissions from building operations increased by approximately 1.4% in 2022, indicating a growing reliance on electricity [7].

To mitigate global warming, global building emissions must be reduced by 50% by 2030, aiming for net-zero life-cycle emissions across all buildings by 2050 [8]. With projected decreases in heating demand and substantial increases in cooling needs due to global warming, sustainable energy management in buildings has become increasingly critical. Strategies such as optimizing HVAC, lighting, insulation, and integrating smart technologies can reduce energy consumption by up to 50%, offering significant environmental and economic benefits. Improved efficiency not only lowers operational costs but also enhances energy security by reducing reliance on fossil fuels [4].

Improving energy efficiency in buildings not only contributes to environmental sustainability but also enhances economic performance and occupant welfare by providing healthier, more comfortable indoor environments. Energy efficiency and electrification drive decarbonization in Net Zero Energy (NZE) buildings sector, reducing dependency but not achieving complete reduction in energy consumption and emissions [9]. Since energy efficiency directly lowers energy demand and related carbon emissions, it is essential to reach NZE by 2050 [10]. In order to provide a shared vision for a peaceful world and its people, the United Nations unveiled the Sustainable Development Goals (SDGs) in 2015 [11]. Energy efficiency in buildings contributes to several goals, specifically SDGs 3, 7, 8, 9, 11, 12, and 13, by reducing energy demand, supporting clean energy integration, fostering innovation, and mitigating climate impacts [12], as illustrated in Figure 1.



Figure 1. SDGs in the context of building energy management, highlighting the role of energy-efficient buildings in promoting sustainability goals across environmental, economic, and social dimensions.

In light of these global objectives, there is a growing need to explore how technological, economic, and environmental strategies within building energy management can advance SDG-aligned targets for efficiency and sustainability. This review, therefore, synthesizes recent advancements in building energy management, encompassing emerging technologies, renewable energy integration, energy storage solutions, simulation tools, and life-cycle

cost (LCC) and life-cycle carbon assessment (LCA) methods. Unlike earlier reviews that have focused on specific technologies such as Phase Change Materials (PCMs), Building Energy Management Systems (BEMS), or solar integration, this study highlights the integrated and complementary role of these approaches in enhancing building performance. By bridging technological innovation with LCC–LCA frameworks, this review presents a holistic perspective on achieving energy-efficient, cost-effective, and environmentally responsible buildings. Furthermore, a structured and systematic methodology was employed to select, organize, and analyze the relevant studies. The literature search was conducted across prominent databases such as Scopus, Google Scholar, and ScienceDirect, with a focus on publications from 2020 to 2025, prioritizing recent studies (2020–2025) to ensure the relevance of the findings. Keywords such as “building energy management,” “BEMS,” “thermal energy storage,” “renewable energy integration,” “digital twin,” “IoT,” and “optimization in buildings” were used to identify pertinent research. The studies were selected based on their contribution to understanding the integration of various systems and technologies, with a particular emphasis on their impact on building energy efficiency and sustainability.

The paper is organized in the following manner:

Emerging technologies in building energy management systems, like Smart building energy management systems, including Internet of Things (IoT), Digital Twins (DTs), Machine Learning (ML) algorithms, are presented in Section 2. Section 3 describes renewable energy integration in buildings. Section 4 presents the energy storage solutions in buildings. Section 5 explains simulation and modeling for energy optimization in buildings. Section 6 describes the Life Cycle Costing (LCC) and Life Cycle Carbon Assessment (LCA) in Building Energy Management Systems. At last, the conclusion and future recommendations are presented in Section 7.

2. Emerging Technologies in Building Energy Management

2.1. Smart Building Energy Management Systems (SBEMS)

A key component of Smart Building Energy Management Systems (SBEMS) is the integration of advanced technologies like Internet of Things (IoT), Artificial Intelligence (AI), and real-time data analytics to optimize building energy performance. These systems are designed to track, regulate, and optimize energy use while preserving occupant comfort and reducing costs. SBEMS are generally centralized systems that consist of sensors, controllers, communication networks, and user interfaces. These elements work in collaboration to collect data regarding building energy performance, analyze energy consumption patterns, and enhance the energy efficiency of system operations [13,14]. The integration of Model Predictive Control (MPC) and Deep Reinforcement Learning (DRL) in SBEMS enables real-time, multi-objective optimization. MPC offers model-based foresight and constraint handling, while DRL provides adaptive, data-driven control in complex environments. Together, they enhance energy efficiency, occupant comfort, and system responsiveness in smart buildings [13–16]. Eini and Abdelwahed developed a learning-based MPC framework for a four-zone smart building, in which occupancy profiles are predicted using artificial neural networks to inform the MPC optimizer. They found dramatic energy savings in EnergyPlus simulations: 40.56% less cooling power consumption and 16.73% less heating power consumption compared to conventional MPC, while maintaining occupant comfort [17].

Figure 2 presents a comprehensive view of the smart building concept, emphasizing its ability to interact with the surrounding environment. Smart buildings are portrayed as interactive entities capable of communicating with other buildings and assets such as electric vehicles, forming smart energy districts. They are designed to be self-operating,

enabling proactive control of HVAC systems and electricity grids. Connectivity and interoperability are central, allowing different systems and devices to exchange information seamlessly. Cost-effective resource utilization is another key aspect, ensuring efficient energy use while minimizing operational expenses. The figure also highlights the importance of user interaction, where occupants, referred to as smart users, actively engage with building systems to make informed decisions. By leveraging advanced technologies such as IoT, AI, and big data analytics, smart buildings optimize energy usage and comfort levels, ultimately striving to enhance their smartness as measured by the Smart Readiness Indicator (SRI) [18].

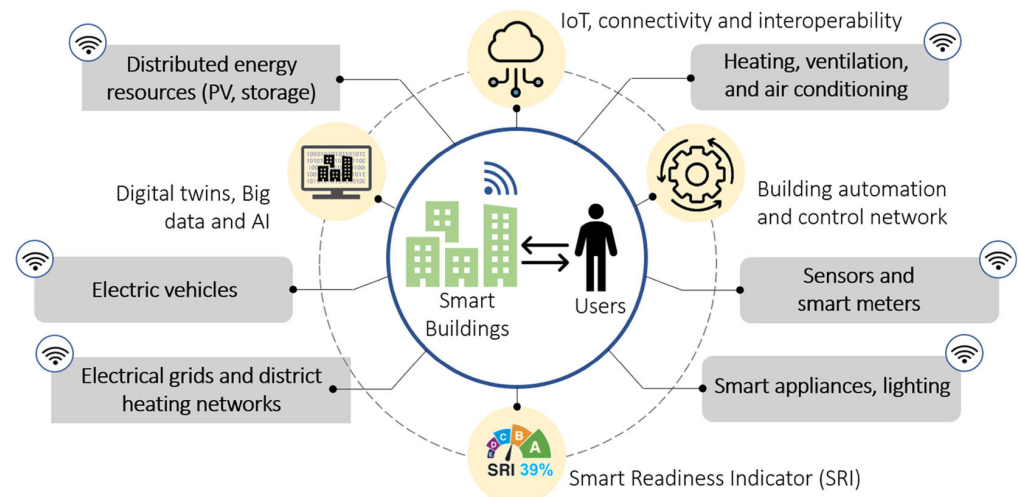


Figure 2. Key components of smart buildings, including energy resources, digital twins, automation, sensors, and smart appliances, all interconnected with users and supported by IoT and connectivity [18].

Role of IoT and AI in SBEMS

The IoT optimizes energy management in smart buildings by enabling real-time monitoring and control. IoT systems deploy sensors to track energy consumption, allowing for dynamic adjustments based on occupancy, weather, and demand patterns. Studies show that IoT integration can reduce energy consumption by up to 30% and operational costs by 20% [19]. Furthermore, IoT plays a vital role in demand-side management (DSM) by using Smart Compact Energy Meters (SCEMs) and other IoT devices. The SCEM is an IoT-enabled device that provides real-time monitoring and control of energy consumption in commercial buildings. Studies have demonstrated that SCEMs can lead to energy savings ranging from 15% to 49% [20]. Additionally, Smart thermostats and automated blinds further optimize building operations by adjusting heating and cooling based on external weather conditions and occupancy patterns [19]. A commercial complex that deployed IoT sensors for lighting, heating, and cooling systems achieved a 30% reduction in energy costs [21].

For instance, IoT-based systems using efficient protocols like the Constrained Application Protocol (CoAP) have demonstrated energy savings of approximately 30.86%. The CoAP is a lightweight, UDP-based application layer protocol designed for resource-constrained IoT devices. It enables efficient communication by supporting asynchronous message exchanges and low-overhead data transmission [22]. IoT systems can manage the incorporation of renewable energy sources (e.g., solar panels) into the building's energy grid, optimizing their use based on demand forecasts [19]. A study developed an IoT-based smart green energy management system for a university campus. The system combined machine learning and reinforcement learning techniques to optimize energy consumption

and solar energy generation. Utilizing data from three campus buildings, the system achieved a root mean square error (RMSE) of 14.72 for energy consumption and 75.45 for solar generation, demonstrating effective prediction and optimization capabilities [23]. While the benefits of IoT in smart building energy management are substantial, challenges such as high initial costs, data security concerns, and system integration complexities remain significant barriers to widespread adoption. Figure 3 shows the applications of IoT in smart buildings.

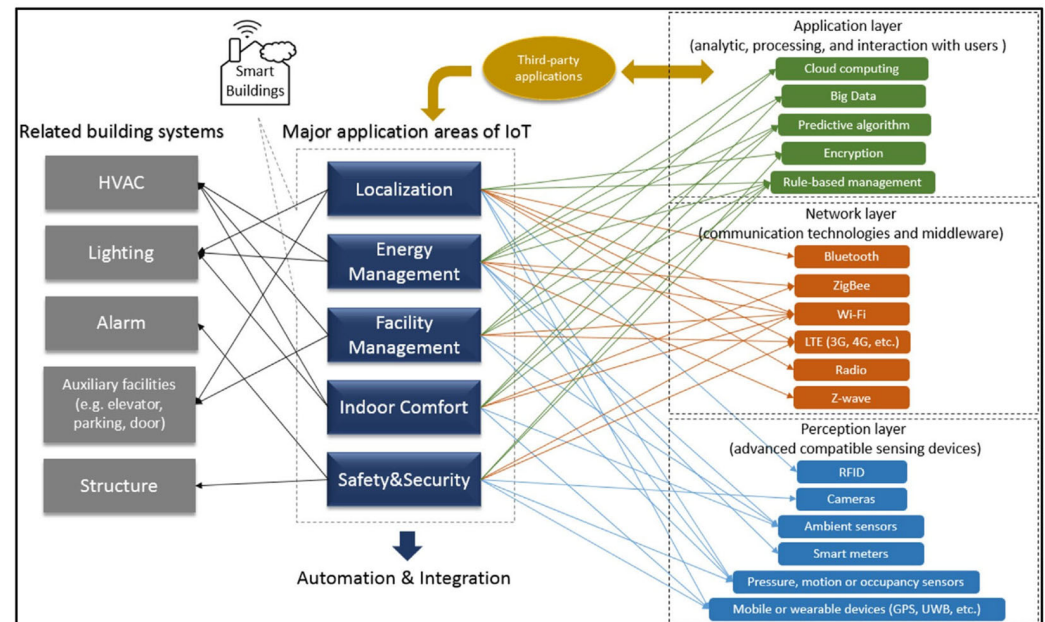


Figure 3. Integration of IoT in smart buildings, showing connections between building systems, IoT application areas, and various technological layers, including application, network, and perception layers [19].

IoT frameworks facilitate intelligent energy management by incorporating advanced technologies such as edge computing and machine learning. These technologies enable smart buildings to perform complex data analysis and make informed decisions about energy usage. For instance, a study proposed a distributed energy management system that combines edge computing and machine learning to optimize energy scheduling. The system achieved a 12% increase in energy utilization efficiency and an 18% reduction in energy waste during demand fluctuations. Additionally, the response time improved by 30% compared to traditional cloud-based solutions, demonstrating enhanced real-time adaptability and efficiency in energy management [24]. Moreover, IoT systems can incorporate cross-domain data, encompassing energy production, pricing, weather information, and user behavior, to formulate actionable strategies for energy consumers [25]. BEMS and IoT-enabled controls are more impactful in commercial and institutional buildings due to higher energy intensity and complex load profiles [26]. For instance, automated climate control systems using distributed temperature, humidity, and occupancy sensors are particularly effective in large commercial or institutional buildings, where they dynamically adjust HVAC and lighting to match real-time usage, yielding significant energy savings [19].

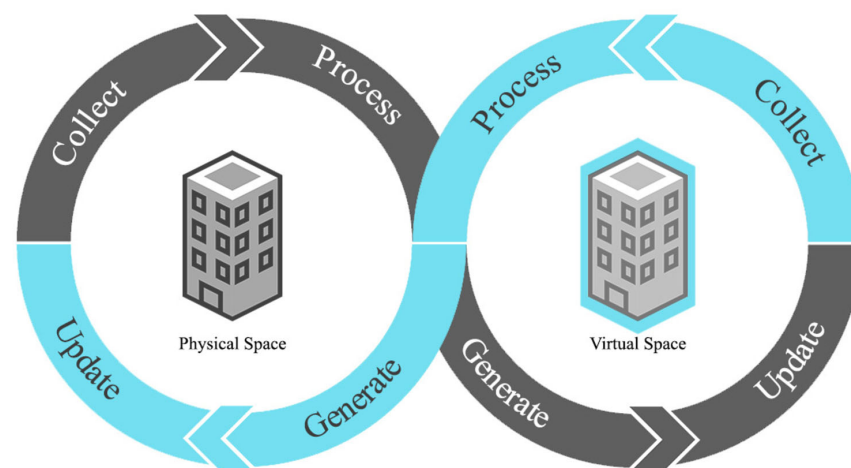
Table 1 summarizes various machine learning algorithms used in SBEMS, the objectives of IoT technologies, the types of buildings they are applied to, along with their advantages and disadvantages.

Table 1. Comparison of Machine Learning Algorithms for IoT-Based Building Energy Management: Objectives, Applications, and Performance Metrics [27–32].

ML Models/Algorithms	Objective in IoT Technologies	Applicable Building Type	Advantages	Disadvantages
Artificial Neural Networks (ANNs)	Predictive analytics for energy consumption	All building types	High accuracy in forecasting energy demand; Adaptable to complex patterns in data	Requires large datasets for training; Can be computationally intensive
Support Vector Machines (SVM)	Classification of energy usage patterns	Commercial, Industrial	Effective in high-dimensional spaces; Robust against overfitting in high-dimensional datasets	Less effective on very large datasets; Requires careful tuning of parameters; Slow speed and complex
Decision Trees (DT)	Decision-making for energy management strategies	All building types	Easy to interpret and visualize; Handles both numerical and categorical data well	Prone to overfitting; Sensitive to noisy data
Reinforcement Learning (RL)	Adaptive control of HVAC systems based on user behavior and environmental conditions	Commercial	Learns optimal strategies through trial and error; Can adapt to changing environments over time	Requires significant computational resources; Long training times can be a barrier
Regression	Behavior prediction	All building types	High speed	Low precision
Deep Learning	It is useful for both data prediction and pattern modeling	All building types	High accuracy and an appropriate speed	Complex
Genetic Algorithms	Optimization issues	Residential	High accuracy	Slow speed

2.2. Digital Twins (DTs) for Building Energy Optimization

DTs offer virtual representations of physical buildings, integrating real-time data from sensors and various sources to model and improve building performance. These virtual models can be employed for numerous purposes, including component monitoring, anomaly detection, predictive maintenance, operational optimization, and the modeling of alternative conditions [33]. DTs enable building operators to analyze energy consumption patterns, identify inefficiencies, and test different energy-saving strategies without disrupting the actual building operations [34]. Figure 4 shows the schematic illustration of conceptual model of building digital twin.

**Figure 4.** Conceptual model illustrating the data flow within a digital twin, integrating both physical and virtual spaces [35].

Recent developments in DT technology have enabled its implementation across multiple domains within the building sector [36]. Studies indicate that integrating DTs into building energy management can lead to energy savings of approximately 20–30% [37]. Furthermore, DTs rely on foundational technologies such as BIM and simulation tools to create accurate,

dynamic virtual replicas of physical buildings. BIM provides the geometric and semantic data needed to construct a detailed 3D model of the building, while simulation tools like OpenStudio allow performance analyses such as energy modeling. A study utilizing OpenStudio showed that decreasing the air handling unit's operating time by 1 h (according to the EN 16798 schedule) saves 451 kWh annually, while reducing it by 2 h raises CO₂ levels beyond recommended limits, compromising occupant comfort [38]. Seo and Yun [39], based in South Korea, utilized Building Information Modeling (BIM) to identify a turn-off strategy that decreased energy consumption by 60% in a university classroom building using LED lighting. Their findings highlighted that while LED lighting is highly efficient, its design can lead to higher energy consumption, necessitating further optimization. Furthermore, the incorporation of ML algorithms into DTs automates optimal control strategies, further enhancing energy management capabilities. A study involves integrating ANN model for forecasting energy consumption, as demonstrated in a case study at the University of Sharjah, where a DT achieved high accuracy in predicting building energy use. The simulation model showed high accuracy with R-values of 0.98106, 0.98651, and 0.99647 for 15 min, hourly, and daily timesteps, respectively. The ANN-based forecasting model achieved an R-value of 0.98667 for predicting energy consumption 15 min ahead [40]. Benefits and challenges of using DTs in different building types are presented in Table 2.

Table 2. Digital Twin (DT) Implementation: Benefits and Challenges Across Various Building Types and Targets.

Building Type	Tool/Platform	Target	Benefits	Challenges	References
Institutional	BIM	Lightings	Power consumption can be reduced by 60% using off strategy	Partial on/off strategy limitations	[39]
Commercial	MATLAB, BIM	HVAC	Average cooling energy savings of 13.2% for four days and 10.8% for three summer months	Complex system modeling; Real-time data streaming	[41]
Commercial	xBIM WeXplorer	Chiller	COP was improved in 90.43% of the data points	Insufficient modeling capability of BIM	[42]
Residential	IoT smart gateway	Electrical appliances	Reduction of up to 20.9% in energy demand and 17.7% cost reduction per household	Standby energy consumption; Data collection on hourly basis for all household appliances	[43]
Institutional	Revit	Test-bed for school (equipped with an HVAC system, geothermal heat, electricity, and lighting)	Energy consumption reduced by 17%.	Integration and visualizing data from embedded sensors	[44]
Intelligent buildings	BIM, VO&M platform	Indoor lighting	Energy use and cost of electricity were reduced by 79%; The accuracy of the intelligent decision control system reached 95.15%	Reliance on independent sensor control	[45]
Residential	Graphisoft ArchiCAD, Autodesk Revit	Zero Energy District (ZED) in a port area	After retrofitting, energy reduced by 15%.	Lack of effective communication; Difficulty in aligning financial objectives with environmental sustainability	[46]
Residential	MC4 Suite for Revit	Smart grid	Cost reduced by 38% from retrofitting.	Challenges in managing data	[47]
Healthcare	MR (Mixed Reality) app	Electric systems	Energy consumption saved by 1% every year; Facility faults avoided by 10% by using DT diagnosis	Many operational tasks are outsourced, leading to quality uncertainties and management challenges	[48]

3. Integration of Renewable Energy Systems (RES) in Buildings

Integrating renewable energy systems (RES) in buildings reduces fossil fuel dependence and supports net-zero carbon goals. This requires selecting appropriate technologies that align with building energy demands and local conditions. Modern designs incorporate RES early, optimizing energy flows through smart systems and storage, enhancing resilience and stabilizing energy costs. The following sections explore key renewable technologies like solar, wind, geothermal, and biomass.

3.1. Solar Systems

The incorporation of solar energy systems within buildings has received significant focus in recent years due to their capacity to reduce traditional energy usage and lower CO₂ emissions. Solar energy is favored for its technological simplicity and local applicability, providing both electrical and thermal energy [49]. This integration encompasses both passive and active solar technologies. Active systems encompass various technological approaches that employ mechanical or electrical components to harness and incorporate solar energy into a building's design and functionality. For instance, Hewlett-Packard (HP) installed a 1 MW solar system on the roof of its facility in Palo Alto, California. The installation is expected to supply 20% of the building's electricity needs, contributing to the company's sustainability goals. Over its lifetime, the system is projected to deliver an estimated savings of \$1 million, demonstrating the financial and environmental advantages of solar energy adoption through third-party ownership models [50].

Conversely, passive solar systems rely on the natural characteristics of the building and its environment to collect and retain solar energy, eliminating the need for mechanical or electrical devices. A case study of a net-zero energy home in Boulder, Colorado, investigated the impact of passive solar design and enhanced insulation on residential energy performance. The house consumed approximately 70% less energy than a typical U.S. residence, achieving around 80% reductions in heating and cooling costs, with the slightly higher construction investment recovered within seven years through energy savings [51].

Solar panels can be integrated into buildings through three main approaches: roof integration, façade integration, and external device integration. Roof-integrated systems can be applied to either continuous or segmented roofing surfaces. Façade integration includes elements such as curtain walls, double-skin façades, rainscreens, and window systems. External integrations refer to architectural elements like canopies, parapets, and balconies that support solar panels in contact with the outdoor environment (Figure 5) [52].

A widely adopted method is the Building-Integrated Photovoltaic (BIPV) system, where photovoltaic panels are embedded directly into the building envelope. These systems serve a dual purpose, generating electricity and acting as functional building components, such as walls or roofing, thereby reducing material and installation costs. An extension of this concept is the Building-Integrated Photovoltaic/Thermal (BIPV/T) system, which incorporates ventilated fluids to cool the PV panels while simultaneously recovering heat. This enhances overall energy efficiency by supplying both electrical and thermal energy for building applications, such as water heating, space heating, or even drying processes [53].

3.2. Wind Systems

The integration of wind energy systems into buildings, known as building-integrated wind technology (BIWT), is an emerging trend focused on enhancing energy efficiency and sustainability in urban environments [54]. Traditional wind turbines are often challenging to integrate into buildings due to space constraints and the need for structural modifications. To address this, a study introduced a novel BIWT system that harnesses wind pressure on the building's exterior to generate electricity (Figure 6). The design incorporates a guide

vane to accelerate wind speed and a rotor with an optimized shape. Computational Fluid Dynamics (CFD) analysis was conducted to determine the optimal system configuration. Performance was assessed through a two-step experimental process, revealing that the system could supply approximately 6.3% of a residential building's electricity demand [55].

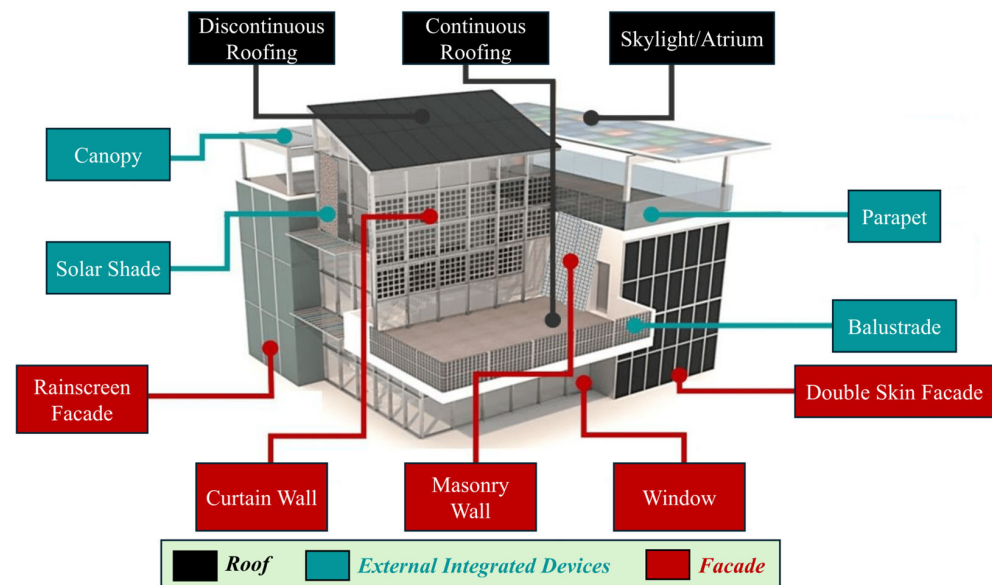


Figure 5. Integration options of solar systems in buildings, including roof-mounted, external devices, and facade-integrated configurations [52].

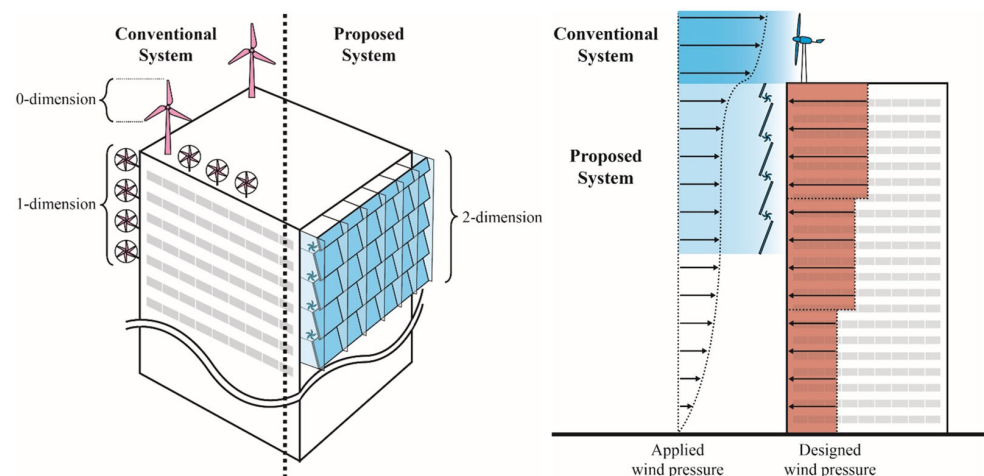


Figure 6. Comparison of installation areas between the conventional BIWT and the newly designed system, along with an analysis of the structural characteristics of the proposed design [55].

Horizontal-axis wind turbines (HAWTs) are best for large-scale energy production in open, windy areas. This is because they produce higher power output. They also perform well with strong, consistent winds. However, they need tall towers and more space. They are also more expensive to install and maintain. In contrast, vertical-axis wind turbines (VAWTs) work better in urban or low-wind settings. They are smaller and quieter. They are easier and cheaper to install and maintain. Another advantage is that they can catch wind from any direction. This makes them more practical for buildings. They are especially useful where space is limited and wind changes direction often [56]. Recent studies show that hybrid or optimized VAWT designs, such as helical or combined Savonius-Darrieus rotors, can improve self-starting and noise characteristics, and in some cases, machine

learning optimization has increased VAWT power output by up to 30% over traditional designs [57].

In 2015, two vertical-axis wind turbines were installed on the second level of the Eiffel Tower, generating approximately 10 MWh of electricity annually. This output is sufficient to power the first floor's restaurants, shops, and exhibitions [58]. Similarly, Strata Tower features three 19 kW, 9 m diameter wind turbines within a rooftop venturi enclosure. Generating approximately 50 MWh annually, they supply 8–12% of the building's electricity needs. This design highlights how wind energy can be seamlessly incorporated into urban architecture [59]. Furthermore, the design and integration of wind turbines in buildings are optimized using CFD simulations. Understanding wind flow patterns and creating systems that can optimize energy capture while reducing structural consequences are made easier with the aid of these simulations. These systems are superior to large-scale wind energy systems in several aspects, including lower prices, longer transmission lines, and less reliance on grid-connected power [60].

3.3. Geothermal Systems

Geothermal energy systems offer a promising solution for integrating renewable energy into buildings, providing emission-free, low-impact, and cost-effective thermal energy for heating and cooling applications [61]. Geothermal energy is mostly utilized in buildings for heat pump technology-based space heating and cooling. The method uses the earth as a heat sink in the summer to remove heat for building cooling and as a heat source in the winter to heat buildings [49].

Geothermal systems have the potential to considerably decrease energy consumption. For instance, a Shallow Geothermal Energy (SGE) system comprising 40 boreholes was implemented within a university building situated in Aveiro City, characterized by Mediterranean climate conditions. This system successfully attained a 55% reduction in energy consumption for heating and cooling purposes. The implementation of geothermal systems also facilitates substantial reductions in carbon dioxide emissions; the aforementioned SGE system mitigated 405.67 tons of CO₂ over a 25-year lifespan [62]. These systems offer considerable energy savings and pollution reductions, and they are especially good at integrating with HVAC systems and building envelopes. A study showed a 29% energy saving rate (for both heating and cooling) compared to conventional systems, with a reduction in CO₂ emissions by more than 7 kg per square meter [63]. Ground Source Heat Pumps (GSHPs) are widely used for both heating and cooling applications, as shown in Figure 7 [64]. Geothermal heat pumps can reduce operational energy use by up to 84% for heating and 83% for cooling compared to traditional systems, with a quick payback period in terms of energy and greenhouse gas emissions [65].

Additionally, incorporating pipe-embedded building envelopes, where pipes are integrated into the exterior walls or roofs of buildings, has shown promise in optimizing energy use and thermal comfort. These systems are particularly effective in climates with large diurnal temperature variations and in buildings utilizing renewable heating sources like solar thermal collectors or heat pumps [66]. Fan et al. [67] investigated a geothermal energy system integrating pipe-embedded envelopes with ground source heat exchangers (GSHEs) for residential buildings in Wuhan, China. They tested three configurations: Case 1 (PE walls + windows), Case 2 (PE walls), and Case 3 (PE windows), compared to a base case without PE envelopes. Case 1 achieved the highest energy savings, 25.2% for cooling and 11.8% for heating, along with a carbon reduction of 3417 kg-CO₂ over 15 years. The study emphasizes the potential of this system but recommends further research on scalability and climate adaptability. Zhao et al. [68] conducted a five-month field test on a double-layer pipe-embedded wall (DPEW) heating system in a Beijing office, integrating

ground heat exchangers with an air-source heat pump. The system achieved heating performance comparable to radiant floor systems, with reduced heat loss and improved efficiency through optimized surface emissivity and startup control strategies. In cold climates, technologies like ground source heat pumps and triple-glazed windows offer substantial benefits, whereas in hot-arid zones, solar thermal collectors and BIPV with proper shading can significantly offset cooling loads [69,70].

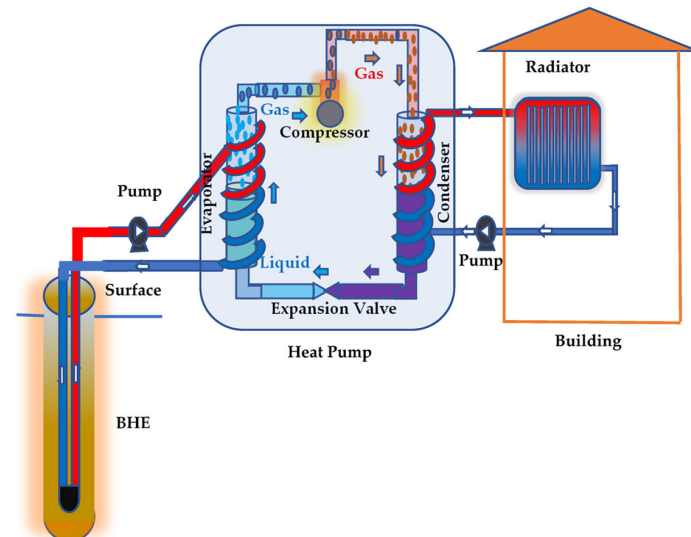


Figure 7. Schematic diagram of GSHP systems for heating applications. In cooling mode, the flow direction is reversed to facilitate heat extraction from the building [64].

3.4. Biomass Systems

Biomass is one of the most significant and abundant energy sources globally, ranking third after coal and oil in terms of energy production. It plays a crucial role in meeting global energy demands, accounting for approximately 10% of the world's total energy consumption [71]. Figure 8 shows the classification of biomass. The integration of biomass systems in buildings can take various forms, including polygeneration [71], trigeneration [72], and combined heat and power (CHP) systems [73].

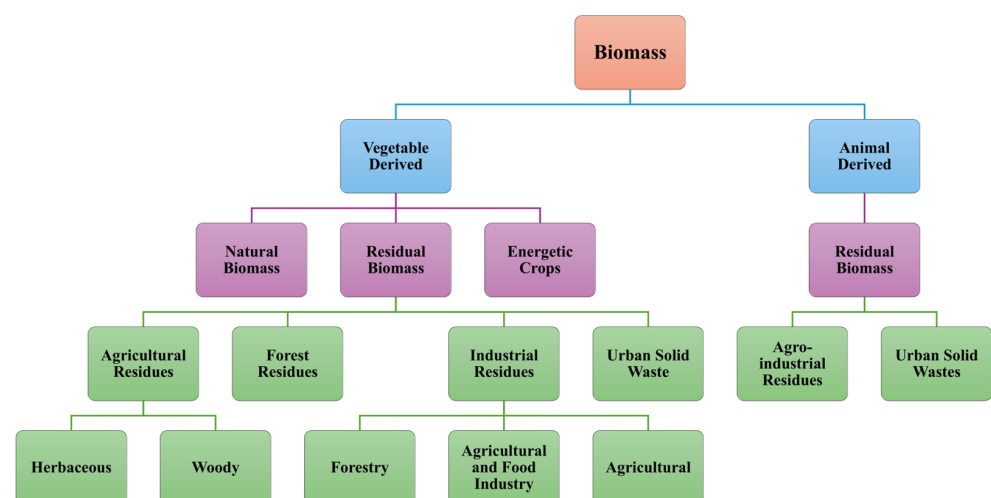


Figure 8. Detailed classification of biomass as a renewable energy source, highlighting the categories derived from vegetable and animal sources [71].

Polygeneration systems produce multiple outputs such as electricity, heat, and synthetic fuels, enhancing overall efficiency by minimizing energy losses. They are particularly

beneficial when integrated with buildings, offering improved efficiency and sustainability [71]. Trigeneration systems provide electricity, heating, and cooling, making them suitable for buildings with diverse energy needs. Biomass gasification combined with internal combustion engines can efficiently meet the demands of buildings. These systems can recover waste heat for space heating and cooling, enhancing overall system efficiency [72]. Biomass-fueled CHP systems can efficiently supply energy with high flexibility, using various technologies like steam cycles, gas turbines, and fuel cells. These systems are adaptable to different building energy demands [73].

Onsite biomass systems, such as the Integrated Cycles for Urban Biomass (ICU) concept, have demonstrated significant potential in reducing CO₂ emissions. According to a study by Meinusch et al. [74], the ICU system can save approximately 6468 kg of CO₂-equivalent emissions annually per residential complex by converting biowaste into biogas, heat, and electricity. The economic viability of such systems is further improved in large-scale implementations, especially in contexts where rising food prices increase the cost-effectiveness of biowaste utilization [74]. It was also recognized that biomass-driven combined cooling, heating, and power (CCHP) systems have the ability to enhance fuel efficiency and provide sustainable solutions. A study of a micro-CCHP system, designed for residential, hotel, and health center applications, reduces CO₂ emissions by up to 15.8% compared to conventional systems. Payback periods are 2.4 years for health centers, 2.5 years for hotels, and 4.1 years for residential buildings. Optimal heating/cooling storage volumes are 15,000 m³ for residential and hotel use and 11,000 m³ for health centers. The system follows a thermal-driven strategy in winter and intermediate seasons, shifting to a cooling-driven approach in summer [75]. Additionally, Microalgae-based biomass systems, such as microalgae photobioreactors (PBRs), have potential for building integration due to their ability to absorb CO₂, recycle wastewater, and release O₂, outperforming other renewable resources. Despite challenges like biorefinery infrastructure and high initial costs, PBRs offer environmental benefits [76].

Biomass energy systems in buildings face challenges due to feedstock variability, combustion characteristics, and emissions control. Unlike other renewables, biomass systems must manage inconsistent moisture content and calorific values while adhering to strict environmental standards. Effective design requires selecting suitable combustion or gasification technologies, along with robust feedstock supply chains. Recent studies emphasize the importance of real-time monitoring and adaptive control strategies to ensure efficiency and minimize emissions such as particulates and NO_x. Without these measures, biomass systems risk reduced performance and higher maintenance [71,77]. Remedies include implementing preprocessing techniques like drying and densification to stabilize fuel quality and incorporating advanced filtration technologies or cleaner combustion methods, such as pyrolysis or gasification, to control emissions. Additionally, integrating real-time monitoring can help adjust operations based on feedstock quality, improving system reliability and efficiency. Site-specific feasibility assessments are essential for optimizing these solutions and ensuring long-term operational success.

3.5. Hybrid Renewable Energy Systems (HRES)

HRES in buildings integrate multiple renewable sources (e.g., solar, wind, geothermal, biomass) with energy storage to enhance efficiency, reduce costs, and ensure stable power supply by mitigating intermittency. These systems provide both thermal and electrical loads, offering flexibility and revenue optimization while supporting grid stability [78]. HRES can utilize solar technologies, such as Solar Dish Stirling, combined with wind turbines to optimize energy production and storage [79]. A biogas-solar-based hybrid power plant with storage was studied for commercial buildings in the United

States. The system can operate with 100% renewable energy if the bio-digester produces 6000–9500 standard m³/year and the battery is fully charged at the start of the year [80]. Similarly, A polygeneration system in Chongqing, China, integrating a ground source heat pump and an anaerobic digester, was studied for rural applications. The system achieved primary energy savings of 21.6% and 32.2% compared to individual technologies [81]. Aloini et al. [82] developed a comprehensive framework for evaluating long-term investments in HRES for off-grid buildings. Their approach utilizes simulations to optimize system design, component sizing, and operational strategies while accounting for interactions between electricity and heat generation components. It also considers building load and evaluates the impact of energy demand uncertainty in an integrated manner. The viability of the investment assessment methodology was substantiated by a case study conducted at an off-grid facility, which demonstrated potential cost savings of up to €47,000 and a reduction of 320 tons of CO₂ emissions. Xu et al. [83] introduced a methodology aimed at enhancing the design of building energy systems that integrate multiple renewable energy sources. A matrix methodology was employed to standardize the modeling of various energy processes within the building, encompassing energy generation, utilization, and storage, as illustrated in Figure 9. The energy system of a building utilizing HRES can be optimized to minimize the overall lifecycle cost. When applied to a renewable energy-powered building in Beijing, China, and evaluated against a prior energy system, the optimized methodology resulted in a 14.9% decrease in the overall lifecycle cost. However, the efficacy of hybrid energy systems is contingent upon the configuration and optimization of their constituent components. It is essential to take into account the environmental implications of each component in order to ensure the overall sustainability of the system [84,85].

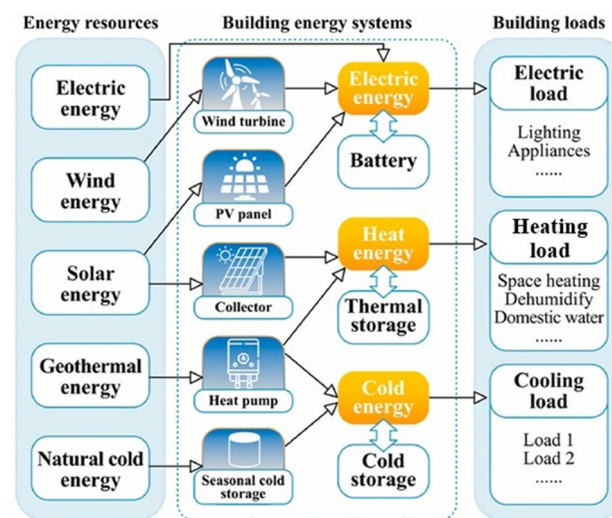


Figure 9. Integration of hybrid renewable energy resources into building energy systems to meet electrical, heating, and cooling demands for building energy management [86].

The economic aspect serves as a fundamental criterion in the selection of an efficient hybrid energy system for a building. In nearly all cases, the substantial capital expenditure required is a significant barrier to implementing renewable energy applications. The upfront investment for HRES can be significant, deterring widespread adoption. Integrating multiple energy systems requires advanced technical knowledge and infrastructure, which can be a barrier in less developed regions [87,88]. Table 3 shows the Summary of different types of renewable energy integration in buildings.

Table 3. Global Applications of Building-Scale Renewable Energy: Key findings and challenges.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
BIPV for building renovation	Switzerland	BIPV integration in building renovations led to up to 122% energy efficiency gains, meeting 2050 targets for Cumulative Energy Demand (CED) and Global Warming Potential (GWP). Payback periods were 14–18 years, with Internal Rates of Return (IRR) between 5.3–5.9%, demonstrating both economic and environmental benefits.	Low renovation rates and adoption barriers	[89]
BIPV for high-rise office buildings	Dubai	BIPV application in high-rise buildings reduced heating and cooling energy consumption by 13.2% to 32.8%. Roof-top Building-Applied Photovoltaic (BAPV) systems were found practical only for low-rise buildings.	Limited applicability of BAPV in high-rise buildings	[90]
BIPV/T with air-cooling systems	Poland	BIPV/T systems with air-cooling configurations showed a heat recovery potential of 330 W/m ² and an electrical efficiency of 5.76%. A channel height of 50 mm and a flow rate of 7.5 m ³ /h yielded the highest efficiency.	Need for further in situ testing and model verification	[91]
BIPV for office buildings	China	The study compared PV rooftop, window, and shading systems in various Chinese climates. PV rooftop performed best in Kunming with 111.78% energy savings, while PV window and shading excelled in Beijing. Optimal BIPV schemes were identified for each climate zone.	Variability in system performance across climates	[92]
BIPV with lithium-ion battery storage	UK	Results indicated that BIPV without battery storage becomes economically viable over its lifespan under the current electricity market conditions, whereas BIPV with battery storage is not financially advisable.	High capital cost of battery storage; Limited economic feasibility	[93]
BIPV for large-scale installation	Japan	A model for estimating the hourly PV potential of BIPV on building façades in Tokyo showed that BIPV could satisfy 15–48% of the annual electricity demand by 2050. Large-scale BIPV installation could increase power generation, but it also raises system flexibility and asset utilization issues.	Negative impacts on power system flexibility and asset utilization	[94]

Table 3. Cont.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
BIPV for vertical facades	Indonesia	An annual energy yield ranging from 179 to 186 kWh was observed for north-oriented BIPV. However, this study identified south orientation as the optimal placement for BIPV.	Uncertainty in energy yield prediction Mitigating excessive daylight	[95]
BIPV with solar angle optimization	Iran	Jask city, with a 30° angle, generates the highest solar power with an 88.8% electricity supply from solar cells. The cost per kWh is USD 0.073, and it prevents the emission of 16.5 tons of CO ₂ annually. The lowest return time is 11.7 years for Jask city, while Ramsar city has a high return time of more than 25 years at a 90° angle.	Variability in payback time and inverter losses	[96]
BIPV for building-integrated windows	Bangladesh	Semi-transparent CdTe BIPV windows in an office building saved 30–61% of electricity consumption and generated 270 kWh annually. South-facing windows were more efficient for power generation, while east-facing windows reduced net electricity consumption.	Lack of policies and guidelines for BIPV implementation	[97]
BIPV for EV charging system	Malaysia	Three scenarios were evaluated: grid-integrated with no battery, 75% battery storage, and 100% battery storage. The system with no batteries showed the lowest LCOE of 0.16 RM/kWh and the highest GHG emission savings of 137,321,924 kgCO ₂ e. The annual energy output was 8.05 MWh, 7.21 MWh and 7.19 MWh for the three scenarios.	Higher LCOE with battery storage; balancing energy demand with sustainability	[98]
Wind-based multi-generation system	Italy	A wind-powered system for a 5-story residential building produced 25.17 GWh of electricity, 17.69 GWh of heating, and 12.66 GWh of cooling annually. It achieved 30.85% exergy efficiency and reduced CO ₂ emissions by 5135.7 tons.	High system complexity and cost rate of \$159.90/h	[99]
Small-scale wind turbine	New Zealand	Placing small-scale Savonius and Darrieus turbines at a step height increased power output by 219.2% and 121.0%, respectively. The torque spectral density improved by 173.9% for Savonius and 83.6% for Darrieus. CO ₂ emissions were reduced by 3738.9–19,857.8 kg for Savonius and 4919.6–26,128.8 kg for Darrieus turbines annually.	Need for step height implementation in urban environments	[100]

Table 3. Cont.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
VAWTs	Türkiye	Integration of 42 VAWTs on a 5-storey building reduced annual energy use by up to 30.88%. Power outputs: 350 W (helical), 430 W (IceWind), 590 W (combined). Payback periods: 12.89, 10.60, and 10.49 years, respectively.	Site-specific wind conditions	[101]
Rooftop-mounted small wind turbines (SWTs)	Dominican Republic	A 29 m urban building rooftop achieved an estimated Annual Energy Production (AEP) of 1030 kWh/year, reducing emissions by 0.64 t CO ₂ /year. Wind flow was significantly affected by building geometry and orientation.	Wind speed loss due to building shape and placement	[102]
VAWTs	China	At a tip speed ratio of 0.34, corner-mounted VAWTs reduced the standard deviation of lift coefficient by 30.9% and lowered wind pressure fluctuations, indicating dual benefits of energy generation and wind load mitigation.	Integration with structural design and wind flow orientation	[103]
Distributed wind turbine	USA	The study demonstrates that a 6 kW distributed wind turbine achieves 77% efficiency with optimized NACA 2101 blades and provides 16 h of backup power when paired with a 20 kWh battery. It reduces energy costs by 23% and cuts CO ₂ emissions by 50%, proving its viability for decentralized renewable energy systems.	Ensuring turbine design efficiency for optimal wind coverage	[104]
Urban wind energy utilizing small building-integrated wind turbines	Dominican Republic	Five cities were identified as favorable locations for harnessing wind energy, exhibiting average wind speeds ranging from 4.83 to 6.63 m/s, with a predominant wind direction from the northeast at angles between 60° and 90°.	Financial and economic issues Vulnerability to atmospheric events	[105]
Savonius wind turbine	Egypt	Integrating a Savonius rotor in a building tunnel at the optimal off-center location improved power coefficient by 104% compared to free stream operation. The maximum performance is attained at vertical location of 90%.	Sensitivity to tunnel geometry and rotor placement	[106]

Table 3. Cont.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
HAWTs	Italy	Results of a high-rise-mounted turbine showed up to 52% power loss at low hub-heights, while higher hub-heights maintained performance near bare turbine levels. Blade bending moments varied significantly, impacting fatigue life.	Performance loss at low hub-heights; structural fatigue concerns	[107]
Rooftop PV and rooftop wind turbines	Belgium	Considering an average wind speed of 5 m/s, roof-mounted wind turbines generate more power than roof-mounted PV systems. A techno-economic comparison indicates that turbines with capacities of 3.2 kW and 5.2 kW are competitive with PV systems solely in terms of power generation.	Lower return on investment for small wind turbine and dependence on building height and wind conditions	[108]
Biomass cogeneration system	UAE	The optimized system achieved 31.79% efficiency and offset 24,548.97 kg CO ₂ /year. It generated 151.7 GWh of electricity, 194.6 GWh of heating, and 158.8 GWh of cooling annually, covering all school energy needs. Operational cost was \$88.02/h.	System complexity and high operational cost	[109]
Whole biomass material envelope system	China	WBMES achieved carbon emissions of 326.54 kgCO ₂ /m ² (production), 14.24 kgCO ₂ /m ² (transport), and 35.55 kgCO ₂ /m ² ·year (operation), with construction cost at \$535.7/m ² .	Airtightness and roof insulation weaknesses	[110]
Biomass-based building material	Mexico	Sargassum-based Concrete (SBC) reduced life-cycle GHG emissions by up to 15.8% over 50 years in extreme climates due to lower thermal transmittance. Benefits were observed in 29 of 32 states.	Performance variability by region and climate	[111]
Biogas-fueled cooling system	Malaysia	Biogas-powered AC system achieved GHG avoidance of 41.1 kt CO ₂ /year and annual savings of MYR 1.004 M. District Cooling Systems (DCS) less viable due to high investment/operating cost. Optimal electricity tariff for DCS viability: MYR 1.49–1.56/kWh.	High cost of DCS; dependency on electricity tariff structure	[112]

Table 3. Cont.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
Biomass waste-driven CCHP system	Iran	At optimal operation, the system is capable of generating 541 kW of electricity, 2052 kW of thermal energy, and 2650 kW of cooling capacity. The levelized cost of electricity generation is calculated to be \$0.083/kWh, with an associated environmental impact factor of 1.33 kg CO ₂ /kWh.	Complex optimization framework and computationally intensive	[113]
Kitchen waste-based bio energy plant optimization	China	A surplus renewable energy feed-in district energy system generates a minimum of 9457 kWh per day and a maximum of 16,793 kWh per day.	High carbon reduction cost and economic–environmental trade-offs	[114]
Hybrid solar–biomass system	Norway	System achieved 36.8% efficiency, 7.75 kg/MWh emission index, and \$9.73/h total cost. Biomass provided 66.55% of heating; PVT covered >80% of annual energy demand. Summer radiation contributed 64.8% of cooling.	Seasonal drop in renewable output; reliance on biomass in winter	[115]
Solar–biomass hybrid power system	India	HRES produced 376,780 kWh/year for a 65 kW peak load, with Cost of Energy (COE) of \$0.207/kWh and Net Present Cost (NPC) of \$507,737. Solar PV contributed 76.6% and biomass 23.4%. CO ₂ emissions reduced by 161 tons/year.	Moderate COE and high upfront investment	[116]
Solar–biomass hybrid energy system	China	System saved 1.05×10^6 MJ/year, reduced CO ₂ by 550.59 tons, and cut coal use by 358.26 tons. Annual income: \$72,735; payback: 2.89 years.	Sensitivity to biomass price and operating parameters	[117]
Solar PVT + heat pump and biomass heating system	Canada	PVT–heat pump system reduced CO ₂ by 7.2 t/year at \$78.9/MWh energy cost. Biomass system achieved 69% efficiency. Night temperature set-back cut 60.3 MWh of energy and 21.1 t CO ₂ /year.	Seasonal dependence and control complexity	[118]
Hybrid solar–biomass heating system (HSBS)	Morocco	Optimal HSBS with evacuated tube collectors achieved 57% solar fraction, 40% energy efficiency, 3.9% exergy efficiency, 656 t CO ₂ /year avoided, \$0.0642/kWh LCOH, 4.9-year payback, and \$0.509 M lifecycle savings.	System complexity and optimal collector sizing	[119]

Table 3. Cont.

Type of Renewable Energy Integration	Country	Key Findings	Challenges	References
Medium-depth geothermal with Deep Borehole Heat Exchanger (DBHE)	China	Heat exchange rate: 141.5 W/m; optimal DBHE depth: 2000 m; temp. effect radius: 13 m. Optimal flow rate: 18 m ³ /h. Geothermal gradient 0.04 °C/m supports 1.33× more load than 0.03 °C/m. Recommended insulation length: 178 m.	Geothermal gradient variability and flow optimization	[120]
Shallow geothermal heating and cooling network	Sweden	Geothermal energy sharing between decentralized borefields reduced purchased electricity by 23%. Heating and cooling performance improved by 31% and 35%, respectively.	System coordination and inter-building integration	[121]
GSHP	Belgium	Optimized borefield sizing via Bayesian algorithm reduced Total Cost of Ownership (TCO) by 33–35% compared to passive-only systems.	Lack of standardized sizing methods for hybrid cooling	[122]
Vertical closed-loop geothermal system	Egypt	Geothermal integration reduced electricity use and CO ₂ emissions by up to 22.93%, especially improving thermal comfort on the ground floor.	High energy consumption for cooling	[123]
Geothermal energy-based air conditioning	Iraq	At an air velocity of 4 m/s, the designed system effectively reduced the air temperature by 10 to 16 degrees Celsius.	Climate variability, sensitivity and limited cooling at shallow depths	[124]
Air–geothermal heat exchanger with air-source heat pump	Italy	A real case study showed ~30% reduction in electricity consumption. Performance sensitive to air inlet temperature, humidity, and ventilation flow rate control.	Performance fluctuation due to ambient conditions and control strategy	[125]
Geothermal Heat Pump System (GHPS)	Serbia	The designed system has the potential to reduce primary inlet energy consumption by a minimum of 30%.	High environmental impact due to electricity mix	[126]
Multi-generation geothermal system with PCMs	Canada & UAE	Annual CO ₂ reduction: 2129.7 kg (Vancouver), 2773.2 kg (Dubai). Vancouver system produced 237,364.6 kWh (electricity), 425,959.4 kWh (heating), 304,732.8 kWh (cooling). PCM uses optimized energy and cost.	Climate variability; PCM type selection	[127]

4. Energy Storage Solutions for Efficient Building Energy Management

Thermal and electrical energy storage technologies are essential for improving building sustainability and energy efficiency. Thermal energy storage (TES) systems, such as phase change materials (PCMs), help regulate thermal loads, while electrical storage solutions, like batteries, improve renewable energy utilization and contribute to grid stability. Batteries, in particular, are used in electrical energy storage systems, which store excess electricity produced by renewable sources like PV systems and release it when demand is high or renewable energy supply is low. Energy storage demand is projected to triple by 2030, driving researchers to develop advanced ESS capable of efficiently managing electricity. ESS can be classified based on factors like type, intended uses, storage length, and efficiency [128]. The projected market size for energy storage systems (ESS) from 2023 to 2033 is expected to reach \$535.53 billion, a significant increase from \$246.54 billion in 2023 (Figure 10). This growth is driven due to the global shift towards cleaner energy solutions [129].

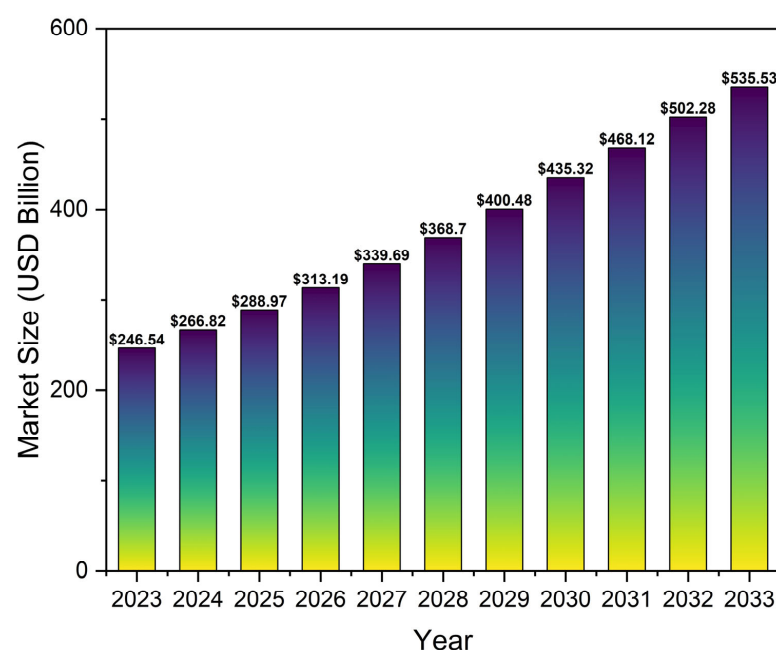


Figure 10. Projected market size of energy storage systems (ESS) from 2023 to 2033, expressed in USD billion [129].

4.1. Thermal Energy Storage

To reduce energy consumption, various techniques can be employed, including improving building insulation. Among these strategies, TES stands out as a highly effective approach, particularly when integrated with renewable energy sources such as geothermal or solar energy. The market size for TES systems was assessed at a valuation of USD 54.4 billion in 2024, with projections indicating a compound annual growth rate (CAGR) of 5.6% from 2025 to 2034 [130]. TES systems facilitate the accumulation of thermal energy during periods of low demand or energy availability, thereby enabling its utilization during peak consumption periods. Furthermore, TES can be employed for both cooling and heating purposes within buildings [131]. TES can be categorized into latent heat, sensible heat, and chemical reactions. In the last two decades, latent heat thermal energy storage (LHTES) has been the most commonly studied method [132]. LHTES accumulates energy in PCM, which absorbs or releases heat through the change in phase. PCMs are further divided into three main types based on their composition: organic, inorganic, and eutectic PCMs [133]. Furthermore, PCM selection is crucial for LHTES materials in buildings. However, the quantity of PCMs exhibiting all the requisite qualities (thermo-physical, kinetic,

chemical, technical, and economic) is nonexistent; therefore, concessions to a specific extent may be applicable in certain instances [134]. Therefore, Yang et al. [135] developed a method for PCM selection based on multi-criteria decision-making (MCDM) to address the contradictory properties of PCMs. The approach demonstrated the ability to achieve reasonable results regarding PCM selection for targeted applications.

Applications of PCMs in Buildings

Both new buildings and the retrofit of existing buildings can benefit from PCM applications [136]. In 1975, Telkes [137] initially explained the use of PCMs for thermal regulation in buildings. Since then, numerous research studies [138] focusing on the incorporation of PCMs into building envelopes (walls, ceilings, floors, etc.) [139] have been published, emphasizing improvements in thermal comfort and energy efficiency [140]. PCMs can be utilized in buildings for passive and active cooling, passive and active heating, as well as hybrid systems, as shown in Figure 11.

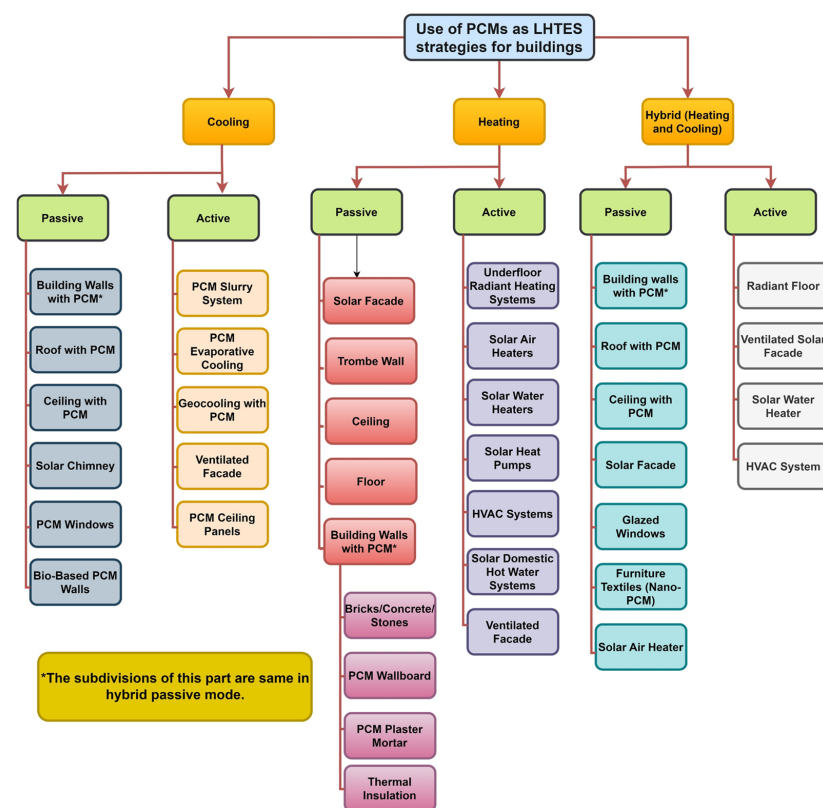


Figure 11. Application domains of PCMs in buildings for LHES in cooling, heating, and hybrid systems [141,142].

Active methods involve the use of mechanical systems to circulate air or fluid through PCM storage units. These systems are more suitable for extreme climates and can meet higher heating and cooling demands [143]. Abuska et al. [144] experimentally evaluated three identical single-glazed solar air heaters (SAHs) to examine the effect of phase change material (PCM)-based thermal energy storage and a honeycomb fin structure on performance, as shown in Figure 12. The PCM-integrated designs improved daily thermal efficiency by 2.6–22.3%, particularly at higher mass flow rates, while the honeycomb configuration significantly shortened charging and discharging durations.

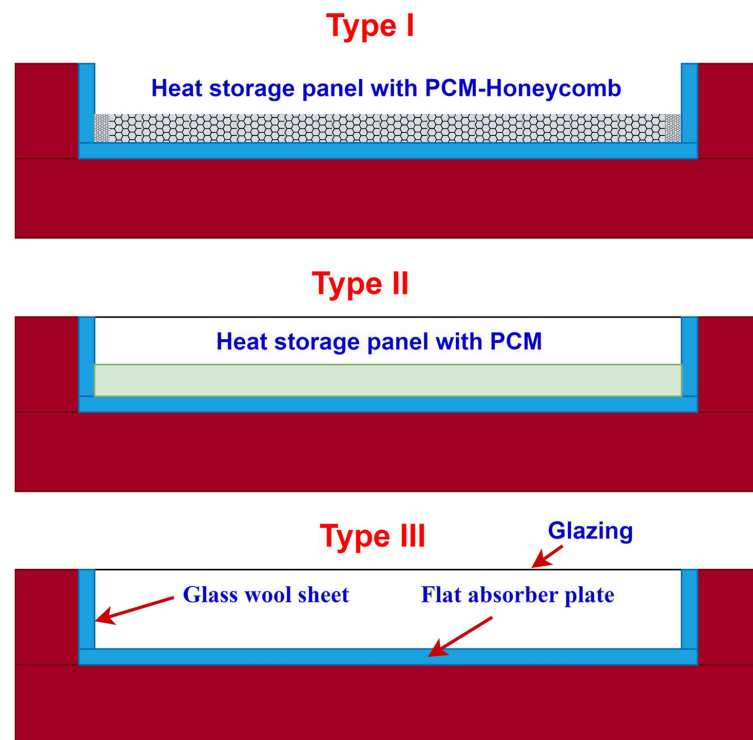


Figure 12. Three types of tested SAHs featuring different heat storage panels: Type I with PCM-Honeycomb, Type II with PCM panels, and Type III utilizing glazing with a glass wool sheet and flat absorber plate [144].

On the other hand, Passive methods involve incorporating PCMs into building envelopes or components without additional mechanical systems. Kara and Kurnu [145] conducted a study on the performance of two Trombe walls in Erusurm, Turkey, with triple pane windows (Figure 13). They used GR35 PCM and GR41 for the walls. Results showed a range of solar energy gain to heat load, with PCM walls having a daily efficiency of 20% to 36%. GR35 was found to be more efficient than GR41 in this application.

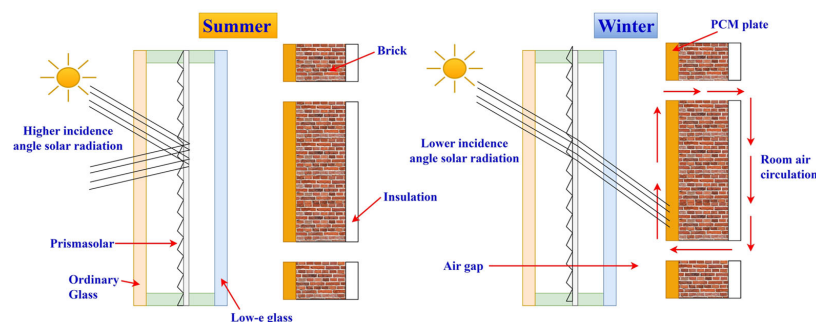


Figure 13. Working principle of the Trombe wall with triple glazing, utilizing solar radiation for passive heating in winter and efficient temperature regulation in summer through strategic material selection and air circulation [145].

The effectiveness of energy management technologies varies significantly depending on building type and local climate. For example, TES systems using PCMs are highly effective in residential and educational buildings in temperate climates, where diurnal temperature variation supports passive energy cycling. However, in hot-humid regions, their performance may be limited unless integrated with mechanical ventilation or dehumidification systems [146,147]. Table 4 shows the building-integrated PCM studies across different types of buildings.

Table 4. Building-integrated PCM studies summarizing PCM name/type, country, melting temperature (°C), study type, application (Passive/ Active/Hybrid; Heating/Cooling), building type, key findings, limitations and reference.

PCM Used	PCM Type	Country	Melting Temperature (°C)	Study Type	Application	Building Type	Key Findings	Limitations	Reference
SP31	Inorganic	Saudi Arabia	31–33	Numerical + Experimental	Hybrid active cooling	Residential	Flat PCM: 8.6% energy savings (best); Corrugated PCM: 7.6% savings but better initial cooling (3 °C ΔT); COP improved to 5.63 (flat)	Summer months only; single PCM; corrugated design requires faster recharge	[148]
RT24	Organic	Denmark	21–25	Numerical + Experimental	Active cooling	Commercial	Up to 10 h passive operation; active water circulation boosts avg heat flux from 4–10 to 45 W/m ² ; with 16–19 °C supply, discharge lasts 2–14 h.	Closed-type ceiling; ventilation not considered.	[149]
Paraffin PCMs	Organic	Iraq	38–41	Numerical + Experimental	Hybrid active cooling	Test room (scaled)	PCM2 (38–41 °C) performed best: 90.13% heat flux reduction, 16.24 °C inner temp reduction, decrement factor 0.127.	PCM may not fully solidify in extreme heat; geothermal backup required	[150]
A28; A36	Organic	UK	28; 36	Experimental	Passive cooling	Residential	Combined A28/A36 achieved best PV temperature regulation (<35 °C) and heat retention (>25 °C for 5 h).	Low thermal conductivity; potential leakage	[151]
RT25HC	Organic	Portugal	22–26	Experimental	Passive cooling	Commercial	Sectioned contact surfaces (H2 geometry) reduced melting/solidification times by 38%/22%.	Double-layered geometries hindered heat transfer; Slow solidification rates	[152]
RT18, RT20, RT25, RT27	Organic	Norway	RT18: 16–18; RT20: 18–20; RT25: 23–25; RT27: 25–28	Numerical + Experimental	Active cooling	Residential	RT25 achieved highest ESR (16–44.7% across climates); Stockholm: 44.7% ESR, Catania: 16% ESR; Budapest saved 353 kWh.	High initial cost (8–31 yr payback); limited to cooling season; dependency on climate	[153]
Blended vegetable oils + beeswax (Bio-based PCM)	Organic	Algeria	27–38.3	Numerical	Passive cooling	Residential	Reduced inner wall surface temps by 2.98–3.95 °C across cities. Optimal PCM layer location identified. Latent heat: 63.85 kJ/kg. Climate-dependent performance.	Limited to summer conditions; performance varies by climate.	[154]
Nextek 18D	Organic	Germany	14–15	Numerical + Experimental	Active cooling	Industrial	Cooling power: Ranged 53–70 W/m ² (5 °C water), 40–53 W/m ² (10 °C), 27–36 W/m ² (15 °C); 30% PCM reduced cooling power by 24% vs. 0% PCM; 30% PCM delayed temperature recovery by 2.37 × (5 °C water) vs. no PCM.	Limited to lab-scale prototype; long-term performance not evaluated.	[155]
RT60 paraffin wax	Organic	India	60	Experimental	Active heating	Residential	Maximum energy efficiency: 72.3%; max exergy efficiency: 7.05%; room air temp reached 35 °C.	Limited to specific PCM and fin configurations; requires further study on other PCMs and fin geometries.	[156]

Table 4. Cont.

PCM Used	PCM Type	Country	Melting Temperature (°C)	Study Type	Application	Building Type	Key Findings	Limitations	Reference
RT8-HC; RT11-HC; RT21-HC	Organic	Spain	RT8-HC: ~8, RT11-HC: ~11, RT21-HC: ~21	Numerical + Experimental	Passive heating/cooling	General (adaptive envelopes)	Whole macrocapsules show lower effective heat capacity than small samples (datasheet values overestimated by up to 164.11%); Higher PCM mass in capsules increases peak heat capacity (30.65% higher for 1 kg vs. 0.5 kg); Proposed model fits experiments well (RMSD: 0.543–1.246 W/m ²).	Differences in effective heat capacity between small samples (datasheets) and whole macrocapsules; hysteresis effects	[157]
OM37	Organic (non-paraffin)	India	37	Numerical + Experimental	Passive cooling	Residential	Reduced indoor temps by 4 °C during sunny hours; 60.6% lower heat flux vs. conventional slab; 49.8% reduction in thermal load; 5.7-year payback period; 44.24% CO ₂ emission savings for cooling.	Limited to climates with high daytime temperatures (>35 °C); Aluminum encapsulation may corrode in concrete over time.	[158]
Commercial paraffin	Organic	France	10–28	Experimental	Passive cooling	Residential	Dynamic PCM reduced indoor avg. temp by 5.1% and peak heat flux by 116% vs. static PCM. Achieved 100% heat gain reduction indoors.	Manual PCM repositioning required; limited to summer conditions; scalability challenges for large buildings.	[159]
Nonadecane	Organic	Morocco	32	Numerical	Passive cooling	Residential	16% PCM mass optimized; T _m = 32 °C most suitable for summer conditions; reduces inner surface temp fluctuations and increases time lag	Numerical only; mechanical/economic/environmental aspects not assessed	[160]
Commercial PCM	Organic	Italy	22–26 (simulation); 10–28 (experimental)	Numerical + Experimental	Hybrid heating/cooling	Residential	Summer heat-gain reduction 135.53–535.73%; winter heat-loss reduction 2.92–58.76%; optimal melting 22 °C; optimal PCM thickness 2 cm (summer)/4 cm (winter)	1-D model assumptions; manual PCM movement in lab; single-climate (Rome)	[161]
OM35 and Eicosane	Organic	India	35–38	Experimental	Passive cooling	Residential	Dual-layer PCM bricks reduced temperature by 9.5 °C and heat gain by 60% during daytime; OM35 more cost-effective than Eicosane.	Low thermal conductivity; high cost of Eicosane; scalability challenges	[162]

4.2. Electrical Energy Storage (EES)

EES systems are transforming building energy management by enabling efficient integration of renewable generation with building loads. These systems, ranging from residential-scale batteries to commercial installations, provide critical flexibility by time-shifting solar and wind energy to match demand profiles. When integrated with BEMS, EES solutions, including stationary batteries and Vehicle-to-Building (V2B) technologies, demonstrate robust load-shaping capabilities, reducing peak demand while ensuring power reliability. By integrating EV batteries with BEMS, V2B enables buildings to utilize stored energy from parked vehicles, especially when combined with renewable sources like PV panels. This approach can significantly reduce electricity bills by up to 15.8% in some regions, and maximize the use of on-site solar generation, allowing buildings to operate more independently from the grid and reduce greenhouse gas emissions [163]. Advanced energy management strategies and optimization frameworks have demonstrated that V2B interactions improve load coverage, grid flexibility, and decarbonization benefits, while also lowering annual electricity costs and the levelized cost of energy [164]. In residential and campus settings, V2B systems can be designed to ensure that EVs are fully charged for drivers' needs while still providing substantial energy support to buildings, even in the absence of dedicated stationary batteries. Moreover, V2B systems lower electricity bills by optimizing EV charging/discharging based on real-time pricing and demand charges, with reported reductions ranging from around 5% to over 15% depending on location and system design [163]. Furthermore, integrating V2B with other storage technologies, such as batteries and hydrogen systems, can optimize supply performance, grid integration, and economic outcomes, offering stakeholders robust pathways toward net-zero and carbon-neutral building operations [165].

A study analyzing virtual energy storage (VES) in rural buildings using vehicle-to-home systems found that the VES system could deliver a maximum equivalent charging power of 432.82 kW, a maximum equivalent discharging power of 385.38 kW, and an equivalent energy storage capacity of 2165.64 kWh. This demonstrates that V2B can effectively participate in energy management for rural electric heating without the need for traditional energy storage systems [166]. For high-rise residential buildings, a hybrid system using battery and hydrogen vehicle storage achieved an annual average self-consumption ratio of 84.79%, a load cover ratio of 76.11%, and a hydrogen system efficiency of 77.06%. The lifetime net present value for the investor priority case was about \$3.64 million, which is 29.88% less than the equivalent priority case, and the system showed negative annual carbon emissions, indicating positive environmental impacts [165]. The optimal configuration of 50% V2B chargers and 1 ESS significantly reduces cumulative peak-hour load and peak power by 51.3% and 42.4%, respectively, in an office park featuring photovoltaic generation [167]. Furthermore, the Smart Energy Management System (SEMS) with V2B strategy can significantly reduce building grid power demand (65%) and carbon emissions (64%), promoting smart, sustainable, and economically viable net-zero cities [168]. Table 5 shows the summary of EES technologies in various types of buildings.

Table 5. Summary of EES Implementations: Technology Configurations, Operational Parameters, and Performance Metrics Across Building Types and Geographical Regions.

Technology	Country	Capacity	Power	Study Type	Building Type	Key Findings	Limitations	Reference
Battery Energy Storage System (BESS)	China	4642 kWh (peak-preference), 314 kWh (off-peak-preference)	C-rate: 0.5 (charging/discharging rate constraint)	Numerical	Commercial	9.2% annual bill reduction, 10.2% IRR—Payback period: 6.8 years; 50% battery price reduction improves IRR by 7.06%.	Does not consider spot markets or ancillary services.	[169]
V2B (Li-ion)	Italy	50 kWh Battery Electric Vehicles (BEVs), 10 kWh Plug-in Hybrid Electric Vehicles (PHEVs)	11 kW (PV)	Experimental	Residential	PHEVs' state of health (SoH): 84.8% with V2B vs. 95.8% without; BEVs' SoH: 92.9% with V2B vs. 95% without.	9 equivalent years tested only; limited to Li-ion Nickel-Manganese-Cobalt (NMC) cells.	[170]
PV, Wind turbine (WT), EES	Iran	EES: 3 kWh	PV: 0.12–0.97 kW, WT: 0.0845–1.4315 kW	Numerical	Residential	Reduced electricity costs by 34.7% and PAR by 10.6%.	Did not consider user comfort or thermal loads.	[171]
Hybrid air-to-water heat pumps (AWHPs)-Boiler-PV-BESS	Italy	BESS: 5 kWh	PV: 4 kWp; AWHP: 6–9 kW; Boiler: 30 kW	Numerical	Residential	ANN achieved 99.16% accuracy in real-time optimization; Cost savings up to 19% in colder cities, 12% CO ₂ reduction, 3% primary energy savings; Non-predictive COP cut-off (1.02 for emissions, 1.71 for energy) enabled real-time control.	Limited to Mediterranean climates; Excluded sub-hourly demand variability; Assumed fixed PV efficiency (15.5%).	[172]
PV-BESS	Japan	5 kWh battery	3.67 kW discharge	Numerical + Experimental	Residential	Improved temperature control accuracy by 15.12%, reduced energy costs by 10.50% using Double-Layer MPC under forecast uncertainty.	Limited to residential HVAC; thermal comfort, including humidity and airflow, was not considered.	[173]
PV-Battery-Hydrogen hybrid system	Canada	BESS: 5–20 kWh	PV: 8–20 panels (450W each), Electrolyzer: 2.5–7 kW, Fuel cell: 3–7.5 kW, BESS: 5–20 kWh	Numerical	Academic	Gaseous hydrogen storage (GHS) + BESS scenario achieved 60.3% renewable factor; LCOE ranged \$0.376–0.789/kWh; CO ₂ mitigation: 6.57–9.75 tons/year.	High initial cost of metal hydride storage (MHS) systems; reduced hydrogen production when adding BESS.	[174]
Solar PV + Li-ion Battery	Libya	67,653 kWh/year	310 W/module	Numerical	Any building type	Annual energy yield: 1353 kWh/kW; Performance ratio: 0.85. High summer efficiency. Battery capacity degrades with high Depth of Discharge/temperature. Inverter efficiency peaks at 96%.	Simulation-only, lacks experimental validation; Desert-specific conditions limit generalizability.	[175]

Table 5. Cont.

Technology	Country	Capacity	Power	Study Type	Building Type	Key Findings	Limitations	Reference
PV-BESS	India	81 kWh (BESS), 41.2 kWp (PV)	35 kW max discharge	Numerical + Real-time data	Commercial	Reduced operating costs by 8.75% and battery degradation by 65.97% via non-linear degradation model and flexible load shifting.	Limited to lead-acid batteries.	[176]
Hybrid Metal Hydride (MH) + Battery Energy Storage System (BESS)	Italy	MH: 16–28 tanks (1.8 wt% H ₂ capacity per tank) BESS: 8–30 kWh	Electrolyzer: 5–18 kW Fuel Cell: 7.5–20 kW PV: 119–130 panels	Numerical	Commercial	Achieves net-zero energy with 57.7–60.5% direct PV supply. LCOE: \$0.354–0.403/kWh; LCOH: \$5.77–7.03/kg. Best scenario (NZ-4) reduces LCC by 12% vs. worst case (NZ-1). Annual CO ₂ mitigation: 13.2 tons.	High upfront cost of MH systems (\$5960/kW); Climate-specific; Excludes battery degradation analysis.	[177]
PV/Battery/Hydrogen Hybrid System	Canada	522 kW PV, 200 kg H ₂ tank, 159 batteries (single house); 1830 kW PV, 300 kg H ₂ tank, 1022 batteries (apartment)	150 kW electrolyzer; 20 kW fuel cell (single house); 200 kW electrolyzer, 30 kW fuel cell (apartment)	Numerical	Residential	Optimal configuration reduced NPC to \$643,608 (single house) and \$1.75 M (apartment) with COE of \$0.78/kWh and \$0.60/kWh, respectively.	High upfront costs of hydrogen components; 25-year simulation period only.	[178]

5. Simulation and Digital Modeling for Energy Optimization

Simulation and digital modeling play a crucial role in energy optimization, particularly in the context of building performance and industrial processes. Several well-established simulation tools, including EnergyPlus, TRNSYS, and DesignBuilder, are widely recognized for their capabilities in accurately modeling energy consumption and optimizing energy systems in buildings [179]. EnergyPlus is a comprehensive building energy simulation software that models various energy flows within buildings, including heating, cooling, lighting, ventilation, and other related processes. It helps in assessing the energy performance of buildings by simulating and analyzing the interactions between building systems, environmental conditions, and energy usage. It is particularly effective for large-scale community modeling, including building-integrated photovoltaic/thermal (BIPV/T) systems. EnergyPlus allows for detailed energy modeling and has been enhanced with new components to improve its simulation capabilities [180,181]. For instance, Liu [182] demonstrated that occupancy-based scheduling could reduce energy consumption by approximately 16% annually compared to constant temperature setpoints using EnergyPlus. To address the limitations of individual tools, researchers have developed co-simulation frameworks and new modeling approaches. For instance, a co-simulation framework between EnergyPlus and Ansys Fluent has been proposed to model PCM-integrated built environments with improved accuracy [183]. Additionally, new tools like Spawn, which couple EnergyPlus with Modelica, aim to bridge the gap between energy simulation and control implementation workflows. Spawn leverages EnergyPlus for efficient envelope simulation and established authoring tools, and integrates the Modelica Buildings Library, enabling advanced, realistic HVAC and control simulations. This combination facilitates the modeling of novel energy systems and control implementations at both building and district scales [184].

DesignBuilder is a user-friendly interface for EnergyPlus, facilitating easier access to its powerful simulation capabilities. DesignBuilder software is a versatile simulation engine that enables energy analysis and automatic optimization of numerous building systems, including HVAC, lighting, domestic hot water (DHW), renewable energy innovations. It also calculates extra KPIs such as thermal comfort, GHG and carbon emissions, and financial assessments, providing a comprehensive tool for evaluating building performance across multiple dimensions [185]. Studies have shown that using DesignBuilder can result in up to a 19.2% reduction in cooling energy use and a 15.3% decrease in total energy consumption in residential buildings [186].

TRNSYS is a powerful simulation tool specifically tailored for modeling transient energy systems in buildings, offering distinct advantages for HVAC and renewable energy integration [187]. Unlike specialized tools like EnergyPlus, TRNSYS provides unparalleled flexibility in modeling complex interactions between building loads, HVAC systems, and renewable energy sources. For instance, in the study by Dai et al. [188], TRNSYS was used to optimize the joint operation of GSHPs in a hotel and office building, achieving 12–14% energy savings compared to traditional control strategies. Its ability to simulate hourly and annual performance enables precise analysis of part-load ratios (PLRs) and system COP, critical for optimizing building energy efficiency. Compared to specialized tools like EnergyPlus, TRNSYS offers greater flexibility for developing new mathematical models, making it more suitable for innovative designs. However, it often requires more detailed inputs than simpler tools, which can affect simulation accuracy. While TRNSYS achieves reliable annual energy demand predictions, discrepancies in hourly predictions can be significant when compared to other tools [189,190]. Table 6 presents the summary of simulation-based optimization studies across various building types, highlighting tools, objectives, applications, and key findings.

Table 6. Summary of simulation-based optimization studies across various building types, highlighting tools, objectives, applications, and key findings.

Building Type	Simulation Tools	Optimization Objective	Applications	Key Findings	References
Office	EnergyPlus	HVAC energy consumption and thermal comfort	HVAC system	Achieved 7% reduction in energy consumption and 3% improvement in mean radiant temperature (MRT) comfort.	[191]
Residential	EnergyPlus; COMSOL	Dynamic insulation and PCM performance	Building envelope retrofits	Achieved up to 11.6% energy savings with dynamic envelopes and 18.2% when combined with PCM.	[192]
Residential	DesignBuilder	Energy efficiency, CO ₂ reduction, payback period	Thermal insulation, HVAC upgrades	Scenario 8 (external roof insulation + HVAC upgrade) achieved 65.5% energy savings with an 8.6-year payback period. Comprehensive retrofits (e.g., Scenario 12) achieved up to 75% energy savings but had longer payback periods (>20 years).	[193]
Education	DesignBuilder; MATLAB	Renewable energy system optimization	Hybrid solar-wind-battery system	Particle Swarm Optimization (PSO) increased energy deficit by 10%, while Genetic Algorithm (GA) improved battery discharge by 4%.	[194]
Commercial	eQUEST	HVAC energy efficiency and thermal comfort	HVAC systems	Energy consumption reduced by 25.07%. Total cost of energy consumption has been reduced by 13.9%.	[195]
Net Zero Energy Buildings (NZEB)	TRNSYS; GenOpt	Maximize energy efficiency and cost-effectiveness	PV systems with Li-ion, lead-acid, and flywheel storage	Achieved 20% energy efficiency and 22% exergy efficiency; flywheel storage showed the lowest environmental impact.	[196]
Education	TRNSYS; Python	Minimize heat pump energy consumption and costs	HVAC control with thermal energy storage	DRL achieved a 4.73 MWh reduction in annual primary energy consumption and a 3.2% decrease in operating costs.	[197]
Residential	EnergyPlus; jEPlus + EA; OpenStudio	Energy consumption, life-cycle cost (LCC), and emissions minimization	Residential building design	Achieved 43.63% energy savings, 37.6% LCC reduction, and 43.65% emission reduction. HVAC systems had the highest impact (67% energy use).	[198]

Table 6. Cont.

Building Type	Simulation Tools	Optimization Objective	Applications	Key Findings	References
Office	EnergyPlus; SketchUp	Energy efficiency and CO ₂ reduction	Solar chemical heat pump (SCHP) system	SCHP system demonstrated 75% lower energy consumption, 72% reduced CO ₂ emissions, and 73% lower running costs compared to conventional systems.	[199]
Education	EnergyPlus; SketchUp	Reduce Energy Consumption Index (ECI)	HVAC and lighting systems	Replacing Constant Air Volume (CAV) with Variable Air Volume (VAV) and fluorescent lights with LEDs achieved 19.8% energy savings, improving ECI to 161,964 kWh/m ² /year.	[200]
NZEB	DesignBuilder; EnergyPlus; MATLAB	Minimize heating costs (HC) and comfort penalty (CP)	Space heating	Up to 17% daily heating cost savings compared to conventional methods while maintaining thermal comfort levels.	[201]
Commercial	EnergyPlus	Energy efficiency, comfort, response speed	HVAC system	Deep Q Networks (DQN) achieves lower energy consumption (e.g., 259.9 kWh for heating), faster response (64.4 s to temperature changes), and higher adaptability (avg. 81.9 score).	[202]
Education	EnergyPlus; eQUEST	Indoor air temperature, CO ₂ concentration	Thermal and air quality	A significant relationship exists between the number of occupants and the rise in air temperature and CO ₂ concentration; proposed retrofit cases can reduce overheating by 2–3 °C and maintain CO ₂ concentration under 900 ppm.	[203]
Hospital	CFD	Average air age	Air quality	Indoor Air Quality Acceptance: 91% of occupants; thermal Environment Satisfaction: 92% of occupants; up-supply and side-return improve air quality, reducing average air age by 223.7 s compared to up-supply and up-return.	[204]

Table 6. Cont.

Office	Rhinoceros; Grasshopper; Honeybee	UDI, Spatial daylight autonomy (sDA), Annual solar exposure (ASE)	Daylighting	Balconies over 1.5 m deep achieve null Annual Solar Exposure (ASE) and are ideal for avoiding glare and overheating due to direct solar radiation; shallower rooms have better daylight performance; north-oriented office rooms have the highest daylight levels but also the highest likelihood of glare.	[205]
Office	EnergyPlus; MATLAB	Minimize HVAC energy use	HVAC system optimization	MPC achieved 17.6% energy savings and 49.7% peak load reduction, outperforming rule-based control strategies.	[206]
Office	TRNSYS; IBE-e	Energy usage	Energy related	Achieves energy-saving goals by using a combination of different energy-saving technologies and energy-consuming simulation software; achieved an energy saving rate of 62.84%.	[207]
Residential	DesignBuilder; EnergyPlus	Energy usage, CO ₂ emissions	Energy related	Annual heating consumption decreases, while annual cooling consumption increases from present to the 2080s; the effect of annual cooling consumption is more than the annual heating consumption on operational CO ₂ emissions of the building.	[208]
Office	Rhinoceros; DIVA	Useful daylight illuminance (UDI)	Daylighting	The area-weighted average UDI can be improved by up to 0.4376.	[209]

6. Life Cycle Costing (LCC) and Life Cycle Carbon Assessment (LCA) in Building Energy Management Systems

Building energy management systems (BEMS) are pivotal in enhancing energy efficiency, integrating renewable energy sources, and reducing operational costs in buildings. To comprehensively evaluate these systems, it is essential to consider both their economic and environmental impacts over their entire life cycle. Life Cycle Cost (LCC) and Life Cycle Carbon Assessment (LCA) are critical methodologies for evaluating the economic performance and carbon reduction potential of energy management solutions in buildings. These approaches provide a comprehensive analysis of costs and environmental impacts over the entire life cycle of a building, from construction to demolition. By integrating LCC and LCA, stakeholders can make informed decisions that balance economic viability with environmental sustainability [210,211].

LCC involves calculating the total cost of ownership over a building's life span, including initial construction, operation, maintenance, and end-of-life costs. This approach helps in identifying cost-effective solutions by considering long-term financial implications [212]. The ISO 15686-5:2017 standard provides the methodological framework for LCC analysis in buildings. The standard utilizes discount rates and cost ratios to normalize future costs to present value [213]. A study conducted an LCC analysis of sustainable technologies in residential buildings over a 20-year period. Key findings revealed that biomass heating was the most cost-effective renewable option, with a net present value (NPV) of €213,339, outperforming gas condensing boilers (€235,496). Heat pumps had higher NPVs (€283,149–€334,322) due to rising electricity costs. Greywater recycling achieved savings of 13,000 m³ of water and €5347 compared to conventional systems, despite higher initial investments [214]. Furthermore, the highest LCC was associated with construction expenditures, which accounted for 55% to 58% of the total LCC. The operation and maintenance costs of the project over a 50-year lifespan constituted approximately 25% to 27% of the overall LCC, whereas the costs related to environmental impact were estimated to represent roughly 17% to 18% of the total LCC [215]. Case studies show that material production and operational energy use dominate both costs and emissions, with interventions such as improved insulation, HVAC upgrades, and renewable energy integration yielding significant reductions in both metrics [216]. Pimpalkar et al. [217] integrate Weibull-based reliability analysis into LCC for rooftop PV in composite climates, showing that Operation and Maintenance (O&M) and failure costs, especially inverter and balance-of-system components, account for ~74% of total LCC, and that optimized maintenance schedules significantly improve cost-effectiveness. Hybrid PV-PCM-TEG systems yield ~17.5% shorter energy payback time and improved LCC compared to PV alone [218]. Furthermore, Abdolmaleki et al. [219] optimized a hybrid solar-hydrogen energy system for a net-zero energy laboratory in Toronto using TRNSYS and EnergyPlus simulations. The optimized system achieved zero grid dependency with a 49.1% renewable fraction, 828 kg CO₂ reduction, and a levelized cost of energy (LCOE) of \$0.389/kWh. However, it resulted in a higher life-cycle cost (LCC) of \$57,374 with a 39.8 m² PV array and 3.9 m³ hydrogen storage.

LCA is a standardized methodology for quantifying environmental impacts throughout a building's lifecycle. The framework follows ISO 14044 standards and encompasses cradle-to-grave analysis, including material production, construction, operation, and end-of-life phases. LCA provides quantitative measures of environmental performance, with Global Warming Potential (GWP) being the primary indicator for carbon assessment [220,221]. Building LCA typically follows the EN 15804 standard, which defines system boundaries across lifecycle phases A1–A5 (product and construction), B1–B7 (use stage), and C1–C4 (end-of-life) [222]. Research has shown that operational energy consumption dominates lifecycle carbon emissions, accounting for approximately 87–90% of

total emissions [223,224]. Studies have established benchmarks for residential buildings, with lifecycle carbon emissions ranging from 5–12 kg CO₂/m²/year for various building types [225]. Commercial buildings show higher intensities, with office buildings demonstrating emissions of 254.5 kg CO₂ eq/m² for decoration alone [226]. Recent studies have integrated machine learning techniques to enhance LCA and LCC accuracy and efficiency in buildings. A study by Gobinath et al. [227] assessed an AI-integrated HVAC system in an Australian office building, demonstrating that despite higher initial capital costs due to sensor deployment and IoT infrastructure, the system achieved operational energy savings of around 9–10%, leading to significant reductions in total life cycle costs and carbon emissions over a 50-year period. Similarly, machine learning models have achieved average percentage errors of approximately 15.71% in predicting embodied carbon impacts [228]. Furthermore, large-scale lithium iron phosphate battery storage reveals >85% of lifecycle cost in upfront capital, with manufacturing driving most global-warming potential [229]. GSHP in a building achieves >24% lower environmental impact than air-source systems and payback periods under 5 years [230]. Comparative analyses in recent studies indicate that while solar photovoltaic and geothermal systems entail relatively higher initial installation costs, they offer substantial reductions in operational and maintenance expenses over their service life. Wind and hydropower systems, on the other hand, are often more site-dependent but provide competitive lifecycle costs in regions with consistent natural resources. Integrating such economic perspectives within LCC frameworks enables stakeholders to identify the most viable renewable option under specific climatic and operational conditions, thereby aligning sustainability goals with long-term financial feasibility [231]. Key stages in assessing a building's carbon footprint: material production, operation (HVAC, lighting), and recycling are shown in Figure 14.

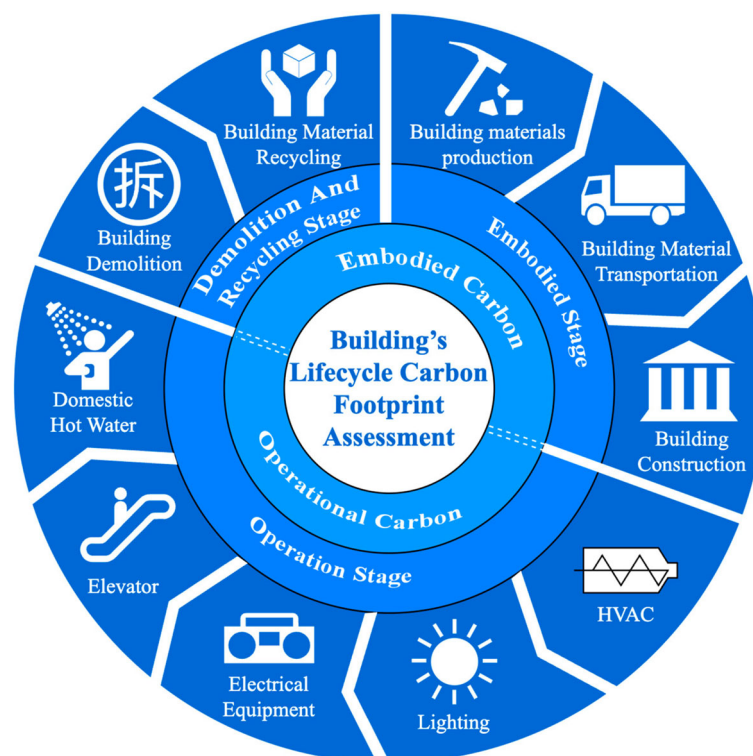


Figure 14. Key stages in assessing a building's carbon footprint: material production, operation (HVAC, lighting), and recycling [232].

Recent studies highlight the effectiveness of integrated LCC and LCA methodologies in comparing energy management solutions across a building's entire life cycle. For exam-

ple, Kneifel [233] evaluated multiple efficiency upgrades in commercial buildings: lighting, HVAC, envelope enhancements, through 576 energy simulations. Results showed average operational energy savings of 20–30% and carbon emission reductions of around 16%, with many interventions paying for themselves via negative LCC due to smaller, more efficient systems. Similarly, Zhang [234] examined deep energy retrofits in mid-rise Canadian residential buildings using EnergyPlus plus LCC/LCA analysis. Measures like solar PV and ASHP demonstrated significant GHG reductions (from 27.64 t CO₂e to 3.77 t CO₂e), though only some, like PV and ASHP, were cost-effective once life cycle costs were included; others, such as window upgrades, only became viable when incentives were applied. Furthermore, a study conducted an LCA and LCC analysis of BIPV systems in three Korean buildings over 50 years. Key results showed that BIPV systems reduced greenhouse gas emissions by up to 30%, with payback times ranging from 12 to 41 years. The NPV was positive for all buildings, reaching €399,493 for apartments under the best-case cost scenario. Additionally, BIPV systems achieved significant energy savings, covering 22–32% of the buildings' primary energy demand, while avoiding land-use changes associated with conventional PV installations [210]. However, the integration of LCC and LCA methodologies presents technical challenges related to data interoperability and software compatibility [235]. Studies have identified the need for standardized data exchange formats and improved software integration capabilities [236]. Furthermore, one of the primary challenges in LCC and LCA studies is data quality and availability. Research has shown that database selection can result in 35.2% variation in embodied carbon calculations [220]. The lack of standardized databases and regional data remains a significant barrier to accurate assessment.

The outcomes of LCC and LCA analyses are profoundly influenced by regional conditions, leading to significant disparities in the effectiveness of sustainable technologies between developed and developing countries. For example, solar energy systems, particularly BIPV, often demonstrate favorable LCC and significant carbon reduction in sun-rich regions like the Middle East and Southern Europe, where high insolation offsets initial costs; however, in less sunny areas, the longer payback periods can be a barrier. Similarly, wind energy integration, especially small-scale VAWTs, can be cost-effective and low-carbon in consistently windy urban or coastal locales in Northern Europe and East Asia, though LCA must account for manufacturing impacts. Furthermore, geothermal systems, such as GSHPs, typically show excellent LCC and LCA performance in temperate regions like North America and Central Europe due to high efficiency and operational savings that outweigh high drilling costs, making them a cornerstone for decarbonization in developed nations, while their upfront investment remains prohibitive in developing countries. However, biomass systems are most viable from an LCC and LCA perspective in rural, agricultural regions with abundant organic waste, such as parts of Southeast Asia and Eastern Europe, where they utilize local resources and avoid emissions from waste decomposition; however, their sustainability is highly sensitive to supply chain logistics and combustion efficiency, with poor management leading to unfavorable LCA results and operational challenges in urbanized areas.

7. Conclusions and Future Recommendations

This review examined the progression of building energy management strategies, demonstrating how the integration of intelligent control, renewable energy technologies, and thermal–electrical storage can improve efficiency and sustainability at both operational and lifecycle levels. Among emerging supervisory control approaches, IoT-enabled Building Energy Management Systems (BEMS) and Model Predictive Control (MPC) consistently outperformed conventional rule-based methods, with studies reporting notable reductions in HVAC energy use, including reductions of around 40% in cooling power consumption

when predictive scheduling is employed. Digital twin-based monitoring and optimization further enhanced performance by enabling continuous model-based adjustment and fault prediction in real operation. Within renewable systems, Building-Integrated Photovoltaic (BIPV) solutions demonstrated the strongest improvement in electricity generation and retrofit feasibility, while Ground-Source Heat Pumps (GSHPs) achieved up to 84% decreases in heating and cooling energy demand, representing the most reliable year-round option in temperate climates. Hybrid solar–biomass systems were shown to be most advantageous in regions with variable solar availability, supporting consistent thermal output. In energy storage, Phase-Change-Material-based thermal storage provided measurable gains in load shifting and heat retention, and solar-plus-storage configurations improved peak-load management and reduced grid dependency. Simulation-based optimization using TRNSYS, EnergyPlus, and DesignBuilder demonstrated energy-saving potentials up to 75%, validating their importance for design and retrofit analysis. Life-Cycle Cost (LCC) and Life-Cycle Carbon Assessment (LCA) findings indicated that systems that combine predictive control, on-site renewables, and storage tend to achieve the most favorable economic and environmental performance across the building lifecycle.

Future research should prioritize the development of self-learning, AI-driven control frameworks linked with digital twins, enabling buildings to continuously adapt operation in response to occupancy, weather, equipment degradation, and electricity price fluctuations. Establishing standardized and comparable LCC–LCA evaluation protocols is essential to support objective decision-making and policy alignment across regions. Further work on region-specific hybrid renewable configurations, for example, solar–geothermal in moderate climates and solar–biomass in resource-rich rural areas, will strengthen both energy reliability and decarbonization outcomes. Advancements in cost-effective PCM formulations, integrated thermal–electrical storage architectures, and secure, interoperable IoT communication layers will be critical for large-scale deployment. Continued coupling of simulation platforms with real-time building data will improve long-term predictive accuracy, operational resilience, and retrofit planning. Collectively, these directions support the transition toward scalable, cost-effective, and climate-aligned building energy systems, consistent with international net-zero and sustainability objectives.

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