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REVIEW ARTICLE

# Green building practices to integrate renewable energy in the construction sector: a review

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**Abstract**
The building sector is significantly contributing to climate change, pollution, and energy crises, thus requiring a rapid shift to more sustainable construction practices. Here, we review the emerging practices of integrating renewable energies in the construction sector, with a focus on energy types, policies, innovations, and perspectives. The energy sources include solar, wind, geothermal, and biomass fuels. Case studies in Seattle, USA, and Manama, Bahrain, are presented. Perspectives comprise self-sufficiency, microgrids, carbon neutrality, intelligent buildings, cost reduction, energy storage, policy support, and market recognition. Incorporating wind energy into buildings can fulfill about 15% of a building's energy requirements, while solar energy integration can elevate the renewable contribution to 83%. Financial incentives, such as a 30% subsidy for the adoption of renewable technologies, augment the appeal of these innovations.

**Keywords** Green building · Carbon neutral construction · Renewable energy · Policy and regulatory framework · Energy transition · Energy self-sufficiency

## Introduction

With the implementation of economic globalization and the expansion of economic regions, the global consumption of energy and resources is growing rapidly at an average annual rate of 2.2% (Chen et al. 2023a; Salam et al. 2020). The construction industry, as the main sector of energy consumption, accounts for 36% of the total global energy consumption (Chen et al. 2022a). The rapid growth of the global population will require more urban building capacity in the next 40 years than in the past 4000 years (Chen et al. 2022b; Gottlieb et al. 2023), but traditional buildings rely heavily on coal, oil, natural gas, and other non-renewable energy sources, and excessive energy use causes energy depletion and high pollution. Environmental instability, such as the greenhouse effect and extreme weather caused by energy, have aroused

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widespread concern for green, low-carbon, sustainable, and other renewable energy. At the same time, international energy deployment has set a goal of near net-zero emissions by 2050, as the construction industry is under intense pressure from energy scarcity and fossil fuel depletion (Zhang et al. 2022). Europe and the USA have redefined regulations and policies related to the development of near-zero-energy buildings for the development of renewable energy (Liu and Rodriguez 2021; Yang et al. 2022b), and China also committed to the international government's "dual-carbon" goal of reaching peak carbon by 2030 and carbon neutrality by 2060 (Osman et al. 2023; Paris Agreement 2015). The application of renewable energy in buildings has, therefore, become a major driver of the energy transition in conventional buildings and an important cornerstone of urban planning and development strategies to reduce the contribution of the building sector to climate change and energy use.

Renewable energy, as an innovative alternative energy, plays a leading role in getting rid of fossil fuel dependence and mitigating climate change. It is used to reduce greenhouse gas emissions stemming from energy consumption during construction projects (Ghaffarian Hoseini et al. 2013; Yang et al. 2022b). This approach aims to create environmentally friendly, energy-efficient, and sustainable buildings. Moreover, it stands as a pivotal contributor to the evolving global energy landscape as governments worldwide commit to addressing climate change and advancing sustainable development goals. Renewable energy was first used in the European Union, where the main objective was to reduce greenhouse gas emissions, thus improving energy efficiency (Yang et al. 2022b). In China, the initial application of renewable energy in building construction encompassed solar, wind, geothermal, and other sources. As technology in this field continues to mature, it plays a pivotal role in fostering the growth of a sustainable energy ecosystem. This is achieved by assessing how various technologies impact the enhancement of performance efficiency and the regulation of overall energy consumption levels (Zhang et al. 2015). Renewable energy is progressively becoming the energy strategy for numerous countries; for instance, the USA is investigating the economic feasibility of incorporating solar and geothermal technologies into heat pump systems (Kim and Junghans 2023), while Poland is employing wind and photovoltaic sources to facilitate its energy transition (Igliński et al. 2022). Therefore, the development and utilization of renewable energy plays a key role in building energy efficiency and emission reduction and promotes the sustainable development of buildings in the energy sector and even globally through existing natural resources and techno-economic measures.

This review systematically analyzes the current status and potential of renewable energy applications in the building sector. The review highlights the advantages of renewable energy applications in the building sector, such as solar, geothermal, wind, and biomass, as well as the challenges of technological innovation and development. It also provides examples of buildings in the construction sector that have successfully used renewable energy, describes the types of renewable energy used and the socio-economic benefits derived from their use, and analyzes the challenges and lessons learned during implementation. In addition, this review provides an in-depth look at the global policy and regulatory framework for renewable energy in buildings, considering the impact of policy on renewable energy adoption and, from there, analyzing the opportunities and barriers to policy implementation. The paper further explores the latest technological advancements like machine learning and Internet of Things technologies in renewable energy within the building sector and systematically evaluates their potential impact on renewable energy utilization for sustainable cities. Finally, the review concludes by discussing the prospects of renewable energy in the building sector, examining both the potential and challenges involved in promoting its widespread adoption.

## Overview of renewable energies in the building sector

Renewable energy derived from natural resources, is less harmful to the environment than fossil fuels and serves as an alternative to traditional energy sources (Dey et al. 2022). Renewable energy in buildings refers to the integration of sustainable energy sources, such as solar, wind, geothermal, and biomass, into the full building life cycle of design, construction, operation, and maintenance to reduce dependence on fossil fuels and traditional energy sources, promoting environmental sustainability and mitigating climate change. The roots of renewable energy in architecture can be traced back to early experiments in passive solar design, maximizing the use of sunlight for heating and natural ventilation to design the orientation of buildings (Gong et al. 2022; Ionescu et al. 2015). With the increasing awareness of environmental protection, the application technology of renewable energy in modern buildings has also gained momentum for innovative development.

The application of renewable energy in buildings depends mainly on the characteristics of the energy required for the building and the type of different energy sources. Among the existing renewable energy sources, solar, wind, hydro, tidal, geothermal, biomass, and hydrogen are widely recognized as key and mature technologies in the renewable energy sector. However, solar, wind, geothermal, and biomass energy have a greater potential to fulfill the energy needs of buildings (Khan and Al-Ghamdi 2021; Wu and Skye 2021), as shown in Fig. 1.

## Solar energy

Solar energy stands as the most accessible and commonly adopted form of renewable energy, achieved by capturing the ionization of the sun's radiant energy. It is acclaimed for its limitless supply and eco-friendly attributes, positioning it as the leading-edge renewable energy technology poised to replace fossil fuels. Aldhshan et al. (2021) defined solar energy as one of the sustainable energy sources for generating electricity using photovoltaic systems. Building solar energy technology, the main source of energy from solar radiation and thermal energy in two aspects, photovoltaic technology and solar thermal energy for the integrated application of buildings is currently commonly used renewable energy technologies, and from the building characterization of the form can be divided into active solar energy and passive solar energy. Photovoltaic systems, solar power generation, and solar hot water are the main components of active solar systems, while building orientation, air circulation, and thermal biomass together constitute passive solar systems (Dey et al. 2022). Wu and Skye (2021) conducted statistics on the total amount of renewable energy utilized in residential buildings in the USA, where solar energy accounted for 31% of the total energy consumption.

The use of photovoltaic technology is critical to reducing building operating costs. Researchers use Geographic Information Systems to model photovoltaic systems and explore the economic and environmental benefits, showing that photovoltaic systems on rooftops could save the government an estimated $202 billion in costs while dramatically improving environmental performance (Asif et al. 2019). At the same time, solar distributed integration technology can meet the functional requirements of different components of the building according to specific requirements. The collected solar technology is applied to building windows to control the increase and decrease of building solar heat and thermal insulation, and the integrated application of distributed energy in building components greatly improves the comfort of occupants and climate energy-saving control (Vasiliev et al. 2019).

Improving the environmental performance of buildings and facilitating climate circulation is one of the characteristics of solar technology as a renewable energy source. For instance, Vassiliades et al. (2022) observed that active solar building integration systems can change the characteristics of buildings and reduce the negative climate impacts of building public spaces. In addition, the integrated application of solar energy and photovoltaic technology has a greater advantage in improving energy utilization efficiency and reducing energy demand. Research in Italy describes how a photovoltaic thermal solar-assisted heat pump system integrated with a photovoltaic thermal collector and a

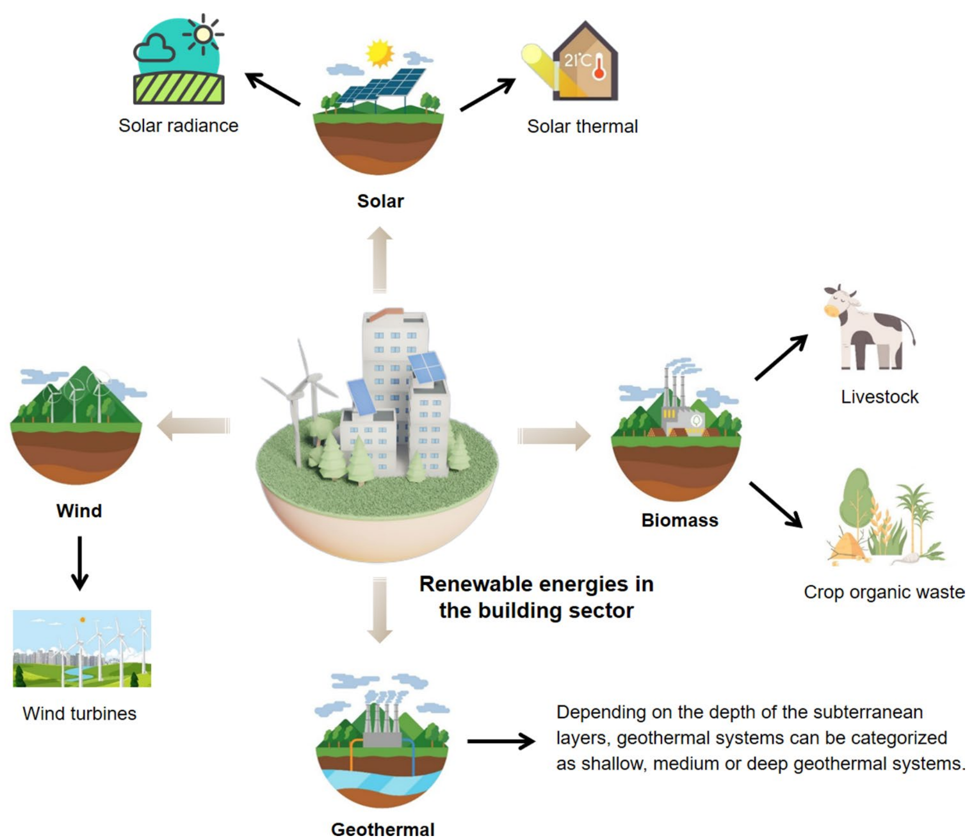


**Fig. 1** Types and sources of renewable energy in the building sector. Advancing the use of renewable energy within buildings is crucial for combatting climate change. The figure presented visually categorizes the types of renewable energy prevalent in the building sector. The dominant forms include solar energy, wind energy, geothermal energy, and biomass energy. Gaining a comprehensive understanding of these energy sources is pivotal. By integrating renewable installations with existing infrastructure and aligning them with energy demand patterns and environmental considerations, we can optimize overall efficiency

vapor-compression heat pump can be used to meet all of a building's thermal needs, increasing the efficiency of solar energy exploitation while reducing the consumption of ground-source heat pumps (Miglioli et al. 2023). Another study analyzed the capabilities of the solar cooling system by developing a dynamic calculation model compared to conventional systems, and the calculation results showed that the solar system can increase the renewable energy factor to 83% and reduce energy demand by 48% (Bilardo et al. 2020).

Building structures and designs need to integrate the use of solar energy resources to maximize the use of solar energy, which is often overlooked in many existing buildings. The building-integrated photovoltaic thermal systems can meet the electrical and thermal energy requirements of a building's domestic use, but the inconsistent supply of solar energy makes it very difficult to integrate building-integrated photovoltaic thermal air collectors into the building structure, and the system design is strongly influenced by the structural load-bearing capacity of the building (Şirin et al. 2023). Building-integrated photovoltaics play an important role in promoting the design and implementation of zero-energy buildings, but economic and technical obstacles need to be overcome. Regular maintenance and replacement of photovoltaic system components and auxiliary equipment are issues that designers focus on. The resulting economic cost directly affects its policies and the proprietor's willingness to support (Maghrabie et al. 2021).

In conclusion, solar energy offers significant benefits for buildings by reducing operating costs, enhancing the functionality of building components, improving energy use efficiency, and diminishing energy demand. Nonetheless, challenges persist, including the need for technological advancements, high maintenance and renewal costs, and the intricacies of structural design tailored for building applications. Therefore, integrated consideration of the utilization of solar energy resources is essential to maximize their potential.

## Wind energy

With the development of offshore wind energy, the application of wind energy in the building sector is gradually becoming widespread and is considered to be one of the most commercially promising renewable energy sources (Zhang et al. 2023). The wind energy system consists of wind turbines, which work on the principle of converting kinetic energy into electrical energy, mechanical energy, and other required energy using wind vortex machines. Similar to solar, wind systems can be categorized into active and passive systems based on the size of the turbine, with the biggest difference between the two being the type of power drive, with the active rotating with the motor and the passive rotating with the wind direction (Palraj and Rajamanickam 2020). Wind power generation using wind energy, development of natural ventilation systems, wind energy testing, and wind impedance design are now common technologies for renewable energy applications in buildings (Deymi-Dashtebayaz et al. 2022; Peng et al. 2020b).

The most direct impact of wind power generation is to reduce carbon emissions and consumption of non-renewable energy. According to research statistics, as of 2017, the use of wind energy resources has avoided at least 600 million tons of greenhouse gas emissions (Yousefi et al. 2019). The integration of wind energy systems in buildings generates renewable energy on the construction site, which can provide around 15% of the building's energy needs (Kwok and Hu 2023). The building design adopts a natural ventilation system to achieve the effect of indoor and outdoor air circulation through natural wind power, which can reduce the degree of dependence on air conditioning and, to a certain extent, reduce energy consumption. In this context, Wang et al. (2021a) developed an innovative energy-efficient turbine damper ventilator, which reduces unwanted exhaust airflow to provide a comfortable indoor environment. Also, it can stabilize the air exchange in the building to meet minimum air quality standards.

Compared with conventional energy sources, wind energy generation equipment requires a significant investment in manufacturing and installation, including maintenance costs at a later stage. The electricity converted by the wind turbine and then supplied by the heat pump was simulated using the Energy PLAN software, and the results exhibited that the total energy cost increases by 653.2% under this scenario (Noorollahi et al. 2021). Noise generated by the operation of wind turbines is a concern for nearby residents, which originates from the mutual collision of turbine components and noise generated by air vibration (Zhang et al. 2023). In urban environments, the height and density between buildings limit the utilization of wind energy. The wind speed and direction between elevated buildings may be affected by blocking and turbulence, reducing the efficiency of wind power generation (Kwok and Hu 2023). Also, due to the uncontrollable and uncertain characteristics of wind, wind power generation is intermittent, which also seriously affects the efficiency of energy use (Roga et al. 2022).

In conclusion, while wind energy substantially contributes to emission reductions and meets the energy demands of buildings, it comes with higher upfront costs. Its efficiency is heavily dependent on natural wind speeds and is significantly influenced by the building's layout. Therefore, there is an urgent need to explore smart or other new technologies to improve the efficiency of wind energy use.

## Geothermal energy

Geothermal energy is derived from the Earth's internal heat (Osman et al. 2023). The constant heat flow within the Earth contributes to the storage of internal heat, while rainfall within the Earth's crust plays a crucial role in completing the water cycle (Palmero-Marrero et al. 2020). Therefore, geothermal energy is a non-intermittent renewable energy source that is not dependent on climate or time of day and can supply energy 24 hours a day independently of external conditions. In terms of usage, solar and wind energy are more used for power generation, while geothermal energy is mainly used for heat production and cooling. In addition, it can work in conjunction with other energy systems, such as solar energy, to add effective for improving industrial competitiveness and positively impact job creation and economic development in the medium to long term. Depending on the depth of the subterranean layers, they can be categorized as shallow, intermediate and deep geothermal systems, but there is no specific universal definition or classification (Romanov and Leiss 2022b). Geothermal technology development can be utilized for power generation, direct use, and heat extraction through shallow ground-source heat pumps.

Compared to conventional heating and cooling systems, geothermal energy systems can improve energy efficiency while significantly reducing energy costs and greenhouse gas emissions. D'Agostino et al. (2022b) conducted simulation modeling based on Energy Plus software to systematically analyze the energy retrofitting of existing buildings with two types of low-hale geothermal systems: ground-source heat pumps and geo-aerothermal heat exchangers. The scholar observed that the use of these systems significantly reduces primary energy demand, energy costs, and $CO_2$ emissions compared to conventional gas boilers, demonstrating their effectiveness in achieving the goal of net-zero-energy buildings. Geothermal systems operate quietly without the noise of traditional heating, ventilation, and air conditioning systems, improving building operating comfort and health (Shah et al. 2022). At the same time, geothermal systems require a relatively small land area, making them suitable for urban environments where space is limited. Studies have estimated the land use intensity of geothermal power plants in buildings to be 7.5 $m^2$ per MW per year, which is much smaller than other energy technologies (Tester et al. 2021). In addition, geothermal systems can be integrated with a variety of architectural styles and provide design flexibility for buildings by utilizing different sizes and configurations of ground-source heat pumps to meet specific heating and cooling needs based on building size, load requirements, and space availability.

Despite the low operating costs of geothermal energy technologies, the need to drill holes and install underground components results in high installation costs and significant upfront investment costs (Hu et al. 2021; Lizana et al. 2018). The geological characteristics of the building project site largely determine the success or failure of a geothermal system (Chen and Feng 2020). Therefore, an accurate assessment of subsurface conditions is essential to determine the feasibility and potential output of a geothermal system, and uncertainties in geology can increase the risk of drilling failures and lead to additional costs. The application of geothermal energy is site-specific, and locations with sufficient thermal potential have become challenging. Studies have calculated subsurface thermal storage capacities of 8,300–16,600 GJ to satisfy winter heating in buildings using finite element methods (Chen and Feng 2020). In addition, the establishment and operation of geothermal systems have potential impacts on the environment. The noise generated by drilling construction and the treatment of geothermal fluids are all challenges faced by geothermal technology.

In summary, geothermal energy offers substantial improvements in energy efficiency, reductions in energy costs, and decreases in greenhouse gas emissions. Its design flexibility for integration with buildings presents a solution for energy transitions in space-limited urban structures. However, its high installation costs and the necessity for thorough evaluations of geological conditions and environmental impacts remain challenges.

## Biomass energy

Biomass derived from organic materials extracted from living or sentient organisms such as animals, plants, or microorganisms can be combusted through aerobic and anaerobic digestion to produce energy and is by far the longest renewable energy source used by humans (Yang et al. 2022a). Biomass in the building sector is usually utilized in the form of biomaterials in structural or non-structural parts of buildings to reduce dependence on fossil fuels and lower emissions. In general, biomass energy predominantly relies on resources like wood, agroforestry residues, plant fibers, as well as various organic waste materials, encompassing human, animal, and plant wastes. Biogas and direct combustion techniques primarily find application in the context of building energy needs. Additionally, biomass, including materials such as construction waste and animal excreta, can be utilized to generate electricity through dedicated power plants (Khan and Al-Ghamdi 2021). For example, Rahman et al. (2015) investigated biomass energy by studying the peak load of a biomass-powered 115 kW power plant, which can meet the power demand of an entire residential building. Thus, biomass can be utilized in buildings in several areas, such as biomass gas, biomass fuel, biomass heat, and biomass power generation (Allouhi et al. 2021; Furubayashi and Nakata 2021; Wu and Skye 2021).

Biomass plays a vital role in advancing the objectives of the Europe 2020 climate and energy strategy (Farghali et al. 2023b). This involves initiatives like replacing conventional boilers with more efficient models and emphasizing renewable energy sources. For example, Las-Heras-Casas et al. (2018) investigated the possibility of substituting central fossil fuel boilers with biomass alternatives across diverse climatic zones in the peninsular region during winter. Their findings indicated the potential for significant reductions in non-renewable energy consumption (up to 93%) and substantial decreases in carbon dioxide emissions (up to 94%). Biomass offers a low-carbon footprint, given its carbon–neutral nature (Wang et al. 2018). Comparatively, using wood chips and pellets as fuel for biomass boilers instead of diesel resulted in substantial greenhouse gas reductions of 40,000 tons of carbon dioxide over 30 years for 54,241 households (Rafique and Williams 2021). Biomass boilers are well-known for their heating efficiency. Solid biomass fuels with calorific values between 14 and 23 MJ/kg exhibit high combustion efficiencies, with peak mass collection efficiencies of around 98% for wood chip pellets powered by 50 kW boilers, though overall collection efficiencies typically range from 70% to 90% (Baumgarten et al. 2022; Wang et al. 2017). The efficiency is further enhanced when biomass wood is compressed into pellets under high pressure and temperature (Hartmann and Lenz 2019). However, it is important to note that biomass combustion can lead to corrosion on heating surfaces due to boiler deposits (Chen et al. 2021b). Furthermore, Pognant et al. (2018) highlighted that woodchip boilers may not be as environmentally friendly as natural gas boilers on a local scale. Nonetheless, woodchip boilers do improve local air quality and significantly reduce local ground-level particulate matter concentrations.

Biomass has a high calorific value of chemical energy and can be used directly in technologies such as combustion to generate electricity or in the production of biofuels. These biofuels can be burned to produce high-quality and high-temperature heat applications for heating buildings (He et al. 2019; Khan and Al-Ghamdi 2021). In addition to energy applications, biomass itself can also be used as a construction material, providing an environmentally friendly alternative to building components such as structural elements or thermal insulation. Studies have observed that the use of phase change materials made of biomass-derived porous carbon in buildings has a positive impact in terms of improved building thermal performance and building energy efficiency (Jiang et al. 2022b). Furthermore, the integration of biomass energy into the construction sector can diversify energy supply chains and enhance energy security by reducing dependence on imported fossil fuels. Smart building energy efficiency systems that mix solar photovoltaic thermal panels and biomass heaters improve energy reliability while meeting building energy efficiency, and the availability of biomass energy throughout the year makes the biomass heaters in the system promote energy security (Behzadi et al. 2023).

As biomass is mainly derived from cultivated products, wood, or other wastes, extensive extraction for energy can exacerbate the destruction of vegetation, and biomass materials often compete with other land uses such as agriculture and forestry for resources such as land and water, balancing competing demands is essential for sustainable biomass extraction (Bungau et al. 2022; Yana et al. 2022). Some biomass materials may be less durable and less resistant to environmental factors such as moisture, pests, and fire than traditional building materials, and ensuring the long-term performance and longevity of biomass-based systems may require additional treatment and protection measures (Liuzzi et al. 2020). In addition, biomass materials have limited availability and may vary in quality and performance depending on factors such as seasonal cycles, climatic conditions, and regional differences (Hiloidhari et al. 2023). Therefore, ensuring a continuous and reliable supply of biomass materials may be a challenge for large-scale construction projects.

In summary, biomass holds a pivotal position in Europe's climate and energy strategy. It notably curtails non-renewable energy consumption and diminishes greenhouse gas emissions. Nonetheless, to harness biomass sustainably in extensive construction projects, challenges like resource competition, material durability, and supply reliability must be tackled.

This section delves into the pros and cons of four renewable energy types for building applications. Renewable energies leverage the inherent benefits of natural resources, curbing our reliance on fossil fuels to elevate energy efficiency and cut down greenhouse gas emissions. Yet, they are often marred by substantial upfront infrastructure costs and hurdles in technological advancement and innovation.

## Case studies of renewable energy use in the building sector

In order to further concretize the above viewpoint and more intuitively demonstrate the application of renewable energy in building practice, the following section will conduct in-depth case studies through two cases: the Bullitt Center and Bahrain World Trade Center. We will elaborate on the successful implementation of renewable energy in these buildings, analyze the benefits of using these energy sources, as well as the challenges and lessons learned during the implementation process. These two cases provide us with valuable insights on how to promote renewable energy more widely in the construction field.

## The Bullitt Center, Seattle, USA

Completed in 2013, the Bullitt Center, situated in Seattle, Washington, goes beyond conventional boundaries in energy efficiency, environmental responsibility, and occupant comfort. It serves as a prominent model of sustainable architecture, showcasing the seamless integration of renewable energy. This groundbreaking commercial structure not only redefines eco-friendly buildings but also establishes fresh benchmarks for energy efficiency, earning global recognition as one of the greenest edifices worldwide.

The core of the sustainable development of the Bullitt Center is the reliance on solar panels as the main source of renewable energy. The roof of the building is decorated with many photovoltaic solar panels, which can capture sufficient sunlight in the Pacific Northwest and convert sunlight into clean, renewable electricity. Solar power generation is the core of the building's net-zero-energy goal, and the building also has renewable technologies such as rainwater collection, composting toilets, and ground-source heat pumps. Based on the work of multiple authors in this field, we can further emphasize the advantages of the Brett Center in renewable energy integration, energy efficiency, and sustainability.

### Benefits

The Bullitt Center has attained net-zero-energy status, a milestone emphasized by Caballero et al. (2023), who highlight the crucial role of photovoltaic systems in this achievement. The extensive array of solar panels installed at the Bullitt Center ensures that it generates more energy than it consumes, thus solidifying its net-zero-energy building designation. This is consistent with the global shift toward sustainable building practices driven by high electricity costs and renewable energy availability. Energy self-sufficiency can be achieved. On-site photovoltaic systems, such as those on the roof of the Bullitt Center, are crucial for energy self-sufficiency in urban areas with limited rooftop space (D'Agostino et al. 2022a). Some researches highlight the importance of combining solar power generation with improved insulation during roof renovation (D'Agostino et al. 2022c). The Bullitt Center utilizes rooftop installation of solar panels to ensure that a significant portion of its energy demand comes from on-site renewable energy, maximizing energy efficiency and renewable energy utilization. This intervention greatly reduces costs. In addition, it adopts an energy-saving design, which maximizes the use of natural lighting in the building and reduces the need for artificial lighting during the day. Efficient heating and cooling systems, as well as advanced insulation technology, ensure that the energy consumption of buildings remains extremely low, ultimately achieving energy self-sufficiency.

By collecting rainwater, the Bullitt Center has reduced its dependence on traditional water sources, saving water and energy required for water treatment and distribution. The framework of the rainwater harvesting system is shown in Fig. 2, as demonstrated by the research of (Ali and Sang 2023); the rainwater harvesting system effectively addresses the water and energy shortages of sustainable urban development. If designed properly, rainwater harvesting is economically feasible (Almeida et al. 2021). At the same time, the performance of rainwater collection system is influenced by climate zones (Ali and Sang 2023), and the Bullitt Center experiences a mild marine climate and regular rainfall, which is conducive to the functioning of rainwater collection systems. To further reduce water waste, the Bullitt Center has adopted composting toilets. These innovative devices reduce water consumption and wastewater treatment requirements, helping to reduce the overall environmental impact of buildings.

The rainwater collection system at the Bullitt Center not only saves water but also helps reduce the risk of urban flooding. The research by Hdeib and Aouad (2023) suggested that rainwater harvesting systems can alleviate urban floods. Although their research focuses on arid areas, these principles apply to various climates. Effectively managing rainwater can help enhance its ability to withstand extreme weather events. In addition, the Bullitt Center also has certain economic benefits. Megahed and Radwan (2020) pointed out the economic advantages of using solar energy, including generating potential revenue by selling surplus energy to the grid. The model proposed by Ye et al. (2023) indicated that photovoltaic panel rainwater harvesting systems can allocate resources more effectively, increasing

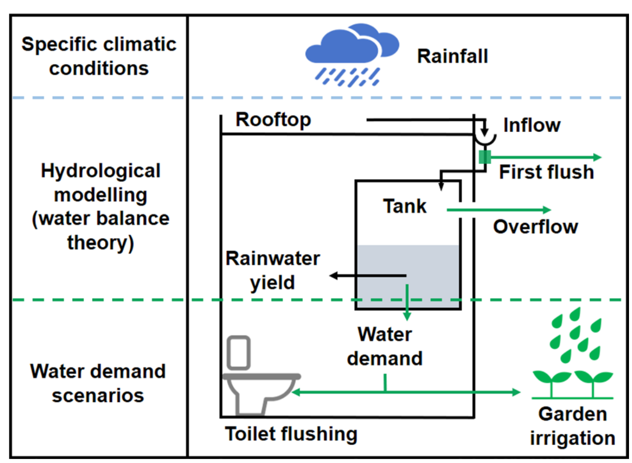


**Fig. 2** The framework of the rainwater collection system. This figure illustrates the operational mechanism of the rainwater harvesting system. The system captures rainwater via the roof, directs it through designated pipelines to a storage tank, and subsequently distributes it for toilet flushing and garden irrigation based on water requirements

revenue while saving water and energy. This method is in line with the spirit of resource optimization and economic efficiency of the Bullitt Center.

### Challenges

Although these technologies bring many benefits to sustainability and energy efficiency, they also pose some challenges during implementation. In the case of the Bullitt Center, we examine the hurdles associated with various renewable technologies. Deploying multiple renewable energy sources frequently demands navigating intricate and continuously evolving regulatory frameworks. The Bullitt Center's commitment to renewable energy, such as solar panels, geothermal heating, and refrigeration systems, requires compliance with various federal, state, and local regulations related to renewable energy generation, grid interconnection, and building codes. Ensuring compliance with these regulations while breaking the boundaries of sustainable design is a daunting challenge. In addition, integrating various renewable energy sources into a building presents challenges related to system compatibility and coordination (Canale et al. 2021). Coordinating the operation of these systems, optimizing their performance, and ensuring their harmonious collaboration require high-level technical expertise and skilled technical personnel. Ensuring that the Bullitt Center has access to the necessary professional knowledge and resources is crucial for the success of these technologies.

The initial capital expenditures linked to the installation of multiple renewable technologies can be substantial. While these investments often result in long-term energy and water savings, securing the necessary upfront funding can be a hurdle, particularly for projects with limited budgets. Furthermore, all renewable technologies entail ongoing maintenance obligations to guarantee their sustained reliability and performance. Solar panels require regular cleaning and occasional maintenance, while geothermal systems require continuous monitoring. The continuous maintenance and monitoring of rainwater collection systems are crucial for preventing issues such as blockage, algae growth, or bacterial contamination (Clark et al. 2019), and key maintenance is needed to ensure water quality and system efficiency. Effectively managing these maintenance tasks and resolving unexpected failures can be resource-intensive and challenging.

The success of the Bullitt Center highlights the importance of adopting a holistic approach to sustainability, which focuses not only on energy efficiency but also on water conservation, material selection, and overall environmental impact. At the same time, the design and planning phase of the Bullitt Center is very detailed, with architects, engineers, and sustainable development experts involved. They need to make cautious, data-driven design decisions that consider local climate, energy, and resource availability. In addition, it is necessary to advocate and collaborate with local authorities to adjust building codes and regulations to adapt to innovative sustainability characteristics. Engaging with policy makers and regulatory agencies can promote the implementation of advanced green building practices. The Bullitt Center's success can be a model for similar projects in different regions and climates. Future endeavors should consider how lessons from the Bullitt Center can be adapted to their unique contexts.

This section delves into the Bullitt Center's accomplishments and challenges related to sustainability. The Bullitt Center achieved net-zero-energy status by leveraging photovoltaic systems, optimizing the use of solar energy and natural light. Furthermore, their efficient rainwater harvesting methods diminish reliance on conventional water sources, while also mitigating urban flooding. These sustainable practices not only benefit the environment but also present potential economic advantages, including the possibility of profit from excess energy. However, the adoption of such innovative technologies is not without its difficulties. Challenges include compliance with regulatory standards, harmonizing multiple renewable energy sources, and navigating both initial investment and recurring expenses. The Bullitt Center's achievements highlight the merit of a holistic approach to sustainability, considering local climatic conditions, available resources, and regulatory frameworks. Their success could pave the way for similar sustainable projects in future.

## Bahrain World Trade Center, Manama, Bahrain

Bahrain is located in the southwest of the Persian Gulf, between Qatar and Saudi Arabia, with a tropical desert climate and hot and humid summers. The Bahrain World Trade Center is located on the Persian Gulf coast of the capital city of Manama, costs $96 million with a total construction area of 12,096 $m^2$, and consists of two identical towers, each with a height of over 240 m and a total of 50 floors. Designers have set up a 75-ton bridge at the 16th, 25th, and 35th floors between the two towers and fix three horizontal axis wind turbines with a diameter of 29 m and their connected generators on these three bridges.

### Benefits

Due to the advantage of geographical location, the potential of wind energy resources has been explored. The study conducted by Adnan et al. (2021) in Pakistan emphasizes the importance of accurately evaluating wind energy resources to ensure efficient utilization of wind energy potential. This analysis includes average wind speed, Weibull parameters, as well as power and energy density, which helps determine suitable locations for wind energy production. In addition, reasonable building layout, height, and corner shape can also improve wind density and utilize urban wind energy (Juan et al. 2022). As shown in Fig. 3, the wind power generation diagram of the Bahrain World Trade Center is located in a coastal urban area. By designing the building as a sail, sea wind convection is formed between the buildings, accelerating the wind speed, and making wind turbine power generation possible. In addition, batteries can be discharged in the event of insufficient wind power, assisting and stabilizing users' electricity usage by setting up to store excess electrical energy.

### Challenges

The Bahrain World Trade Center was a pioneer in incorporating wind power into its architectural design but faced several major challenges during its implementation. These challenges not only include technical and engineering aspects but also affect the functionality and overall sustainability of the building. The efficiency of wind turbines needs to be considered in urban environments characterized by turbulent wind patterns. Traditional wind farms are usually located in open areas with consistent wind flow to ensure optimal energy generation. In contrast, urban environments have complex wind patterns due to the presence of high-rise buildings and structures that disrupt and redirect airflow. To address this challenge, computational fluid dynamics simulations and wind tunnel tests can be used to evaluate the wind direction around buildings (Arteaga-López et al. 2019). These results can provide a basis for the design and layout of turbines, maximizing their exposure to the mainstream wind direction while reducing the impact of turbulence.

Maintaining wind turbines at considerable heights in coastal environments is a unique challenge. In this case, the standard maintenance procedures for ground turbines are not sufficient. Professional equipment, such as cranes or elevators, that can reach extreme heights is crucial for turbine maintenance. In addition, daily inspections and repairs need to consider harsh coastal environments, including exposure to salt water and humidity, which may accelerate wear and corrosion (Mourad et al. 2023). Developing maintenance plans for Bahrain World Trade Center turbines is crucial for their long-term reliability.

Managing the noise and vibration generated by wind turbines is crucial for creating a favorable working environment for the occupants of buildings. Excessive noise and vibration may disrupt office space, affect attention, and reduce the overall comfort of occupants (Karasmanaki 2022). Innovative solutions, such as sound barriers or damping mechanisms, may be incorporated into turbine design to mitigate these impacts. In addition, the layout and insulation of the building may have been optimized to reduce the spread of noise and vibration into the internal space.

Incorporating the relevant research findings into the context of the Bahrain World Trade Center, we can find that the wind turbine integration of the Bahrain World Trade Center is not only a symbol of architectural originality but

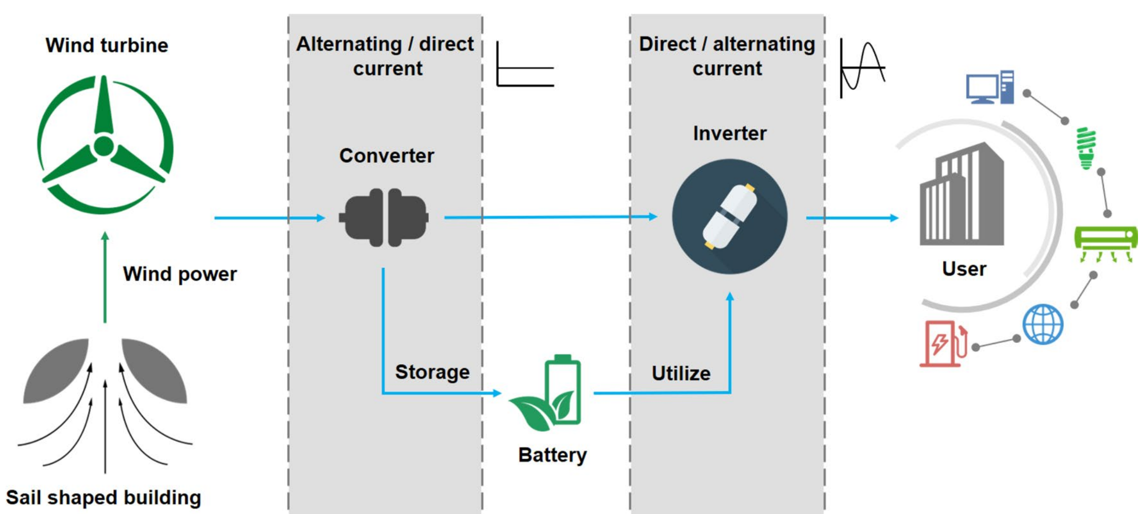


**Fig. 3** Schematic diagram of wind power generation for Bahrain World Trade Center. Incorporating an innovative design, the structure resembles a sail, strategically positioned to harness the prevailing sea winds. This unique design promotes wind convection between the buildings, channeling the flow efficiently. Positioned at an optimal height within the structure, a wind turbine captures this enhanced airflow, converting the kinetic energy of the wind into electrical power. This generated direct current is then processed through a converter, facilitating its efficient storage and transmission. In the final step, an inverter transforms the stored direct current back into alternating current to meet the building's electrical needs. This seamless integration of architecture and renewable energy technology not only serves the building's power requirements but also stands as a testament to sustainable and forward-thinking design

also a practical model for sustainable urban development: by strategically placing wind turbines between the twin towers, Bahrain World Trade Center effectively utilizes wind energy, reduces dependence on traditional energy, and contributes to environmental sustainability. In addition, by incorporating wind energy, the Bahrain World Trade Center aligns with the broader concept of hybrid renewable systems and demonstrates how multiple renewable energy sources work together to improve energy efficiency. As emphasized by the research institute, the Bahrain World Trade Center reflects the importance attached to the utilization of wind energy resources and the assessment of wind energy potential in urban environments.

This section highlights the Bahrain World Trade Center's innovative approach to harnessing wind energy, using its unique sail-inspired design to optimize sea wind convection and turbine output. While integrated batteries ensure power during low-wind situations, challenges arise from urban wind dynamics, demanding sophisticated placement strategies. Additionally, maintaining turbines in coastal heights brings its own set of challenges, and addressing noise and vibration is crucial for ensuring comfort within the building.

## Policy and regulatory framework

### Renewable energy policies and regulatory frameworks in the building sector

As a key sector of national economic growth, the construction industry has played an indispensable role in promoting China's urbanization process, but it has also had an irreversible impact on the global environment, the most direct impact on human survival being the series of chain reactions brought about by the greenhouse effect (Ahmed et al. 2021). The overexploitation and consumption of non-renewable energy sources, especially fossil fuels, is the main driver of anthropogenic greenhouse gas emissions. According to the Global Carbon Atlas, greenhouse gas emissions from fossil fuel combustion account for 28.9% of total global emissions in 2022 (Liu et al. 2023b). However, primary energy sources, such as fossil fuels, have limited reserves globally, and the scarcity of resources is facing a serious challenge, and there is an urgent need for the global energy mix to transition to sustainable energy sources (Chen et al. 2023b; Hoang et al. 2021b).

Notably, the year-on-year decline in the cost of renewable power generation has contributed to a trend of continued growth in renewable energy sector applications, with approximately 77% of capacity additions to sustainable energy generation due to solar and wind energy in 2017 (Al-Shahri et al. 2021). Besides, according to the World Health Organization, 7 million people die each year due to air pollution, which mainly stems from the burning of fossil fuels (Arya 2022). The development and implementation of regulatory frameworks and policies aimed at accelerating the deployment of renewable energy are therefore critical for mitigating climate change, enhancing energy security, and promoting sustainable development (Lu et al. 2020).

In the construction industry, policies and regulatory frameworks influence the use of renewable energy (Gielen et al. 2019). Inês et al. (2020) reviewed the development of energy policies in five countries, namely the USA, Germany, the UK, Denmark, and China, to provide a comprehensive overview of sustainable energy policies that promote renewable energy. Meanwhile, the concept of biomaterials has been applied in the construction industry, where the use of biomaterials can reduce the carbon footprint of the construction process, improve sustainability, and reduce dependence on limited resources (Raza et al. 2023). However, the disposal of construction materials and waste management can be affected by waste regulations related to biomaterials (Philp 2018). Figure 4 shows the history of the evolution of policy and regulatory frameworks for renewable energy in construction. These policies and regulations will vary between countries and regions, but they are all guiding the construction industry to adopt renewable energy for more sustainable practices.

Since the onset of the oil crisis in the last century, growing environmental concerns and energy security issues have prompted the exploration of strategies related to renewable energy and sustainability in a variety of fields, including buildings (Economidou et al. 2020). Renewable energy and sustainability strategies have evolved from environmental awareness to a fully market-driven phase, where experimental initiatives in the 1990s to the development of mandatory standards in the 2000s became an important turning point, such as the Renewable Portfolio Standard and the Renewable Energy Standard, which marked a successful transition of renewable energy policies from theory to practice (Solangi et al. 2021; Tan et al. 2021). International agreements such as the Kyoto Protocol and the Paris Agreement have played a key role in the development of global sustainability strategies, emphasizing the importance of coordinated action and shared commitment in combating climate change (Cifuentes-Faura 2022; Ottonelli et al. 2023). In addition, technological advances have become an integral part of renewable energy strategies, with smart building technologies, decentralized energy production, and energy storage solutions increasing efficiency and resilience (Walker et al. 2021). Future strategies will emphasize circular economy principles, resilience, and the integration of multiple approaches to create holistic and adaptive solutions for sustainable development (Farghali et al. 2023a; Hoang et al. 2021a).

The strategic principles for the development and implementation of policy and regulatory frameworks in the field

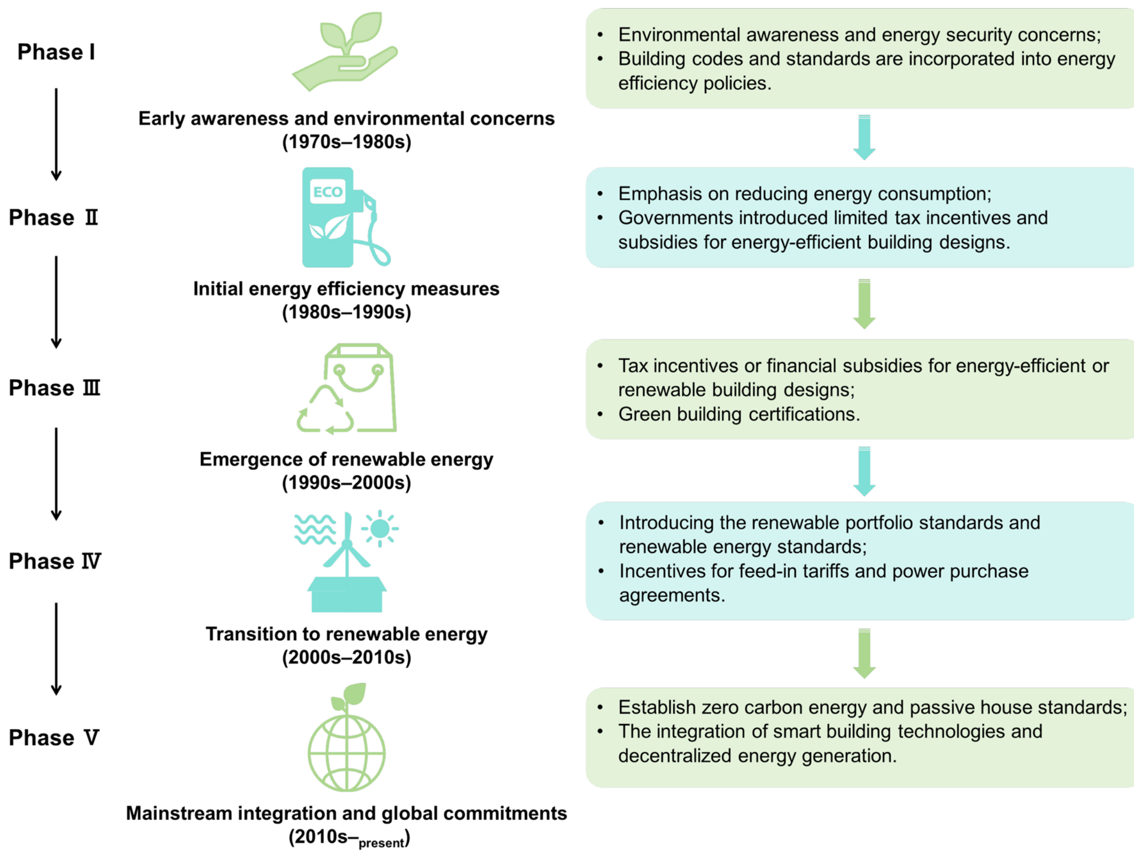


**Fig. 4** History of the evolution of renewable energy policies and regulatory frameworks in the building sector. The figure presented delineates a quintet of stages marking the evolution of renewable energy policies within the building sector. It chronicles a journey from nascent environmental consciousness to an unwavering global pledge, underscoring the pivotal influence of such policies on sustainable development and climate initiatives. Central to this narrative is the indispensable role of governmental regulations and policies in championing the emergence and growth of renewable energy technologies. In alignment with tenets of sustainable development, these policies foster the adoption of cleaner energy modalities, curtail ecological adversities, and enhance societal well-being

of renewable energy and sustainable development reflect a proactive, forward-looking approach to adapting to changing environmental challenges and technological advances (Jiang et al. 2022a). As promised in the Paris Agreement, policymakers prioritize international cooperation to align national strategies with global sustainable development goals (Iacobuţă et al. 2022). Effective strategic markets include market-driven incentives that are predominantly government-led, using mainly economic instruments to promote the use of renewable energy and application practices in the building sector (Solaymani 2021). It also emphasizes the importance of circular economy principles and builds the capacity to cope with future uncertainties. Together, these principles guide policy development and implementation to support renewable energy adoption, sustainability, and resilience in response to the changing global landscape.

In summary, governments and international organizations play an indispensable role in the development and implementation of renewable energy policies and regulatory frameworks. The formulation of strategic policies plays a pivotal role in curbing energy consumption, mitigating environmental repercussions, and steering the building sector toward elevated sustainability benchmarks, aligning with the escalating imperative for sustainable development. Nevertheless, an inclusive consideration of stakeholders is paramount to guarantee that these policies are both robust and effectively enforceable.

## Impact of policies and regulations on the adoption of renewable energy

In the context of addressing the global climate crisis, countries around the world have committed to autonomous greenhouse gas contributions at the United Nations Climate Change Conference (Meinshausen et al. 2022). The European Union is at the forefront of global carbon action, announcing the "European Green Deal" in 2019, which sets an ambitious goal of achieving net-zero greenhouse gases emissions by 2050 (Lu et al. 2020). The realization of the target is based on a comprehensive policy framework for the development and implementation of climate, energy, environmental, and economic policies and regulations to improve energy efficiency, reduce greenhouse gas emissions, and promote the sustainable development of buildings. Policies that encourage the adoption of renewable energy in buildings are the most effective and carbon-reducing actions (Topcu and Tugcu 2020). Policies to support the application of renewable energy are diverse, ranging from economic incentives such as financial subsidies and tax breaks to the setting of stringent energy efficiency standards and renewable energy portfolio mandates (Romano et al. 2017). Table 1 shows the variety of policies that have been adopted to promote renewable energy solutions in the built environment in major energy countries, both nationally and internationally.

Based on the analyses in Table 1**,** the results of the study indicate that policies to promote the development of renewable energy in buildings fall into four main categories: policy regulation, economic incentives, market transformation, and building performance and quality assurance. Government documents are developed or revised to mandate minimum energy requirements for buildings, renewable energy development regimes, and, most commonly, feed-in tariff harmonization. Economic measures such as financial subsidies and tax breaks incentivize renewable energy applications and expand their reach, and this is because the financial viability of renewable energy projects in buildings is influenced by the incentives and feed-in tariff subsidy rate, which determines the attractiveness of the investment. The development and application of renewable energy technologies such as solar, wind, and geothermal energy in buildings are now maturing, and actively exploring innovative developments in new renewable energy technologies and looking for market transitions is a strong guarantee that renewable energy can be sustainable in the long term. In addition, energy-efficient design, construction, and operation of buildings are legally encouraged through the creation of independent performance certificates for building materials, quality, structural elements, or technologies, and certified buildings typically consume less energy, thereby reducing greenhouse gas emissions and overall energy demand.

Economic incentives, mainly tax credits and financial subsidies provide substantial benefits to stakeholders such as real estate developers, for whom the government clears financing barriers and increases the economic attractiveness of clean energy investments to investors (Zhang et al. 2021). Through a series of renewable energy policies such as tax credits to subsidize photovoltaic projects and high government prices for surplus solar power, the US has invested $250 million in encouraging the development of solar rooftops since 2010, and photovoltaic applications have exploded, with a 20-fold increase in new installations alone in six years (Song et al. 2016). The knock-on effect of this policy has also led to the increasing integration of solar panels, wind turbines, and energy efficiency systems into building projects, thus increasing renewable energy capacity.

Based on the linear relationship between financial investment and renewable energy development, it can be seen that the implementation of financial incentives expands the competitiveness of the renewable energy market and drives the application of renewable energy in the building sector toward more efficient and cost-effective solutions, thus contributing to the economic growth of the renewable energy building sector (Shahbaz et al. 2021). Policies such as Leadership in Energy and Environmental Design, which combines green building certification with renewable energy, provide a new direction for sustainable building practices and renewable energy integration, lowering the operating costs for owners and occupants and improving energy efficiency, thus stimulating renewable energy use (Abd Rahman et al. 2021).

In conclusion, policy frameworks and regulations have a direct impact on the adoption of renewable energy in the construction sector. The implementation of policies and regulations stimulates the development of renewable energy and leads to technological advances in the sustainable building-related chain. These strategic initiatives not only align with global sustainable development aspirations but also expedite the shift toward an environmentally friendly and sustainable architectural landscape.

## Opportunities and obstacles to policy development

In the development of sustainable development policies, the circular economy has been favored by policymakers for its ability to promote economic growth while also reducing dependence on raw materials and energy (Knäble et al. 2022). Its principle is to advocate the reuse and recycling of materials, thus maximizing the use of waste recycling to promote sustainable practices from construction to deconstruction and to reduce resource consumption to achieve the goal of sustainable development, which is consistent with the concept of renewable energy (Hossain et al. 2020). Hoang et al. (2021a) integrated renewable energy into a smart city energy system by integrating more than two renewable energy components into the building system, achieving good emission reduction benefits and laying the foundation for exploring more sustainable and cleaner energy production in future. Researchers have determined that 1112 million tons of standard coal were consumed in the building sector in 2018 (Guo et al. 2021). With the depletion of non-renewable energy resources globally, it is important to develop competing policy frameworks that are in line with circular economy practices in order to adapt to the rapidly changing trends of the energy revolution (Danish and Senjyu 2023b).

The development of renewable energy policies based on the combination of circular economy principles and

**Table 1** Policies to encourage renewable energy in buildings

| Country | Types of policies | Measures | Key findings | Reference |
|---|---|---|---|---|
| China | Economic incentives | Government financial subsidies | Making full use of government subsidies is to provide tax incentives for building construction companies and promote the application and scope of renewable energy building energy efficiency equipment | Nie et al. (2023) |
| | | Feed-in tariff subsidies | Increasing the efficiency of maximizing the use of solar photovoltaic is by supporting rooftop and building-integrated systems, implementing feed-in tariff subsidy policies, and encouraging direct investment by exempting value-added tax | Kılıç and Kekezoğlu (2022) |
| | Market transformation | Innovative technology development | The government reduces the investment risk of technology developers by increasing the capital for research and development of innovative technologies for the application of renewable energies, such as the photovoltaic power generation industry and other renewable energies in the field of construction, and at the same time, it strengthens the protection of intellectual property rights to ensure that the economic and social benefits brought about by the innovative technologies will be conducive to the expansion of the market | Zhao et al. (2021) |
| New Zealand | Regulatory policy | Building code development | Strict regulations are for the supply of renewable energy for heating, ventilation, and air conditioning, building lighting, based on building envelope regulations following the thermal energy requirements of each region of the country | Tori et al. (2022) |
| | Economic incentives | Tax incentives | Expanding the use of renewable energy in building homes is by reducing local housing property taxes and mortgage interest rates and increasing real estate developers' investment in net-zero or zero-carbon buildings and homeowners' willingness to buy | |
| India | Regulatory policy | Building code improvements | Increasing building-integrated photovoltaics technology development through improved policy standards allows building-integrated photovoltaics to utilize solar energy to a greater extent and promote solar power generation | Shukla et al. (2018) |
| | | Feed-in tariff policies | Promoting the integration of renewable energy is by revising tariff policies to reduce the cost of use for consumers while increasing the quality of supply of renewable energy sources such as solar, wind, biomass, and hydropower | Kumar and Majid (2020) |
| | Economic incentives | Financial investments | Financial support focuses on research institutions to strengthen research and development efforts on building-integrated photovoltaics systems and energy efficiency to improve performance design and renewable energy efficiency | Shukla et al. (2018) |

**Table 1** (continued)

| Country | Types of policies | Measures | Key findings | Reference |
|---|---|---|---|---|
| USA | Government regulation | Policy formulation | Building electrification has been promoted through the development of national energy codes, with some cities issuing permits for new construction that prohibit buildings from being connected to natural gas. Also, the development of building appliance standards to encourage the use of renewable energy in buildings has helped to increase the demand for renewable electricity | Gold (2021) |
| | | | Expressly prohibited is the use of natural gas in new buildings in cities and issue building energy efficiency is codes to improve the energy efficiency of buildings | Wei et al. (2021) |
| | Economic incentives | Government financial support | The state assembly bill sets up funds dedicated to building decarbonization, with direct financial incentives for the adoption of renewable energy technologies in buildings (e.g., electric heat pump heating, ventilation and air conditioning systems, and heat pump water heaters), and 30% financial support for low-income housing | |
| South Korea | Government regulation | Revision of building energy codes | Public building mandates should meet a mandatory minimum percentage of on-site renewable energy generation or use of qualified renewable energy systems | Kim (2021) |
| | Economic incentives | Financial subsidy | Government financial subsidies for renewable energy programs for residential and non-residential buildings, the Korean government bears the cost of specific installations in renewable building systems similar to the Green Homes, and the government subsidies have been expanded from only solar photovoltaic applications to include wind, geothermal, solar thermal, and fuel cell applications in buildings. For non-residential buildings, the government also explicitly requires geothermal and solar applications in renewable energy regulations | |
| | Market transformation | Renewable portfolio standards | The government introduced the Renewable Portfolio Standards policy to encourage competition among renewable energy sources such as solar photovoltaic, wind, hydropower, fuel cells, ocean energy, bioenergy, and to reduce the financial pressure of the feed-in tariff policy | |

**Table 1** (continued)

| Country | Types of policies | Measures | Key findings | Reference |
|---|---|---|---|---|
| German | Building performance and quality assurance | Green building certification | The government and non-profit organizations worked together to develop the Energy Conservation Ordinance to promote energy efficiency in buildings, to determine energy consumption in buildings through mandatory energy framework calculations, and to promote the development of renewable energy buildings | Franco et al. (2021) |
| | Economic incentives | Financial subsidy | From subsidizing the cost of photovoltaic roofs to providing low-interest rate loans for photovoltaic system projects, to reduce costs, the government has mandated that feed-in tariffs be reduced by 5% per year | Song et al. (2016) |
| Italy | Economic incentives | Tax relief | Government tax deductions of 110% are available for the cost of energy-saving measures in the production of buildings, while sustainable materials that meet energy-saving standards for insulating the building envelope or replacing a heating system with a micro combined heat and power system are eligible for a tax deduction of 110% for five years | De Masi et al. (2022) |
| | Policy supervision | Feed-in tariff tax subsidies | Government incentives range from the energy consumed by solar photovoltaic systems to the level of degree of photovoltaic energy building integration to tax subsidies that will be available for photovoltaic power plants to support the large-scale deployment of photovoltaic systems in Italy to increase photovoltaic power generation and photovoltaic building integration applications | Bianco et al. (2021) |
| Japan | Building performance and quality assurance | Green building programs | A green building certification system was built through sustainable energy retrofitting of buildings to reduce energy demand and improve the energy efficiency and environmental performance of buildings | Balaban and de Oliveira (2017) |
| | Policy supervision | Policy formulation | It is adopting an energy policy that provides for an increase in the zero-energy target for all new public buildings by 2020 and all new residential buildings by 2030 | Taherahmadi et al. (2021) |

This table presents the renewable energy policy frameworks of major energy nations, focusing on the construction sector. Governments have introduced both incentives and mandatory regulations at institutional, economic, and technological levels. These policies, targeting stakeholders like construction firms and investors, fall under four categories: policy regulation, economic incentives, market transformation, and building performance assurance. The table details each country's policy implementation and its specific building application. It underscores that policy development is influenced by energy security, environmental concerns, technological advances, and economic factors smart renewable energy systems has great potential for expanding the use of renewable energy in the construction sector. Nag et al. (2022) applied circular economy principles to develop a wind turbine-based renewable energy system, whereby the refurbishment and remanufacturing of wind turbines achieves an extension of the life of the wind turbine. This synergy is aligned with the broader Sustainable Development Goals to minimize energy demand through resource optimization and material reuse. Smart city energy, on the other hand, relies on smart technological resources to improve energy efficiency in a high-quality manner, mainly by intelligently managing heating, cooling, and lighting systems, among others, to facilitate energy sharing within the community (Wang et al. 2021b). In essence, the harmonious combination of circular economy and smart renewable energy systems will provide for a more sustainable, efficient, and resilient adoption of renewable energy in the building sector. The organic combination of financial incentives, energy efficiency, and market transformation is achieved for policymakers, symbolizing the transition of renewable energy policy toward a greener, more resource-based future.

However, the process of promoting and developing renewable energy in the building sector is not without obstacles, and Fig. 5 shows the challenges and practical implications of implementing renewable energy policies in the building sector. Although many governments have provided financial support for the development of renewable energy, the cost of renewable energy development is much higher than conventional energy sources compared to the high initial cost of renewable energy technologies, and the amount of government subsidies does not solve the fundamental problem, which poses a significant barrier for building owners (Chen et al. 2021a). Frequent policy changes and regulatory uncertainty also make building investors and developers hesitant, and research has found that policy stability determines the long-term planning of renewable energy projects (Alola and Saint Akadiri 2021). The intermittent nature of solar and wind energy poses a challenge to grid integration and stability, as renewable energy access to building community grids is subject to both national regulations and policy regulations. At the same time, complex permitting procedures and technical requirements for grid integration further add to the complexity of implementing renewable energy systems in

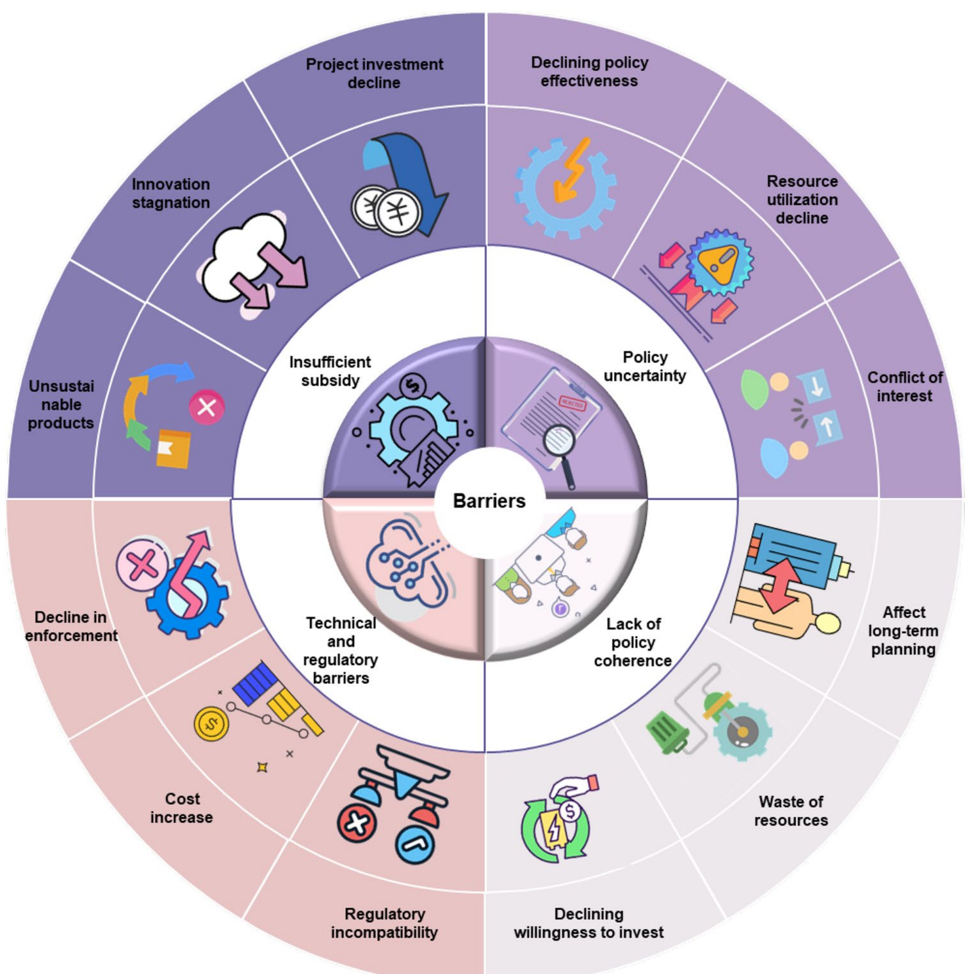


**Fig. 5** Barriers to and impacts of renewable energy policies in the building sector. The figure delineates the predominant obstacles hindering the extensive integration of renewable energy within the building sector. These encompass limited governmental financial support, ambiguity in policy direction, intricate regulatory systems, a dearth of expertise, and the efficacy of policy execution. Moreover, the figure also illustrates the actual impacts and consequences of these barriers, providing a comprehensive overview of the challenges faced by various stakeholders and emphasizing the multifaceted nature of these barriers and their potential impacts. Overcoming these challenges is pivotal for enhancing renewable energy assimilation, realizing sustainable development objectives, and cultivating a robustly built milieu

buildings (Wainer et al. 2022). Besides, the extent to which policies on renewable energy in buildings are developed and implemented at the national and regional levels is an important indication of the effectiveness of ensuring policy regulation (Busch et al. 2021).

Lessons learned from the implementation of renewable energy policies emphasize the flexibility of policy formulation and the need to continuously adapt to regional differences and new technologies that are continuously evolving. A sound assessment of the underlying national circumstances to develop renewable energy policies that are appropriate to the changing environment and regular policy reviews determine the longevity of policy implementation (Agyekum et al. 2021). At the same time, the adoption of different stakeholders' opinions ensures the policy's relevance and breadth (Neij et al. 2021). A study by Scheller et al. (2021) suggested that stakeholders influence the entire process of solar photovoltaic residential decision-making, and the shift in the role of participants from passive engagement to active information searching averts potential risks and challenges for policy makers and ensures that policies take into account a wide range of interests and needs. In addition, renewable energy portfolio standards, energy efficiency standards for appliances and buildings, are tailored to the specific needs of the local building sector for renewable energy to maximize the effect and impact of policy development (Danish and Senjyu 2023a).

In conclusion, while potential avenues exist for renewable energy policies, especially at the nexus of smart and circular economic synergies, challenges such as high upfront investments, grid instability, and policy inconsistencies persist. This section delves into the policy and regulatory landscapes that bolster renewable energy adoption in buildings. An in-depth analysis of the policies and regulations championed by nations to facilitate renewable energy integration is presented, considering economic, social, and institutional dimensions. The resultant effects on sustainability and energy efficiency are also dissected. For effective execution of these renewable energy strategies, it is crucial to harness potential opportunities like smart and circular economy synergies, while concurrently navigating impediments like hefty initial investments, scarcity of expertise, and policy ambiguity, all within a cohesive and sustainable framework.

## Innovations in renewable energy for building sustainability

### Recent technological advancements in building-based renewable energy

In recent years, as the construction industry gradually gets rid of its dependence on fossil fuels and countries to reduce carbon emissions to achieve sustainable development requirements, the use of solar energy, wind energy, geothermal energy, and other renewable energy has received widespread attention. Renewable energy technologies can address issues such as the global energy crisis, food insecurity, and climate change by providing environmentally friendly clean energy and are expected to make a significant contribution to the sustainable development of the construction industry (Izam et al. 2022). At present, renewable energy is not only a resource but has become a viable alternative to major transformational technologies. To this end, countries around the world are trying to innovate and improve renewable energy technologies and methods to promote the application of mature renewable energy technologies in the field of construction to achieve the best use of renewable energy in the construction industry.

Solar energy is one of the most environmentally friendly and sustainable renewable energy sources available today (Dehghani Madvar et al. 2018; Kannan and Vakeesan 2016). Research has shown that solar energy is the most abundant source of renewable energy, easy to obtain and low-cost, and has shown great potential to meet world energy needs in future (Adenle 2020). Due to its reliability and efficient performance, solar energy has become one of the most popular energy sources and will play an important role in future of energy. At present, the application of solar technology in the construction field mainly includes solar photovoltaic power generation, concentrated solar power generation, solar hot water systems, and solar air conditioning refrigeration technology. The main contribution of the above technology in the building is to save energy for heating (namely space heating and water heating), refrigeration, ventilation, electricity, and lighting (Bosu et al. 2023).

At present, the global installed capacity of solar photovoltaic power generation continues to increase and has become a rapidly developing industry (Diwania et al. 2020). However, the low conversion efficiency, high price, and large impact of climatic conditions of photovoltaic cell energy storage are the main obstacles to the promotion and stable development of this technology in the construction industry (Durganjali et al. 2020). As Table 2 shows, improvements in solar systems and innovative applications for integration with other energy sources or materials have led to significant advances in many aspects, including power generation and heating efficiency. The application of information technology, such as the Internet of Things and artificial intelligence, to solar photovoltaic systems has become one of the feasible solutions to the above problems. In addition, machine learning technologies such as artificial neural networks and support vector machines have great potential in predicting solar radiation intensity and power generation, and applying them to solar photovoltaic systems can also significantly improve the efficiency of photovoltaic power generation (Mellit and

**Table 2** Innovations and improvements in building-integrated solar energy systems

| Technology | Study description | Technological advances | Key findings | Reference |
| --- | --- | --- | --- | --- |
| Solar photovoltaic power generation | A low-cost and high-efficiency distributed solar photovoltaic device based on the Internet of Things technology is proposed and an object-based network integrated auxiliary platform is built to automatically track and monitor solar cells | Improving the design of solar cell systems is based on Internet of Things technology | The system realizes the integrated joint design of solar photovoltaic equipment and buildings | Wu et al. (2022) |
| Solar photovoltaic power generation and heating | The case for integrated power generation with solar collectors combined with organic Rankine cycle systems was evaluated technically and economically and applied to small-scale homes | The solar collector is combined with other thermal power generation systems to form a combined heat and power system | The system improves the utilization rate of solar energy and has good economic feasibility | Garcia-Saez et al. (2019) |
| Hybrid solar technology | A hybrid cooling system combining photovoltaic panels with heat pipes and phase change materials is proposed, and the temperature of photovoltaic panels and the efficiency of the system are evaluated | Innovative applications are for the integration of photovoltaic panels with multiple materials/components | Compared with traditional photovoltaic panels, the hybrid photovoltaic system can improve the power generation performance of photovoltaic panels and save costs | Gad et al. (2022) |
| Passive solar technology (solar chimneys) | It developed an advanced control system that combines wind towers and solar chimneys with passive geothermal and evaporative cooling systems and applied this integrated system to a residential building in Spain | Innovative applications of passive solar technology are integrated with other renewable energy systems | This new design overcomes the difficulty of estimating both the ventilation flow and the room temperature at the same time and achieves power savings of approximately 42% | Soto et al. (2021) |
| Passive solar technology | A new design based on the dynamic application of phase change materials in a building envelope is proposed, which breaks down the main technical barriers to the application of phase change material as a passive cooling system | The phase change material is applied to the building envelope to optimize the design parameters of the building and improve the utilization efficiency of solar heat energy | This new dynamic phase change material system can be used not only as insulation but also as a cooling supply system | de Gracia (2019) |

The table illustrates the marked advancements in enhancing different solar systems and their integration with innovative applications across aspects like power generation and heating efficacy. Passive solar technology is often augmented with phase change materials and selective elements like solar spectroscopy to bolster thermal energy storage capabilities. These technological strides not only boost the energy efficiency of solar systems but also curtail operational expenses, thereby piquing the interest and enthusiasm of both developers and governmental bodies in embracing solar technology

Kalogirou 2014; Sobri et al. 2018). In addition to improving solar technology, the integrated application of multiple energy sources or materials, as well as the development of various new materials of solar cells, have also contributed to the innovation and technological progress of solar power generation in the construction field. For the solar heat collection/refrigeration system using solar heat for building space heating, energy-saving technologies such as roof pool heat storage, phase change material heat storage, and new materials are directly or indirectly applied to the building design to maximize the use of solar energy provides an effective solution (Peng et al. 2020a).

In addition to solar energy, other renewable energy technologies such as wind and geothermal energy, are also widely used in the construction sector. The most important part of any wind energy system is the wind turbine, which converts wind energy into mechanical energy that can be used for a variety of applications (Kumar et al. 2016). However, most of the early wind turbines installed in urban environments were restricted by limited land resources and distance from buildings. As a result, the design and performance of wind energy systems are increasingly advanced and innovative, especially in building-integrated wind energy systems (Rezaeiha et al. 2020; Stathopoulos et al. 2018), including Savonius-Darrieus hybrid rotors, piezoelectric generators, flag type triboelectric nano-generators, bladeless turbines, and more (Acarer et al. 2020; Bagheri et al. 2019).

As the demand for green and low-carbon technologies continues to rise, biomass applications in the building sector are poised to play an increasingly crucial role in promoting energy conservation, emission reduction, and sustainable development. For instance, Ebrahimi-Moghadam and Farzaneh-Gord (2023) devised an eco-friendly tri-generation system driven by an externally-fired gas turbine cycle, utilizing municipal solid waste biomass. This innovative system incorporates a double-effect absorption chiller/heater and undergoes a comprehensive evaluation based on energy, eco-exergy, and environmental analyses to gauge its reliability. The research employs a pioneering optimization strategy, combining Artificial Neural Networks and a multi-criteria Salp Swarm Algorithm to determine the optimal system size and operational parameters. Practical application is demonstrated through a case study, where the developed models are used to meet the electrical, heating, and cooling requirements of a selected building using real data and advanced energy architecture software. The findings underscore the significance of factors like municipal solid mass flow rate and compressor pressure ratio in shaping system performance. Additionally, eco-exergy analysis reveals that a substantial portion of the total cost is attributed to specific system components, particularly the gas turbine and gasifier (40% and 23%, respectively). At peak efficiency, the system can generate 541 kW of electricity, produce 2052 kW of heat, and provide 2650 kW of cooling. Remarkably, the levelized cost of electricity generation stands at $0.083/kWh, with an associated environmental factor of 1.3 $kgCO_2$/kWh, showcasing the potential of biomass-fired gas turbine cycles to satisfy building energy demands efficiently.

Integrating wind energy and biomass integration represents another promising and sustainable energy option. In this context, Liu et al. (2023a) aimed to create a near-zero-energy neighborhood in an industrial city to reduce greenhouse gas emissions. They utilized biomass waste for energy production and incorporated a battery pack system for energy storage. The Fanger model was employed to assess occupants' thermal comfort, and hot water production was detailed. Using TRNSYS software, the building's transient performance was simulated for one year. Wind turbines were employed as electricity generators, with excess energy stored in batteries for use during low-wind conditions. Hot water was generated through a biomass waste system and stored in a tank, while a humidifier provided ventilation, and a heat pump addressed heating and cooling needs. The findings indicated that a 6-kW wind turbine could supply the building's power needs and charge the batteries, resulting in a zero-energy building. Biomass fuel was used to maintain hot water, with an average consumption of 200 g per hour.

In addition, geothermal energy, as a non-intermittent and potentially inexhaustible energy source, can be divided into shallow, medium, and deep geothermal energy technologies according to depth, which can meet the heating and cooling needs of building groups with different energy efficiency levels and has great potential in space regulation in buildings (Romanov and Leiss 2022a). Recent technological innovations and advances in geothermal systems in the building factor have focused on the optimal design of shallow geothermal systems to improve their efficiency and the application of new materials and integration with other technologies. In pursuit of achieving clean heating in northern rural regions, a novel cooperative heating system, comprising a biomass boiler and a multi-source heat pump, has been introduced. This system is designed based on building heat load requirements and available resources, seamlessly integrating biomass energy, geothermal energy, and air energy sources. A dynamic simulation model, facilitated by TRNSYS software, has been developed to maintain energy balance, and an optimization model is proposed to minimize annual costs. The effectiveness of this model is demonstrated through its application in the Miaofuan rural community in Linzi Town, Linyi County, Dezhou City, Shandong Province, China. The optimized cooperative system exhibits significant cost reductions of 9.6%, 14.2%, and 11.7%, respectively, compared to the individual operation of geothermal heat pumps, air source heat pumps, and biomass boilers. Consequently, this cooperative heating system emerges as a highly suitable solution for rural areas seeking efficient and sustainable heating solutions (Hou et al. 2023). As shown in Table 3, the main recent findings of various researchers on the technological advances and integrated innovative applications of wind and geothermal energy systems in buildings are summarized.

In summary, the latest technological advancements in the application of renewable energy in the construction field include the application of new materials, improvements, and new designs to the structure of renewable energy systems and integrated applications with other technologies or multiple energy sources. The continuous improvement and innovation of renewable energy technology have enabled it to overcome key technical shortcomings and fully leverage the advantages of renewable energy. It not only provides more environmentally friendly and sustainable choices for the construction industry but also provides greater creative space for architects and designers. With the continuous development and innovation of renewable energy technology in future, the construction industry is expected to bring more innovation, support the better integration of renewable energy systems into buildings, and create more opportunities for the construction industry to achieve significant decarburization and cost savings.

## Impact of technological advancements on renewable energy adoption in buildings

As shown in Table 4, technological progress has significantly influenced the application of renewable energy in the construction field. In recent years, the pursuit of higher efficiency has been the main driving force for innovation. Efficiency is also very important at the level of renewable energy systems, and various variables stimulate people's desire for more efficient technologies (Rathore and Panwar 2022). The floating photovoltaic technology is considered to have good development prospects due to its high power generation efficiency and no need to occupy land resources. The system is being developed based on new cell technologies, biodegradable materials, and advanced tracking mechanisms. However, the ecological impact, economic benefits, and optimization of size and system used are still challenges that need to be further addressed (Gorjian et al. 2021).

The modern technological development of wind power systems and their components, as well as reasonable architectural design optimization, have also made significant progress in generating power output and efficiency. Secondly, although nuclear energy has broad application prospects, natural disasters, and human hazards have always threatened this technology. Therefore, the development and application of nuclear energy are prudent, and the scale of utilization is still relatively low (Wei et al. 2023). Technological progress and innovation can not only improve the conversion and output efficiency of renewable energy systems but also reduce costs, thereby improving their performance and durability, making them more suitable for different regions and types of building applications. In future, the growth of the renewable energy industry mainly depends on reducing system costs and government policy support (Buonomano et al. 2023).

Energy storage technology can quickly and flexibly adjust the power of the power system, and the application of various energy storage devices to wind and solar power generation systems can provide an effective means to solve the problem of unstable renewable energy generation (Infield and Freris 2020). Giving full play to the advantages of various artificial intelligence technologies and cooperating with the energy storage system in the power system can improve the service life of the energy storage system and realize the optimal control of the multi-objective power system, which is the research direction of the integrated application of energy storage system and renewable energy in future (Abdalla et al. 2021). Chen et al. (2021b) proposed an artificial intelligence-based useful evaluation model to predict the impact of renewable energy and energy efficiency on the economy. This model can help enhance energy efficiency to 97% and improve the utilization rate of renewable energy. Another study applied artificial neural networks and statistical analysis to create decision support systems and evaluated the solar energy potential of Mashhad City, Iran, using photovoltaic system simulation tools. The results show that the artificial neural network model can successfully predict electricity consumption in summer and winter, with an accuracy of 99% (Ghadami et al. 2021). Overall, machine learning technologies such as artificial neural networks and artificial intelligence have brought enormous potential for renewable energy applications in the construction industry, which can improve energy efficiency, reduce energy costs, reduce carbon emissions, and promote the development of the construction industry toward a more sustainable and environmentally friendly direction. The continuous development of these technologies will help create a smarter and greener building environment.

In conclusion, technological advancements offer promising prospects for integrating renewable energy into the construction sector. These advances encompass innovative design potential, superior system performance and resilience, heightened environmental benefits, augmented socio-economic returns, and data-driven innovations. Additionally, the strategic optimization of building layouts combined with the adoption of novel materials and technologies can further decrease the operational costs of renewable energy systems.

**Table 3** Overview of renewable energy utilization in sustainable buildings

| Energy source | Country/region | Study description | Technological advances | Key findings | Reference |
|---|---|---|---|---|---|
| Wind | Europe | Optimizing two key design parameters is for improving the wind energy performance of high-rise building pipeline openings through Computational Fluid Dynamics simulation | Integrating wind turbines into optimized high-rise building openings for on-site power generation is an alternative to the traditional installation of wind turbines on building roofs | Optimizing the design of building openings by changing the filet radius and diameter of the air ducts can maximize the wind power generation efficiency of building openings and increase the wind density by 650% compared to free flow | Alanis Ruiz et al. (2021) |
| Wind | India | The performance of off-grid rooftop photovoltaic-micro-wind cell hybrid system was studied for 1.5 years | The integration of a hybrid energy system is based on micro-wind turbines into the building structure | Hybrid systems with multiple micro-wind turbines have a greater generating capacity than a single turbine-based system | Sinha et al. (2021) |
| Wind | Australia | The stator blades are attached to the linear cascade wind turbine power window to optimize the airflow direction in the device and improve the power generation performance of the power window | A new multifunctional wind energy system suitable for installation on buildings is proposed | By using the stator blade to control the angle of attack, the direction of rotation of the stator blade enhanced power window will remain unchanged regardless of the wind direction, thus improving the practicability of the device in practice | Jafari et al. (2019) |
| Wind | China | A double-beam wind energy collector is designed to avoid the need for complex structural design to accommodate the self-aligned guide vane | Through structural innovation, the wind energy acquisition technology is improved and optimized | The collector improves the wind output by enhancing vortex-induced vibration and extending the operating speed range to meet the requirements of collecting wind energy from all incident winds | Shi and Kong (2021) |
| Wind | China | Based on the WERC database, an efficient machine learning algorithm, the Light Gradient Boosting Machine, is trained to predict the lateral wind spectrum of rectangular tall buildings. The unsupervised machine learning algorithm K-means clustering is used to improve the understanding of wind spectrum characteristics on the side of high-rise buildings | An accurate prediction method of wind spectrum and the related response of high-rise buildings based on machine learning technology is proposed | This method has high computational efficiency and can predict the lateral wind spectrum and related lateral wind response of rectangular high-rise buildings quickly and accurately | Lin et al. (2022) |
| Geothermal | Europe | Combinations of pipe and grouting products with different thermal conductivity in shallow geothermal systems under different building types, sites, and climates were analyzed to assess the potential impact of new material optimizations in actual installations | Improving the operational efficiency of borehole heat exchangers is by optimizing the materials for individual components (piping, grouting) and the overall setup | Increasing the thermal conductivity of piping and grouting products will significantly reduce the total length of borehole heat exchangers required for installation, thereby saving installation costs and improving the efficiency of the geothermal system | Badenes et al. (2020) |
| Geothermal | China | A fresh air treatment module, which consists of a shallow geothermal ventilation system and heat recovery unit, is proposed to solve the problem of insufficient fresh air in buildings in cold regions of China | By combining the shallow geothermal ventilation system with other energy systems to form an integrated system, the operation efficiency of the combined energy system can be improved | Compared with traditional air source heat pump units, the proposed system has considerable economic and ecological benefits | Li et al. (2020) |

**Table 3** (continued)

| Energy source | Country/region | Study description | Technological advances | Key findings | Reference |
|---|---|---|---|---|---|
| Geothermal | Germany | This research mainly studies the large-scale geothermal collector system combined with 5G District Heating and Cooling Networks as a renewable heat source and analyzes the planning and design of several kinds of collector systems | A renewable heat source such as a large geothermal collector system is combined with a 5G District Heating and Cooling Network to achieve no distribution loss in buildings in low-temperature areas | Combined with a large geothermal collector system, the network itself has a heat gain of up to 50% of the heat demand, depending on the network size and fluid temperature | Zeh et al. (2021) |

This table provides an overview of the advancements made by various countries in harnessing optimized or cutting-edge wind and geothermal energy systems for building-related functions, including power generation, heating, and cooling. As these technologies continue to innovate and improve, they not only elevate public appreciation and acceptance of renewable energy but also diminish the environmental footprint of buildings. Such progress is instrumental in steering the construction sector toward a more sustainable and eco-friendly future

## Emerging trends in renewable energy technology

The limitations of standalone renewable energy systems, like wind and solar power, characterized by unpredictability and uncertainty, lead to reduced utilization rates and increased construction expenses associated with these sources. In order to overcome these problems, hybrid renewable energy systems are receiving increasing attention from scholars and are widely used to address the challenges mentioned above (Farghali et al. 2023a; Hajiaghasi et al. 2019). The use of machine learning and artificial intelligence technology for design optimization and cost control of hybrid renewable energy systems is an emerging trend, including support vector machines, genetic algorithms, and particle swarm optimization algorithms. Wen et al. (2019) proposed a deep recursive neural network model for aggregating power loads and predicting photovoltaic power generation and optimized the load scheduling of grid-connected community microgrids using particle swarm optimization. The results indicated that the community microgrid based on deep learning for solar power generation and load forecasting has achieved a reduction in total cost and an improvement in system reliability. Ramli et al. (2018) used a multi-objective adaptive differential evolution algorithm to optimize the design of a hybrid photovoltaic/wind/diesel microgrid system with battery storage. In addition, new algorithms such as the ant colony algorithm, bacterial foraging algorithm, and artificial bee colony algorithm are gradually being applied in the prediction and optimization research of hybrid renewable energy (Wei et al. 2023).

In recent years, there has been increasing research on the thermal storage performance and application prospects of phase change materials, among which the application of phase change materials in solar energy, architecture, and automobiles is prominent (Sikiru et al. 2022). The system combining solar collectors with suitable phase change materials has been proven through experiments to have better overall performance than traditional flat panel solar collectors (Palacio et al. 2020). As a commonly used thermal storage material, phase change materials have the disadvantage of low thermal conductivity. Therefore, Abuşka et al. (2019) developed a new type of solar air collector that combined phase change material Rubitherm RT54HC with aluminum honeycomb and studied the effect of using honeycomb cores on the thermal performance of phase change material thermal storage collectors under natural convection conditions. The results showed that the honeycomb core can effectively improve the thermal conductivity of phase change materials and is a promising thermal conductivity-enhancing material, especially during discharge. In addition, recent breakthroughs in nanomaterials, including quantum dots, nanoparticles, nanotubes, and nanowires, have significant implications for creating the next generation of efficient

**Table 4** Impact of technological progress on renewable energy applications in construction

| Energy sources | Technology | Key findings | Potential impact | Reference |
|---|---|---|---|---|
| Wind energy | Improved Darrieus wind turbine | The design optimization of turbine blade geometry can effectively improve the overall performance of vertical-axis wind turbines suitable for urban environments | Improving wind system performance | Yousefi Roshan et al. (2021) |
| Wind energy | Machine learning technology | The generative adversarial network model can accurately predict the pressure coefficient of high-rise buildings under any interference conditions, and this model can save 70% of wind tunnel test cases | Saving testing costs | Hu et al. (2020) |
| Wind energy | Mini-ducted wind turbine | The optimized mini-ducted wind turbines are more suitable for generating electricity in urban environments | Innovating structural design | Nardecchia et al. (2021) |
| Geothermal energy | Medium and deep geothermal energy technology | Deep well heat exchangers have become an effective alternative method for utilizing geothermal energy | Optimizing system design parameters and improve economic benefits | Pan et al. (2020) |
| Geothermal energy | Medium and deep heat exchange system | The combined heating system of solar collectors and borehole thermal energy storage with small thermal power plants can serve as a feasible alternative to boilers or cogeneration systems | Reducing greenhouse gas emissions and improve economic benefits | Welsch et al. (2018) |

This table highlights how technological advancements have enhanced the efficiency of utilizing renewable energy in buildings. Furthermore, such progress has driven improvements in the overall performance of renewable energy systems. Additionally, these advances are pivotal in the sustainable deployment of these systems, offering promising implications for the integration of renewable energy within the construction sector and low-cost solar cells. The safe and easy solution bonding of non-aggregated, monodisperse, passivated semiconductor nanoparticles with good photoelectric properties opens a new door for photovoltaic devices currently under study (Baviskar and Sankapal 2021).

In summary, technological advancements in renewable energy open new avenues for sustainable building and eco-friendly design. With science and technology's relentless evolution, the incorporation of renewable energy within the construction realm is poised to embrace intelligence, diversity, and digitization. At the same time, technological progress can also help solve the challenges of some renewable energy systems in practical applications, promoting their wider application in the building factor.

This section delves into the latest innovations concerning four prevalent renewable energy types used in buildings, scrutinizing the prospective influence of these breakthroughs in construction. Continuous refinement and inventive strategies in renewable energy systems, coupled with the amalgamation of diverse technologies, materials, and energy forms, bolster a building's environmental, energy, and economic advantages, thus championing a broader adoption of renewable methodologies in construction. Finally, the recent research hotspots and emerging development trends in the field of renewable energy are presented.

## Perspective

With the increasing population and density in urban areas, having low-energy buildings with the least greenhouse gas emissions has become more important (Shirinbakhsh and Harvey 2023). In future, the vibrant prospects of renewable energy in the construction industry will be influenced by a series of complex and closely interrelated factors. This section will provide an in-depth outlook on the development of renewable energy in the construction industry from two main perspectives, namely prospects and potential challenges.

### Energiewende

Energiewende is becoming a booster for the application of renewable energy in the construction industry. In the context of energiewende, renewable energy is widely regarded as the core element driving the development of building energy. In future, the construction industry will increasingly rely on the application of renewable energy, especially solar, wind, and geothermal energy. Besides, solar energy, as one of the most common and renewable energy sources, will play an important role in buildings. Photovoltaic power generation systems will be widely used on roofs, walls, and windows of buildings, turning them into distributed power producers. This distributed power generation model helps to reduce dependence on traditional energy and achieve a greener and more sustainable energy supply.

Additionally, wind energy is also an important part of the transformation of building energy. Wind power generation devices will not only be limited to traditional wind farms but will also be integrated into high-rise buildings, bridges, and other building structures. The widespread application of this type of wind energy will effectively utilize the wind energy resources in cities, provide clean electricity for buildings, and reduce environmental loads. In addition, geothermal energy, as a stable and reliable form of energy, will also be widely used in the construction field. Geothermal energy can be used in heating and cooling systems of buildings, reducing reliance on traditional energy and improving energy efficiency. Through underground heat exchange technology, buildings can achieve efficient energy conversion and reduce energy consumption in different seasons.

Biomass holds promising prospects for expanding renewable energy adoption in the building sector. As a versatile and sustainable energy source, biomass can be used for various applications, such as heating, cooling, and electricity generation, making it a valuable addition to the renewable energy mix. Additionally, biomass offers the advantage of energy storage through technologies like phase change materials, enhancing its suitability for meeting variable energy demands in buildings. Furthermore, the utilization of agricultural and forestry residues as biomass feedstock can contribute to waste reduction and resource optimization, aligning with sustainable building practices. As efforts to decarbonize the building sector intensify, biomass's potential to provide renewable, locally sourced energy while reducing greenhouse gas emissions positions it as a compelling option for advancing the adoption of renewable energy in buildings.

In summary, the introduction of renewable energy to the construction realm offers significant technological advancement. This shift also ensures a move toward greater sustainability. The synergy of architects, engineers, energy specialists, and other experts fosters the seamless integration and innovation of renewable energy solutions within architectural designs.

### Energy self-sufficiency and microgrid technology

Energy self-sufficiency and microgrid technology are becoming leaders in the construction field. With the continuous innovation of technology, buildings are gradually moving toward the goal of energy self-sufficiency. By integrating solar power generation, energy storage systems, and intelligent energy management technologies, buildings are expected to achieve a certain degree of separation from traditional power networks and achieve the goal of self-power supply. This concept of energy self-sufficiency will further reduce reliance on traditional energy, enabling buildings to meet energy needs more independently.

The rise of microgrid technology will bring significant changes to building energy management. A microgrid is a small energy network composed of multiple energy components (such as solar cells, energy storage devices, and gas generators), which can achieve efficient utilization and sharing of local energy. Microgrid technology utilizes renewable resources to ensure the stability and sustainability of buildings or cities based on artificial intelligence, such as metaheuristics (Evolutionary, Swarm, Physically based, Human based, hybrid, and other standalone algorithms), and machine learning (Model-based Control, Reinforcement Learning, Fuzzy Logic), which helps better cope with energy fluctuations and intermittency (Tajjour and Singh Chandel 2023). The development of microgrid technology will also enhance the reliability of building energy. In traditional central power systems, once a fault or interruption occurs, the entire area may be affected. Additionally, microgrid technology allows the energy system inside the building to automatically switch to backup energy in the event of a power outage, ensuring the continuous operation of key equipment and improving the reliability and stability of energy supply.

## Carbon neutrality and sustainable development

The United Nations General Assembly, with sustainable development as its core, has formulated the 2030 Agenda for Sustainable Development, aimed at addressing environmental, economic, and social challenges in the process of human development. This agenda is an action plan for humanity, the Earth, and prosperity (Woon et al. 2023). Meanwhile, carbon neutrality and sustainable development have become important issues that cannot be ignored in the construction industry. With increasing global attention to climate change and environmental issues, the construction industry is actively responding to carbon neutrality goals and striving to reduce carbon emissions. In this context, renewable energy is seen as a crucial solution for achieving carbon neutrality goals.

Renewable energy, as a non-emission energy source, has obvious advantages. Renewable energy sources such as solar energy, wind energy, and hydropower not only do not produce harmful gases such as carbon dioxide in the energy production process, but their sustainability enables them to provide clean energy for buildings in the long term. This makes renewable energy one of the important means to achieve carbon neutrality goals.

In future, the construction industry will gradually reduce its dependence on high-carbon-emitting energy sources such as traditional coal and oil and turn its attention to renewable energy. Photovoltaic power generation systems will be more widely installed on roofs, walls, and even windows of buildings, and wind power plants may become a part of high-rise buildings. Geothermal energy technology will play a greater role in heating and cooling. Biomass systems, including biomass boilers and biogas generators, can be integrated into buildings to provide reliable and carbon–neutral energy. These changes will not only bring significant reductions in carbon emissions but also provide greater security and reliability in the energy supply. In addition to direct carbon emissions reduction, the promotion of renewable energy will also stimulate innovation and technological progress. While seeking higher energy efficiency and lower carbon emissions, the construction industry will face pressure from technological upgrading and innovation, which will promote the development of new materials, new equipment, and intelligent energy management technologies, thereby further promoting the application and development of renewable energy.

## Intelligent building and energy internet

Intelligent buildings and the energy internet have been widely recognized as important directions for the future development of the construction industry. With the continuous progress of technology, buildings will gradually become intelligent and digitized, creating more intelligent conditions for efficient energy utilization. In future, intelligent building technology will play an important role in enabling buildings to achieve intelligent regulation and optimize energy use. Through the application of sensors, data analysis, and automatic control systems, buildings can collect environmental information such as energy consumption, temperature, humidity, brightness, and room occupancy, allowing for energy decomposition and equipment identification and generating timely and personalized recommendations to achieve efficient energy utilization (Alsalemi et al. 2022). For example, in cold winter, the system can automatically adjust the temperature and time of the heating system to ensure a comfortable indoor environment while minimizing energy waste.

The integration of architecture and energy internet will further enhance the effective utilization rate of energy. By connecting the building energy system to the energy internet, buildings can achieve precise matching with energy supply. The energy internet will allow buildings to flexibly adjust according to actual demand and energy supply, thereby maximizing energy utilization. For example, when there is sufficient energy supply, buildings can store excess energy, and when there is a shortage of energy supply, priority can be given to utilizing reserve energy to ensure the normal operation of the building.

This section delves into the envisioned future of the construction sector, with a spotlight on the transformative influence of renewable energy. It forecasts the industry's trajectory toward energy autonomy, underscores the advantages of adopting microgrid systems, and highlights the worldwide momentum toward carbon–neutral commitments. Furthermore, it explores the synergistic melding of smart buildings with the energy internet to enhance energy consumption efficiency.

### Technological innovation and cost reduction

Technological innovation is the core driving force behind the application of renewable energy in the construction industry. With the continuous progress of technology, renewable energy technologies are also constantly innovating and evolving. However, despite significant progress, further efforts are still needed to reduce costs and improve efficiency to better meet the needs of the construction industry. In the field of renewable energy, cost has always been considered one of the key factors restricting its widespread application. To achieve the large-scale application of renewable energy technology in buildings, it is necessary to find ways to reduce the costs of production, installation, and maintenance. Especially for some emerging technologies, such as solar thin films and wind energy storage, their research and manufacturing costs are relatively high, requiring continuous investment and efforts to achieve cost reduction.

### Energy storage technology

The role of energy storage technology in the field of renewable energy is becoming increasingly prominent, especially in the face of the intermittency and volatility of renewable energy. These characteristics make energy storage a key factor in achieving a stable supply of renewable energy. However, current energy storage technologies still face a series of challenges in terms of cost, efficiency, and reliability, requiring continuous improvement and innovation.

With the continuous growth of renewable energy sources such as solar and wind energy, the demand for energy storage technology is becoming increasingly urgent. Photovoltaic and wind power generation systems have fluctuating production capacity due to weather and other factors, while energy demand is all-weather. Therefore, efficient energy storage technology can store excess energy for release when needed, thereby ensuring the stability of the energy supply. However, there are still some limitations to current energy storage technologies. On the one hand, cost issues have limited the popularization of energy storage technology. Currently, some commonly used energy storage technologies, such as lithium-ion batteries, have superior performance but high manufacturing costs, especially for large-scale applications. On the other hand, the efficiency and reliability of some energy storage technologies also need to be improved. For example, some energy storage systems may experience certain losses during the energy conversion and storage process, which reduces the overall efficiency of the system.

In the future, the improvement and innovation of energy storage technology will be a hot topic in the field of renewable energy. Scientists and engineers are exploring new energy storage materials and technologies to reduce costs, improve efficiency, and extend the lifespan of systems. The research on new battery technologies and energy storage materials will provide new possibilities for addressing the challenges posed by the volatility of renewable energy.

### Integrated design and multidisciplinary cooperation

In the context of the increasingly urgent global energy situation, achieving the maximum potential of renewable energy has become an urgent task in the construction field. In order to achieve this goal, the energy system, building structure, and function in architectural design need to achieve close integration, which can maximize the application effect of renewable energy. Therefore, interdisciplinary cooperation has become crucial, and cross-border cooperation in professional fields such as architects, engineers, and energy experts will help find the best technology integration solutions to create more efficient and reliable renewable energy applications.

Implementing integrated architectural design requires close cooperation from experts in various fields. Architects need to integrate the needs of energy systems into their architectural design, considering how to maximize the utilization of renewable energy sources such as solar and wind energy without affecting the appearance and functionality of the building. Engineers need to ensure the coordination between the building structure and the energy system, optimize the layout, and ensure the efficient operation of the energy system. Energy experts need to provide energy analysis and technical support for the entire system to ensure the rational application of renewable energy.

Based on interdisciplinary cooperation, innovative technology integration solutions will be born. This may include integrating photovoltaic power generation systems into the exterior walls of buildings, utilizing the exterior scenery of buildings to enhance wind power generation, or organically integrating ground-source heat pump systems with building structures. By integrating multidisciplinary expertise, the most suitable and innovative renewable energy solutions can be found for each construction project. This integrated design and multidisciplinary collaboration can help solve the problem of energy waste in traditional architectural design. Traditional buildings usually consider energy systems and building design separately, resulting in inefficient energy utilization. By implementing integrated design, buildings can respond more intelligently to energy needs and reduce unnecessary waste.

## Policy support and market recognition

In the context of global energy issues gradually heating up, policy support and market recognition have become the two pillars to promote the application of renewable energy in the construction industry. The government's policy support not only provides important guarantees for the development of renewable energy but also stimulates the enthusiasm of building owners and developers to adopt these technologies at the policy level. The government can effectively promote the transformation and upgrading of the industry by focusing on investment in the field of new technology research and development, formulating incentive policies to promote technological progress and innovative technology pilot diffusion, increasing research and development investment, guiding social capital participation, and fully leveraging the lateral incentive effect of policies (Xie et al. 2023).

At the same time, market recognition is also crucial for the promotion and application of renewable energy. The realization of market recognition requires people to deeply recognize the enormous economic and environmental benefits that renewable energy can bring in long-term operations. This not only involves the return on initial investment but also relates to the savings in energy costs and the reduction of environmental burden in long-term operations. With the increasing awareness of environmental protection in society, people's demand for green performance in buildings is also increasing, which further strengthens the market's demand for renewable energy.

Policy support and market recognition have jointly built the foundation for the development of renewable energy in the construction industry. The guiding role of government policies enables renewable energy technologies to quickly enter the market, while market recognition ensures the stability and sustainability of these technologies in practical applications. This dual support not only promotes technological innovation in renewable energy but also provides a solid guarantee for the sustainable development of the construction industry.

## Upgrade of energy infrastructure

To achieve the large-scale application of renewable energy in the construction industry, it is necessary to focus on upgrading energy infrastructure. Nowadays, the demand for energy in the construction industry is increasing, and traditional energy infrastructure often finds it difficult to meet the effective transmission and utilization needs of renewable energy. Therefore, by upgrading our existing energy infrastructure, we can create more favorable conditions for the integration and application of renewable energy. Upgrading energy infrastructure is not only about technological progress but also about optimizing and innovating existing systems. The introduction of intelligent technology is crucial in this process. By introducing technologies such as intelligent monitoring, data analysis, and remote control, energy infrastructure can more efficiently manage and control renewable energy. This will help address the challenges of intermittency and volatility in renewable energy, ensuring a stable supply of energy.

On the other hand, upgrading energy infrastructure also requires attention to equipment updates and renovations. The new generation of equipment and technologies, such as advanced transmission lines and efficient energy storage devices, will provide more reliable and efficient support for the transmission and utilization of renewable energy. By integrating these innovative devices with existing energy systems, we can achieve the upgrading and modernization of energy infrastructure. In addition, upgrading energy infrastructure also requires cooperation with multiple parties. Building owners, energy suppliers, technology providers, and other parties need to work closely together to promote the upgrading process of energy infrastructure. The government's support will also play a crucial role in promoting the smooth upgrading of energy infrastructure through policy guidance and financial support.

In summary, renewable energy in the construction industry will play an increasingly important role in achieving energiewende, reducing carbon emissions, and promoting sustainable development. Although facing multiple challenges such as technology, costs, and policies, these challenges will gradually be overcome with the continuous innovation of technology and the gradual recognition of the market. Cross-disciplinary cooperation, policy support, and market guidance will be key to achieving the development of renewable energy in the construction industry. Through continuous efforts, the construction industry is expected to achieve a green transformation of energy and create a more sustainable and environmentally friendly building environment for humanity.

This section expounds upon the prospects and obstacles of weaving renewable energy into the construction landscape. It accentuates the imperative of technological breakthroughs and cost-cutting measures and underscores energy storage's role in offsetting renewable energy's intermittency. The section also champions interdisciplinary teamwork for optimal design solutions and underscores how regulatory backing and market acknowledgment can bolster renewable energy adoption. Furthermore, overhauling the existing energy framework and embracing contemporary technologies and systems emerge as quintessential to meet the requisites of seamless renewable energy integration.

## Conclusion

Renewable energy, known for its environmental benefits, is crucial in addressing growing energy demand and mitigating global warming. This review assesses its application in construction, covering technologies like solar, wind, biomass, and geothermal energy. While offering eco-friendliness, renewables enhance building energy efficiency and cut operational costs. In addition, this work also introduces successful application cases of renewable energy technology in the construction field, which can often achieve multifunctional sustainable development through the adoption of renewable energy technologies, and finally analyzes the difficulties and challenges faced in the application process. From a policy perspective, governments and international organizations play a crucial role in formulating and implementing renewable energy-related policy standards. However, problems such as high initial investment, unstable power grids, and inconsistent policies may be encountered when implementing policies. The implementation of the above policies and regulations will stimulate the sustainable development of renewable energy in the construction industry while promoting innovation and progress in related technological research. This paper presents the latest technological advances and innovative designs for various types of renewable energy systems. The results show that the application of advanced artificial intelligence technologies, such as machine learning, plays an important role in the optimization and improvement of various renewable energy systems. Secondly, the application of hybrid renewable energy systems and innovative building design and layout are also effective ways to enhance the advantages of renewable energy and achieve multi-purpose. In the future, the improvement and innovation of energy storage technology will be a research hotspot in the field of renewable energy, providing new possibilities for addressing the challenges brought by renewable energy fluctuations. Meanwhile, policy support and market guidance will be key to achieving the development of renewable energy in the construction industry.

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**Authors' contribution** LC was involved in conceptualization, writing, and review and editing. YH, RW, XL, ZC, and JH were involved in data gathering, writing, and review. AIO was involved in writing, review and editing, and supervision. MF was involved in writing, review and editing, and data editing. LH was involved in writing and review. JL and LD were involved in data gathering, writing, and review. DWR and PSY were involved in review and editing and supervision. LC, YH, RW, and XL jointly conceived the study and led the writing of the article with equal contributions. All other authors have contributed to data collection and analysis, interpretation of results, and writing of the article and are listed in alphabetical order.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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