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Review

Application of Photovoltaic and Solar Thermal Technologies in Buildings: A Mini-Review

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Abstract: Buildings account for a significant proportion of total energy consumption. The integration of renewable energy sources is essential to reducing energy demand and achieve sustainable building design. The use of solar energy has great potential for promoting energy efficiency and reducing the environmental impact of energy consumption in buildings. This study examines the applications of photovoltaic and solar thermal technologies in the field of architecture, demonstrating the huge potential of solar energy in building applications. To ensure a fresh and thorough review, we examine literature that encompasses the advancements made in the utilization of solar energy in buildings over the past decade. The key factors to consider in this study are reliability, performance, cost and aesthetics in real applications of photovoltaic and solar thermal technologies in the field of architecture, which have a significant impact on people's acceptance of solar energy technology. Recent developments in feasible and effective optimization solutions for solar energy technologies are summarized. Accurate and convenient simulation techniques are also summarized for reference. The results show that the rapid progress of BIPV systems is fueled by advancements in three crucial areas: enhancing solar cell and module efficiency, reducing manufacturing costs and achieving a competitive levelized cost of electricity. The results can provide researchers with a reference for understanding recent technological developments in the integration of solar energy into buildings.

Keywords: solar energy; building; technological development; solar thermal technology; solar photovoltaic technology

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1. Introduction

Climate change has become a major concern in recent years due to its potential impact on the environment and negative effects on human life, which has led to an increase in the use of green and renewable energy sources. The IPCC has suggested that the 1.5 °C target, commonly known as 'achieving carbon neutrality', requires the global achievement of net zero carbon dioxide (CO_2) emissions by 2050 [1]. The building sector is considered to have significant potential in mitigating global warming [2]. According to the European Union (EU), the urban population will continue to grow and, by 2050, cities will account for 66% of the world's population. This presents significant challenges and opportunities for sustainable urban development. In other words, the 26th United Nations Climate Change Conference (COP26) requires countries to limit the increase in global temperature to 1.5 degrees Celsius by 2050 [3]. By accepting and signing the agreement, all countries, regardless of their level of development, are committed to taking actions to separate CO_2 emissions from economic and demographic trends. As buildings are responsible for about one-third of the total direct and indirect energy-related carbon emissions worldwide [4], Net Zero Carbon Building is an innovative energy-saving development model worth adopting to achieve the net zero goal of the built environment by 2050. It refers to buildings that have minimal or no carbon emissions in their energy use. By integrating renewable energy sources, energy efficient design and reducing energy consumption, these buildings achieve net zero carbon emission status [5].

Fossil fuels such as coal, natural gas and other non-renewable sources are known to emit harmful CO_2 emissions when burned to generate electricity [6]. Solar energy, on the other hand, contributes to reducing carbon dioxide emissions and improving environmental quality [7]. Moreover, solar energy is the most affordable and abundant of all long-term natural resources to date [8]. The development of solar thermal and photovoltaic technologies in the renewable energy sector is promising [9], with continued innovation and technological breakthroughs expected to further increase their applications and market scale. For example, solar energy is considered to be an ideal source for meeting the energy needs of the world due to its widespread availability [10]. Thanks to dramatic cost reductions, solar technology improvement, complementary renewable energy policy and diversified financing, the global photovoltaic (PV) industry has experienced a remarkable growth, with an average compound annual growth rate exceeding 35% for the last decade [11]. What is more, solar energy technology is increasingly being used in building construction, particularly in urban areas, which can reduce reliance on traditional energy sources [12]. Progress in distributed energy systems is expected to increase the use of solar thermal collectors and photovoltaic/thermal systems in residential buildings [13]. In this context, continuous progress is needed in the application of solar energy in buildings. This paper can serve as a reference for researchers, architects, manufacturers and designers working on solar building systems.

Literature is reviewed which reflects the research progress in solar energy applications in buildings over the last decade, focusing primarily on reliability, performance, cost and aesthetics. The remaining sections of this article present methods to ensure the reliability and enhance the performance of photovoltaic and solar thermal technologies in the field of architecture through testing optimization and finding cost-effective solutions, demonstrating the huge potential of solar energy in building applications. The present work also summarizes accurate and convenient simulation techniques for reference. It then explains the development of hybrid photovoltaic and solar thermal technologies, exploring their impact on building performance and aesthetics. Moreover, attention is paid to aesthetics when using innovative and advanced technologies. The results can help to further promote the development of the solar energy application and help researchers better understand the requirements of the latest technologies. Figure 1 illustrates the main content of this article.

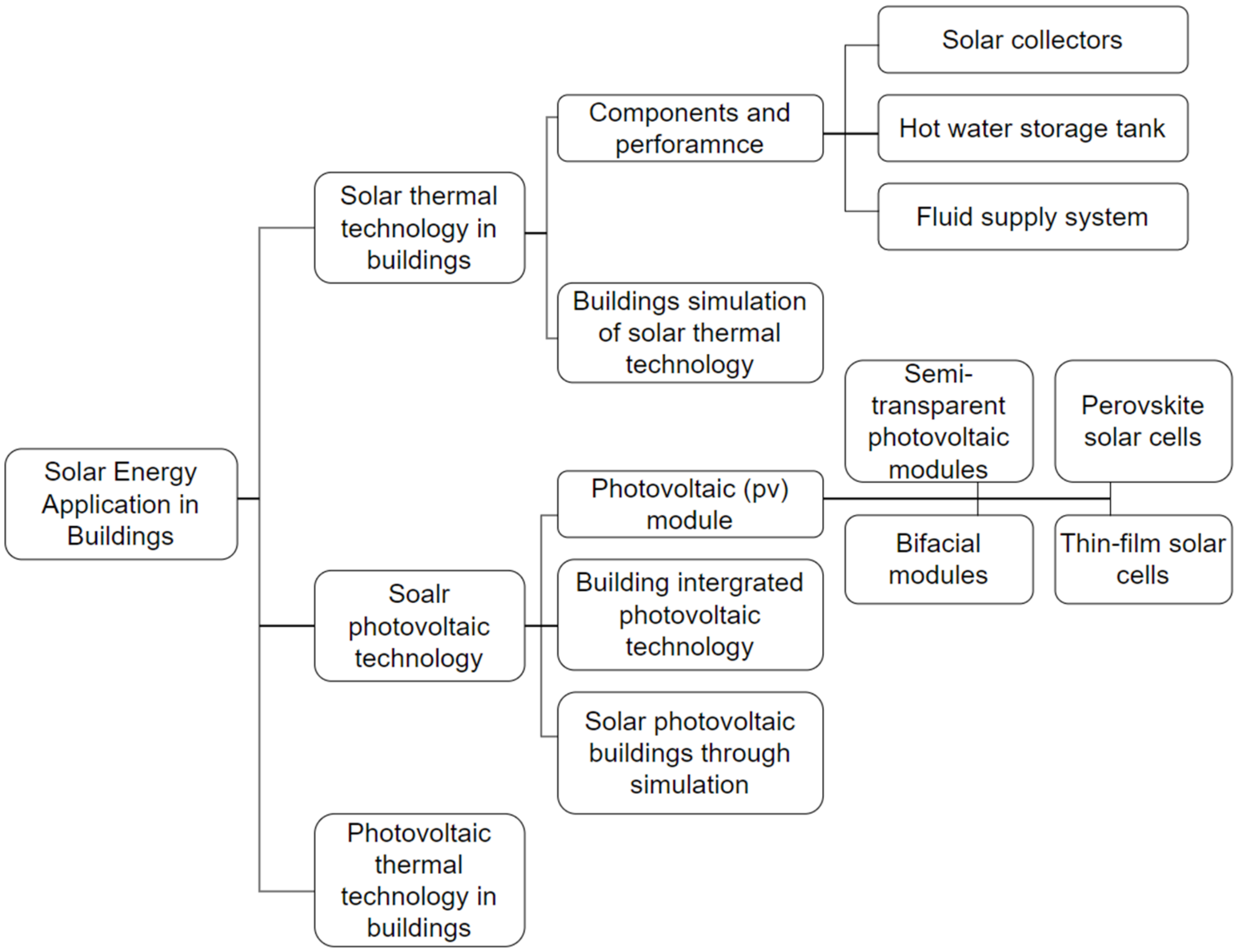

Figure 1. Applications of solar technologies in buildings.

2. Solar Thermal Technology in Buildings

The integration of solar thermal technology into buildings is an important direction in the pursuit of sustainable development and energy efficiency in architecture. It offers a clean and renewable energy alternative for buildings, significantly reducing dependence on traditional energy sources and mitigating environmental impact. As the technology continues to innovate and develop, solar thermal technology will play an increasingly important role in the field of architecture.

2.1. Components and Performance of Solar Thermal System

In general, water heating, space heating and air conditioning are the main consumers of energy in public buildings [14]. Nowadays, solar thermal technology, which converts solar energy into usable thermal energy, is generally regarded as a simple and effective way to harness solar radiation and address both the energy crisis and environmental concerns. Solar water heating systems (SWHS) are widely adopted by households worldwide due to their cost effectiveness, which is one of the most common applications of solar thermal technology [15]. They use solar energy to heat water to provide hot water for buildings. A typical solar water heating system consists of several components as follows:

2.1.1. Solar Collectors

Solar collectors typically consist of a set of tubes or panels that absorb solar energy and convert it into heat for water heating. Different types and designs of solar collectors are available to meet specific application requirements and building environments. The most common types include flat plate collectors (FPC), evacuated tube collectors (ETC) and parabolic trough collectors (PTC) [16]. Figure 2 displays the characteristics and innovative directions of each collector mentioned in the text.

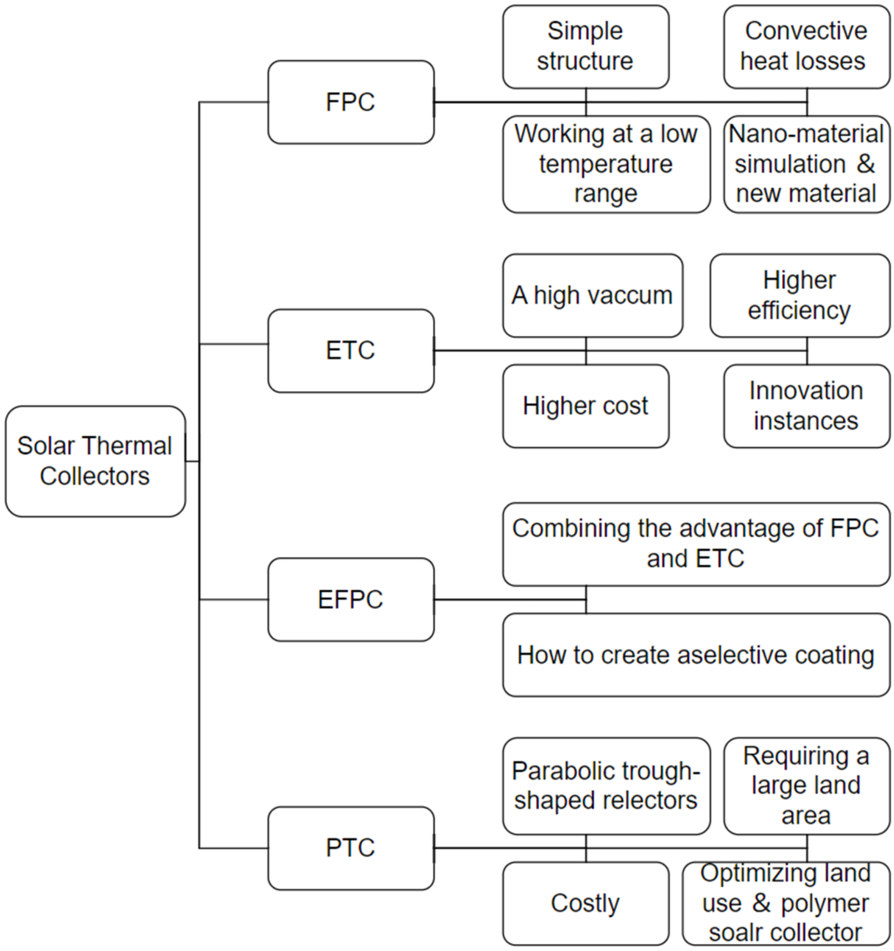

Figure 2. The characteristics and innovative directions of each collector (acronyms are described in the text).

A typical flat plate collector is designed to operate under low temperature conditions. As a result, the heated fluid it produces is primarily used in domestic applications, such as providing hot water or space heating in homes. Due to the lower cost and simple structure, design modification can be considered as an effective method to improve FPC's performance [17]. Moreover, huge efforts have been invested in studying the effects of incorporating nanomaterials in the field of solar energy. These endeavors have yielded substantial improvements in performance, as evidenced by recent research [18]. Simultaneously, simulations to improve the feasibility of the optimization scheme [19] and the development of new materials [16] are still in progress today.

The evacuated tube collector was developed based on the flat plate collector. It maintains a high vacuum in the interlayer between the heat absorber and the glass tube. As the key element of ETC, the vacuum tube determines its higher efficiency and cost. In addition to the applications of nanofluids [20] mentioned above, the optimization of this technology is looking for breakthroughs in various aspects, including, but not limited to, an optimal reflectance angle, a reflector of PCM and the usage of energy storage medium. At an optimal angle of reflectance, solar radiation is directed onto the solar collector to enhance sunlight reflection onto the heating plate, thereby boosting the electricity generation capacity of the solar power plant [21]. Furthermore, employing reflectors enhances the irradiation received by the PV panel, yet simultaneously results in an increase in the PV module temperature. In order to mitigate the efficiency impact of high temperatures on the components, phase change materials are integrated into the reflectors [22]. Instead of adopting a single technique for improving the thermal efficiency of the system, a combination of more than one technique has been broadly chosen [21]. As a promising technology, an evacuated flat plate collector (EFPC) combines advantages of FPC and ETC. In practice, evacuated flat plate collectors (EFPC) are similar to typical FPCs, but they reduce convective heat losses from the absorber plate to the cover due to the absence of internal gas [23]. The inevitable variations in film thickness during the manufacturing process affect the stability and reliability of the absorber coating performance. Therefore, a key challenge in the field of EFPC is to create a selective coating that is both durable and has a low emissivity [24]. However, there are several drawbacks associated with selective solar absorbers, including lower durability, complex production techniques, and higher cost [25]. For instance, in the industrial mass production of these absorbers, the performance of the coatings can be significantly affected by imperfect control of deposition parameters caused by errors in layer thickness [24].

PTC is a linear imaging concentrator composed of parabolic trough-shaped reflectors and receivers for an operational temperature range of medium temperature. Currently, there are numerous pieces of research focusing on using hybrid nanofluids, which cause a high-efficiency heat transfer [26]. Higher efficiency of PTC could also be achievable via novel designs of receivers and inserted fins. Numerous theoretical and numerical investigations play a pivotal role in producing PTC for various applications. So far, a large number of theoretical and numerical studies have been used to conduct simulations of PTC to improve its performance [27]. However, not only are PTCs costly, but they also require a large land area [28]. Accordingly, to realize the full potential of parabolic trough solar collectors, it is critical to focus on optimizing land use [28]. A new type of polymer solar collector has been proposed, and experimental and numerical evaluations of its thermal characteristics have been conducted [29]. While their structures and operating principles may vary, their primary objective remains the same: to convert solar energy into heat to meet the hot water and space heating needs of buildings.

As research on solar collectors continues to deepen, the efficiency of solar collectors has significantly improved, leading to an increase in their domestic and industrial applications. Among them, the SWH system has attracted widespread attention due to its low cost, minimal impact on global warming, and long lifespan. Regional geographical conditions, especially climate conditions and solar radiation availability, have a crucial impact on the thermal performance of solar energy systems. There is a need for more research articles focusing on the specific conditions of solar thermal energy utilization in a particular region to support the specific and practical application of solar energy in buildings.

2.1.2. Hot Water Storage Tank

The hot water storage tank is used to store the heated water from the solar collectors. Typically, the tank is insulated to minimize heat loss and has a volume sufficient to meet the daily hot water demand. Various innovative designs have been proposed to improve the design of hot water storage tanks.

Heat loss is a major concern for these tanks, as the mixing of hot and cold fluids exacerbates heat loss and reduces system efficiency. To address this issue, thermal stratification structures, such as diffusers, baffles, membranes and fabrics, have been invented. These structures not only reduce energy loss but also help maximize energy collection from solar heaters. Recent studies have shown that the use of diffusers can reduce shadowing losses in solar thermal utilization [30], while passive baffles can suppress natural convection within the tank, thereby reducing stagnant heat loss [31]. Additionally, fabric membrane materials exhibit higher heat transfer coefficients, poor thermal insulation properties and higher light transmittance performance [32], all of which are significantly influenced by solar radiation intensity. These findings are crucial for the design and optimization of solar thermal systems, and ongoing improvements continue to enhance this design [33]. Research has shown that the initial temperature significantly affects thermal stratification, while higher initial temperatures can reduce the range of initial mixing and improve the output rate of hot water [34]. With the aim of improving engineering accuracy, methods utilizing artificial neural network (ANN) models to calculate the accuracy of the overall conductance, equivalent to thermal resistance, have been proposed [35]. Furthermore, the presence of a baffle inside the tank has been found to have a significant impact on natural convection by altering the flow, ultimately reducing heat loss from jacketed baffled solar storage tanks [31].

2.1.3. Piping System

The piping system connects the solar collectors to the hot water storage tank, allowing heated water to flow from the collectors to the tank. Valves and pumps are typically used in the piping system to control the flow of water. Introducing obstacles of various shapes in the fluid path is one method to increase the efficiency of SWHS (Solar Water Heating Systems) [15].

In addition to solar water heating systems, solar thermal technology can be integrated into buildings for other applications. For example, solar air heating systems use solar thermal energy to heat air and transfer it to the interior of a building for space heating. Solar floor heating systems use solar thermal energy to transfer heat through radiant floor panels, further enhancing indoor comfort. All these applications require solar collectors as the key component for capturing solar energy. And these diverse applications require the use of solar collectors as the fundamental component for efficient solar energy capture. Being the most widely used components of solar equipment, solar collectors require optimization to maximize performance and minimize costs [36]. Currently, nanofluids have been utilized in heat pipes powered by solar energy, allowing for efficient capture of solar energy and simultaneous fast transfer of the collected thermal energy to its desired applications [37].

Through extensive testing, several thermal efficiency improvement techniques have been developed and evaluated. In particular, in building integrated PV thermal (BIPV/T) systems, the incorporation of innovative flow deflectors, semi-transparent PV technology and multiple inlets have demonstrated significant improvements, achieving thermal efficiencies of up to 33% [38]. Heat pumps have emerged as a promising solution to meet carbon reduction targets in the residential sector. However, challenges such as electricity consumption and low supply temperatures have hindered their widespread adoption. To overcome these limitations, researchers have sought to improve the efficiency of heat pumps in residential buildings through the integration of phase change materials (PCMs) and building-integrated photovoltaics (BIPVs). PCMs possess the capability to absorb and store significant amounts of latent heat at a constant phase transition temperature, facilitating passive heat storage and temperature control [39]. With proper selection of parameters, a solar air heater using a paraffin–wax–aluminum compound as a thermal storage material encapsulated in a cylinder has a better performance [40]. In order to adapt to various climatic conditions in different regions, researchers have made numerous attempts and have confirmed the effectiveness of these methods. For example, the performance of a solar heater designed for the winter conditions of the city of Baghdad was improved by adding aluminum chips, paraffin wax and nano-SiC [41].

According to the existing literature, a high-quality SWHS should possess superior heat transfer capabilities while minimizing frictional losses. By introducing obstacles to the flow of fluids, vortices are created, facilitating effective liquid mixing and enhancing heat transfer. These obstacles not only alleviate pressure drop penalties but also promote increased heat transfer rates [15]. As examples, the effect of obstruction enhancers is given in [19], and the effect of utilizing a helical enhancer in an absorber pipe is described in [42].

A numerical investigation has been conducted on the heat transfer and hydrodynamic flow characteristics in a horizontal tube with trapezoidal dimples on its surface, using water as the working fluid and applying a constant heat flux on the outer surface of the tube [43].

Another factor that can make a difference to thermal performance is the use of perforations. Perforations have the potential to further improve the overall thermal performance by reducing excessive longitudinal vortex interactions in the mainstream without significantly decreasing impingement to the thermal boundary layer [44].

2.2. Buildings Simulation of Solar Thermal Technology

The employment of effective building performance simulation can reduce the energy consumption and carbon emissions, enhancing the quality and productivity of indoor spaces while also promoting innovation and technological advancements in the construction industry [45]. Due to factors such as cost and time efficiency, parameter optimization, ethics and safety, building energy simulation (BES) plays an important role in prediction and forecasting [46]. Only when models of emerging technologies are credible and accurate will they gain traction with stakeholders [11]. The use of simulation in academic research has increased, driven by recent technological advances [47]. Table 1 presents a brief comparison of the previously conducted studies on the numerical values of thermal efficiency in simulation tests.

Table 1. Software and simulation programs are used for optimization, design and analysis of solar thermal energy systems.

Reference	Significant Findings	Software
[19]	Optimisation of FPC.	Fluent 17.2
[48]	Comparison among the most popular BPS tools, namely TRNSYS, EnergyPlus and IDA ICE.	TRNSYS 17, EnergyPlus 8.6 and IDA ICE
[49]	A co-simulation framework between BES tool (EnergyPlus) and CFD tool (Ansys Fluent) is developed.	EnergyPlus and Fluent
[50]	The most economical solar fraction design values for SAASHP systems are predicted.	TRNSYS 18, MATLAB and GenOpt
[46]	A detailed systematic review on building energy simulation is provided.	Many types of software are mentioned.
[40]	Simulation of solar air heater with PCM.	MATLAB 2009
[51]	Analysis of how incorporating solar space heating can enhance a hybrid solar GSHP system.	TRNSYS
[52]	The flow pattern charts of R600a are illustrated in a collector/evaporator of a DX-SAHP, which were generated in a horizontal pipe with varying inclination angles.	Inhouse code
[53]	The optimal matching method for pairing a solar collector with a heat pump is identified.	Inhouse code

To assess the suitability and accuracy of each simulation software, researchers have compared the most popular building performance (bp) tools, namely TRNSYS (a software package for simulating the behavior of transient systems), EnergyPlus (a building energy simulation program used for simulating the energy use of buildings and their HVAC systems) and IDA ICE (a building performance simulation software that offers detailed simulations of building energy use, indoor climate conditions and thermal comfort). The results demonstrated that all tools were highly accurate in the absence of phase change materials (PCM), while IDA ICE was recommended when PCM was present [48]. To overcome the limitations of using a single simulation tool to predict system performance, the researchers developed a co-simulation framework between the BES tool (EnergyPlus) and the CFD tool (Ansys Fluent, a computational fluid dynamics software used for simulating fluid flow, heat transfer and other related phenomena). The utilization of the co-simulation framework helped them obtain more accurate predictions compared to existing BES tools [49]. To economically optimize the system design, the researchers developed a proxy model and compared its economic cost. First, they designed a solar-assisted air-source heat pump (SAASHP) system according to the national design standards for solar thermal systems in China using TRNSYS software. Second, they used the artificial neural network toolbox of MATLAB and the results of GenOpt (a generic optimization program used for optimizing complex systems and processes) to predict the most economical solar fraction design values for solar-assisted air source heat pump systems [50].

A two-dimensional temperature-based finite-volume numerical simulation model was developed and experimentally validated to analyze PCM energy storage and temperature regulation [54]. The results demonstrated the potential for optimizing the use of solar energy to drive heat pumps while storing thermal energy in PCMs for radiant floor heating. What is more, a hybrid solar–ground-source heat pump system (HSGSHPS) was implemented, which comprised a ground-source heat pump system (GSHPS) and a solar-assisted ground-source heat pump system (SAGSHPS) for heating and cooling a building. The study demonstrated that the optimized use of this system can effectively save electrical energy. Furthermore, the researchers designed a borehole heat exchanger (BHE) and borehole thermal energy storage (BTES) that are compatible with the two heat pump units [51]. They analyzed the operating efficiency of the hybrid solar–ground-source heat pump system and confirmed that solar space heating can significantly improve the performance of solar-assisted ground-source heat pump (SAGSHP) systems.

Additionally, flow pattern maps for horizontally aligned pipes for a direct expansion solar-assisted heat pump system (DX-SAHP) were presented based on another mathematical model [52]. Researchers have also developed a thermal simulation model that accounted for the hysteresis effect of phase change materials. For heating residential water, a solar-assisted heat pump system was constructed, and the mathematical model was verified using experimental data [55]. In addition, a dynamic model for the solar water heating mode of the indirect solar-assisted heat pump (i-SAHP) systems was presented, which can be used for the design and evaluation of solar heat pump systems [53]. These optimized integrations led to improved energy efficiency in the solar thermal system, resulting in a cost-effective and efficient heating system for residential buildings.

Through simulation, designers can evaluate the effectiveness of various building components, systems and configurations. This empowers them to pinpoint areas for enhancement, enhance energy efficiency and reduce the environmental footprint. By analyzing simulation outcomes, designers can make informed decisions and integrate inventive design approaches that result in more sustainable and resource-efficient building solutions.

3. Solar Photovoltaic Technology

The utilization of building-integrated photovoltaics (BIPVs), which are solar power-generating systems incorporated into buildings, has become increasingly popular as a novel approach to promoting renewable energy in residential areas [47]. It is obvious that the drawback of PV system is intermittent operation, depending on the weather condition. If there are alternative forms of power generation assistance available, the performance of photovoltaic systems will be significantly improved. In addition to grid-connected systems [56], photovoltaic power generation is also linked to other wind-powered generation systems [57], fossil fuel power generation [58] and batteries [59] for assistance. What is more, it is predicted that the share of photovoltaic energy in total electricity demand will significantly increase. This is primarily driven by costs falling through economies of scale and efficiency improvements achieved through research on passivating contacts in silicon photovoltaic technology [11].

However, photovoltaics can only generate electricity during the day, leading to an imbalance in power supply and demand. Battery Energy Storage Systems (BESS) have the capability to address this issue. It is feasible to use Energy Storage Systems (ESS) to store energy from photovoltaics and the grid during periods of low demand and supply it back to the grid during periods of high demand. This can enhance the efficiency of the distribution system integrated with photovoltaics [60]. The optimization of this system can be achieved through the use of genetic algorithms (GA) and particle swarm optimization (PSO) [61]. Specifically, this involves reducing the costs associated with voltage deviations, power losses and peak demand in the distribution system to improve its performance. This, in turn, helps in finding the optimal BESS location and scale.

Another notable drawback of photovoltaic (PV) technology lies in the fact that over 80% of renewable energy is converted into heat. If this thermal energy is not properly stored in a collector, it can potentially harm the PV cells [62].

3.1. Photovoltaic (PV) Module

Numerous studies have demonstrated significant progress in enhancing efficiency, reducing costs [63], and exploring potential applications of photovoltaic modules in photovoltaic technology. Table 2 compares the four PV modules to be discussed next.

Table 2. Comparison of four types of PV modules.

	Semi-Transparent PV Modules	Bifacial Modules	Perovskite Solar Cells	Thin-Film Solar Cells
MainFeatures	Power generation, transparency, heat insulating effect	Generation of electricity from both front and rear surfaces	High efficiency and low-cost production potential	Flexibility, lightweight design, potential for lower costs
Integration withBuildings	Integrated into various building components	Primarily used in ground-mounted applications	Research on integration into modules, including steel substrates	
Negative		The reduced efficiency or performance of a bifacial module caused by soiling	Stability is still a challenge.	

3.1.1. Semi-Transparent Photovoltaic (PV) Modules

The development of semi-transparent photovoltaic (PV) modules, including thin-film solar panels, has made it possible to integrate BIPV systems into various building components, such as skylights, windows, and visually appealing facades. Their main features are power generation and transparency, as well as possessing a heat insulating effect. For instance, PV glass exhibits the same mechanical properties as conventional architectural glass used in construction. Additionally, it provides free and clean energy. Given these properties, PV glass maximizes the performance of the building envelope [49,64]. In contrast to CdTe modules of 50% transparency [65], CdTe semi-transparent PV windows with 10% transparency showed improved performance in working PV hours in the range of 500 to 2000 irradiance.

3.1.2. Bifacial Modules

The solar energy industry is constantly evolving, and one of the latest innovations being adopted is the use of bifacial photovoltaic (PV) modules, which are now considered to be one of the standard technologies for ground-mounted applications [11]. These modules can generate electricity from both sides by capturing sunlight from both the front and rear surfaces, increasing overall power output. However, the negative impact of soiling on one side of a bifacial module should not be overlooked [66].

3.1.3. Perovskite Solar Cells

Perovskite-based solar cells are a promising new technology with high efficiency and low-cost production potential. Researchers are actively exploring ways to integrate perovskite materials into photovoltaic modules. One of the emerging technologies in photovoltaic research involves organic–inorganic metal halide perovskite solar cells (PSCs) [67]. Numerous advanced perovskite solar cells (PSCs) have been successfully fabricated on inflexible glass substrates before. Recently, studies have proposed a robust design for perovskite solar cells (PSCs) on steel substrates [68]. This research could potentially drive advancements in utilizing perovskite solar cells (PSCs) on surfaces other than glass, leading to a broader range of applications. What is more, research has found that a positive aging process of perovskite materials is confirmed to result in an increase in photoluminescence (PL) intensity and lifetime [69].

3.1.4. Thin-Film Solar Cells

Thin-film technologies, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) solar cells [70], are gaining attention due to their flexibility, lightweight design and potential for lower manufacturing costs. When compared to CdTe modules with 50% transparency [65], CdTe semitransparent PV windows with 10% transparency showcased improved performance in working PV hours within the range of 500 to 2000 irradiance. A promising strategy is to create novel hole-transporting materials with high work function (WF) and transmittance, such as transparent Cu-containing selenides with high work function, that contribute to high-efficiency bifacial CdTe solar cells. These transparent selenides have potential applications in the field of bifacial CdTe solar cells [71].

In summary, PV modules have evolved significantly in terms of performance, shape and color to accommodate various building PV skin alternatives. This is important, as architects require a high degree of design freedom when considering technological solutions for the customization of building skin [72]. The published report by Smith et al. provides insights into the minimum sustainable price (MSP) benchmark for PV modules and the technological evolution of PV modules in 2020 [63]. With the advent of c-Si-cell-based PV technologies, the most cost-effective renewable energy source is steadily shifting towards PV energy [73].

3.2. Building Integrated Photovoltaic Technology

The rapid development of BIPV systems has been driven primarily by improvements in three key areas: solar cell and module efficiencies, reductions in manufacturing costs, and the realization of competitive levelized electricity costs [74]. The current outlook for building-integrated solar PV systems has been studied, and it has been found that BIPV systems have gained attention in recent years as a way to restore the thermal comfort of the building and generate energy [47]. Studies on the technology frontiers of BIPV revealed an evolutional path and defined three key frontiers of BIPV: (1) light, convenient, low-cost and esthetically pleasing support systems of installed PV modules; (2) improved BIPV components; (3) PV intelligent control systems using Social Network Analysis (SNA) and text clustering [12]. In addition, researchers have explored the social and environmental impacts of BIPV technology and identified benefit-related and cost-related factors, such as environmental, health, design, and social issues in the adoption of BIPV technology [75]. Figure 3 displays the main explanatory aspects of this section.

Photovoltaic systems can experience various failure modes in the field [11]. An effective monitoring system can provide early warning and facilitate the troubleshooting of faults, thereby reducing downtime and increasing the reliability and availability of the system. In the past, using traditional wired cables for real-time monitoring not only added significant cost, but also had an environmental impact. Now, with the advent of wireless monitoring systems, the constraints imposed by environmental conditions have been significantly reduced, enabling faster real-time decision-making [76]. There is already a novel monitoring system that supports the use of Artificial Neural Network (ANN) technology to detect shading and other faults in photovoltaic panels (PV) [77], and an efficient monitoring and control system for solar photovoltaic modules has been developed that combines the use of a nonlinear maximum power-point tracking (MPPT) backstepping controller with a custom wireless sensor network (WSN) [78]. Also, the variations in energy yield are likely due to environmental changes, shading or faults. Therefore, an intelligent monitoring system is required to determine the condition of the photovoltaic panels. A novel real-time monitoring system using a small but efficient artificial neural network that is suitable to run on a low-cost system is presented. The presented PV monitoring system can identify if the photovoltaic panel shows degradation due to fault conditions [79].

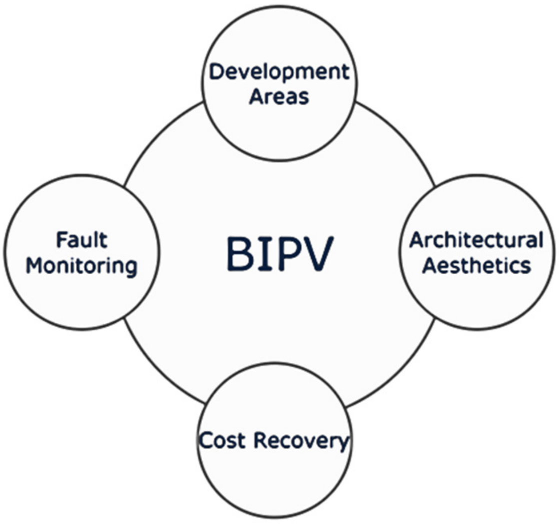

Figure 3. BIPV Comprehensive Overview Chart.

BIPV systems have gained popularity due to their sustainability and economic feasibility [80,81]. Due to these advantages, BIPV systems have been implemented on building envelopes, such as roofs, facades and shading systems. To reduce energy consumption and dependence on conventional energy sources, it is crucial to improve the efficiency and effectiveness of building integrated photovoltaics. It is known that high temperature is a common issue that hinders the efficiency of photovoltaic systems. Under high temperature conditions, the power output of photovoltaic modules decreases, resulting in a reduction in electricity generation efficiency. High temperatures can also cause aging and damage to photovoltaic components, increasing the risk of system failures. With the development of photovoltaic technology, temperature elevations can be mitigated through techniques such as air-flow ventilation, water circulation, and the utilization of phase change materials [82]. Researchers have also evaluated the performance of BIPV modules and identified factors like the orientation and azimuth angle of the building [83], the location, azimuth, and tilt of the cells, as well as optimizing the transmittance of surface glazing [82], which can improve their performance. The methods of using installation types to improve the effectiveness of building integrated photovoltaic (BIPV) systems and bifacial PV systems have been extensively discussed [47]. A solar panel can achieve its economic payback typically within 15 years, and further studies on new materials for solar cells and additional cooling measures for the panels can improve its sustainability [84].

Compared to the other form of building-integrated photovoltaics, such as building-applied photovoltaics, building-integrated photovoltaics blend seamlessly with the design and aesthetics of the building, creating a more aesthetically pleasing and harmonious overall effect [85]. It is believed that the future development of aesthetically appealing building-integrated photovoltaic (BIPV) systems is promising [86].

Although the upfront cost of BIPV installation is typically higher compared to traditional building materials, the long-term cost savings can be substantial. While it may take several years to realize the return on investment, BIPV systems can lead to reduced electricity bills and potentially generate revenue from excess energy that can be fed back into the grid.

3.3. Solar Photovoltaic Buildings through Simulation

Simulation and optimization techniques play a crucial role in the analysis of building-integrated photovoltaic (BIPV) systems. In academic research, there has been an increase in simulation work due to recent advances in technology. These advances have made it easier and more cost-effective to analyze and design BIPV systems [47]. Table 3 presents a brief comparison of the previously conducted studies for simulation tests.

Table 3. Software and simulation programs are used for optimization, design, and analysis of solar photovoltaic systems.

Reference	Significant Findings	Software
[87]	A unique design of the BIPV roof makes the building greener.	PVSyst
[88]	A novel method has been created to evaluate urban BIPV potential for building façades by enhancing geometric accuracy beyond LOD2.	ArcGIS.
[81]	A detailed systematic review is provided on building energy simulation.	Many types of software
[89]	Power conversion efficiency (PCE) of PV cells has been evaluated, and key parameters influencing power output are identified in different conditions.	MATLAB/Simulink and COMSOL
[65]	Windows integrated with crystalline silicon cells and CCPC optics have the potential to provide best daylight availability when applied to rooms with large Window-to-Wall Ratios at high latitudes.	RADIANCE 5.1

Using spectral reflectivity data sets from the SMARTS modeling software, nine different ground surface resources were simulated and reflectivities R(λ) for different ground materials were obtained [90]. A computational method has been proposed that matches existing LOD2 solar radiation analysis with architectural typological indicators to obtain a better estimation of the urban BIPV potential of facades, referred to as LOD2.5 [88]. In addition to that, the PVSyst software was utilized to conduct comprehensive system simulations. The proposed system not only enhances the energy efficiency of the building but also mitigates its CO_2 emissions [87]. ML-based PV parameter estimation studies published from 2020 to 2022 were analyzed and summarized [81], revealing that the popularity of ML methods, in descending order, were neural networks, random vector functional links and support vector machines. Furthermore, mathematical and numerical models were developed using MATLAB/Simulink and COMSOL Multiphysics to enhance the potential for power conversion efficiency (PCE) [89].

It should be noted that, with the introduction of new technologies and materials, widely used simulation software may exhibit significant errors in data modeling. For example, simple EnergyPlus models may struggle to explain the differences between STPV module types (c-Si and a-Si modules) [91]. Future building energy tools need continuous improvement.

Modeling and simulation of photovoltaic (PV) modules play an important role for technology development and the evaluation of new designs, as well as their interaction with the previously mentioned key factors. To ensure the successful application of the model in practical scenarios, simulation software was utilized to evaluate the performance of photovoltaic components in real world applications. For one example, two steady-state photovoltaic (PV) module temperature models were assessed when applied to building integrated photovoltaic (BIPV) rainscreens and curtain walls [92]. For another, predictive models were optimized to determine the optimal tilt angle of Building Attached Photovoltaic Integrated Shading Systems (BAPVIS) to achieve the best performance in achieving zero energy buildings [93].

Overall, these studies highlight the progress made in understanding the historical development of BIPV, improving the performance of BIPV modules, and exploring the prospects of building-integrated solar PV systems. Researchers have focused on improving the sustainability, economics and performances of BIPV buildings through simulation-based studies.

4. Photovoltaic Thermal Technology in Buildings

In solar energy utilization, the integration of photovoltaic/thermal (PVT) technology allows for the simultaneous generation of electricity and heat, greatly improving the overall efficiency of solar energy utilization compared to standalone photovoltaic or solar thermal systems. Therefore, PVT technology effectively alleviates energy crises and environmental pollution, making it an efficient means of harnessing solar energy. BIPV-T systems have the same beneficial characteristics as BIPV. First, they save on material and electricity costs, thereby reducing fossil fuel consumption and associated carbon dioxide emissions. Second, they provide an architectural enhancement to the building. And third, as an attractive architectural element, they positively influence the appearance of the structure, making it a visually appealing masterpiece.

The majority of solar radiation absorbed by photovoltaic cells is converted into internal energy, which increases the temperature of the cells and reduces their electrical efficiency [94]. There are several effective methods of cooling the collector that have been shown to be feasible. Adding copper tubes at the bottom of the PVT system and using water as a cooling agent instead of air can lower the temperature of the collector by approximately 30% [95]. Compared to water cooling, the use of nanofluids (MWCNT, Al_2O_3, and CuO) has been shown to increase the power generation and energy efficiency of photovoltaic/thermal (PVT) systems [96].

Compared to active cooling methods, PCM not only effectively solves the challenges associated with complex structures, high manufacturing costs and poor stability that are prevalent in traditional thermal management technologies, but also enables significant heat absorption and energy storage with minimal temperature fluctuations. Furthermore, PCM facilitates heat transfer at a constant temperature [97]. An example of PCM application in practice is Xia et al.'s utilization of transparent wood with phase change heat storage, which has broad application prospects for energy saving in buildings and improving indoor thermal comfort [98]. The phase change material itself possesses an excellent latent heat storage capability, enabling it to absorb and release heat within a narrow temperature range [99].

Moreover, PCM has been proven effective in assisting with improving system efficiency. By encapsulating phase change material (PCM) and immersing it in nanofluid, along with the use of specific single-package designs, both thermal and electrical efficiencies of the system can significantly improve [100]. To enhance the thermal performance of building envelopes and maintain comfortable indoor thermal environments during winter through clean energy sources, a novel expanded perlite-based composite phase change material wallboard has been developed and integrated with solar thermal systems using capillary tubes [101]. The results demonstrate their excellent mechanical and thermal properties. In addition, the combination of spiral absorption tubes with nanocomposite PCMs can also improve the efficiency of PVT collectors [102].

By combining the two separate systems, the photovoltaic/thermal (PVT) system not only reduces the footprint and cost, but also improves efficiency and saves a lot of materials. It has been confirmed that Building-Integrated Photovoltaic/Thermal (BIPV/T) systems have vast potential in the field of residential cooling and heating.

5. Discussion

Table 4 provides a comprehensive summary of the literature examined, offering a succinct overview of the key findings and relevant information obtained from the research sources. These findings showcase the rapid progress made in recent years and the immense potential of this technology from diverse perspectives. Beyond efficiency and cost, aesthetics should also be taken into consideration for photovoltaic or solar thermal technologies applied in buildings. In particular, building-integrated technologies require not only providing clean energy but also showcasing an appealing appearance that can be admired. However, some limitations are worth noting.

Table 4. Literature studies classified according to the region of interest with their focus and significant findings.

Region of Interest	Reference	Description	Focus
Optimization of solar thermal system	[17]	A multi-criteria robust design of the flat plate collector system obtains more reliable results.	The design of FPC and its influence on thermal performance
	[18]	The effects of nanotubes are investigated on the fluidic and thermal performance of FPC.	The applications of two carbon nanotubes and their influence on FPC
	[16]	Solar thermal technology developments are analyzed using patent records and search traffic. A new methodology is proposed for patent retrieval.	A new methodology for patent retrieval
	[20]	Graphene, graphite and nanoparticles improve charge/discharge rates, while PCMs with added composite materials and PEG support enhance thermal energy storage.	Thermal performance enhancement via new materials
	[21]	Techniques are reviewed such as heat transfer enhancement, energy storage mediums, nanomaterials, reflecting surfaces, and hybrid approaches to improve ETC performance.	Heat transfer enhancement, energy storage mediums, nanomaterials, reflecting surfaces, and hybrid approaches for ETC's performance improvement
	[26]	Hybrid nanofluids are found to be more effective than monofluids in enhancing the thermal characteristics of the heat transfer fluid used in the absorber tube of the parabolic trough collector.	Hybrid nanofluids used in PTC
	[14]	This paper analyzes solar thermal collectors in public buildings and explores potential benefits of nano-coated absorber surface.	Solar thermal collectors, nano-coated absorber
	[15]	The parameters of a solar water heating system are optimized with an obstacle using a specific decision-making method.	SWHS, optimized parameters
	[19]	A numerical analysis was conducted on a small-scale solar flat plate collector with four different pipe arrangements to enhance its efficiency.	FPC, numerical analysis
	[20]	Previous research on efficient nanomaterials used in solar energy storage and conversion are discussed.	Solar energy storage and conversion performance, PCM

Table 4. *Cont.*

Region of Interest	Reference	Description	Focus
Optimization of solar thermal system	[23]	A detailed parametric analysis is performed on an efficient evacuated flat plate collector and its daily performance in Athens investigated.	PTC, parametric analysis
	[24]	Three Cr_2O_3/Cr-based multilayer coatings are designed and optimized.	EFPC, performance
	[27]	Numerical studies are conducted on PTC systems, with a specific emphasis on discretization methods.	PTC, simulation
	[39]	Efficient thermal management systems are introduced based on PCM.	Thermal management, battery, PCM
	[41]	A solar heater is proposed utilizing aluminum chips and tubes filled with nano-silicon carbide (SiC) added to paraffin wax to improve its thermophysical properties.	Solar air heaters, thermal performance
PV technology	[57]	Potential of hybrid power generation is explored including PV power generation for dynamic operation.	Hybrid power generation
	[65]	Four types of photovoltaics are studied, and the best performance was found in crystalline silicon cells with crossed compound parabolic concentrators applied to rooms with large window-to-wall ratios and at high latitudes.	PV windows
	[74]	A roadmap has been developed to identify key areas of development needed for terawatt-scale PV installation, focusing on reliability, characterization and applications.	PV technology
	[66]	Soiling impact on one side of bifacial PV modules was studied through experiments.	The negative impact of soiling on individual side of a bifacial module
	[67]	Organic-inorganic perovskite solar cells (PSCs) have high efficiency but need stable hole-transporting materials for commercialization, recent progress in developing such materials was discussed.	Development and guidance for PSCs
	[67]	The recent progress in PSCs is discussed, involving unstable hole transporting layers (HTLs) and a positive aging effect of perovskite materials.	PSCs' performance
	[71]	The superior performance of CdTe solar cells and their advantages in architectural applications	CdTe solar cells
	[73]	PSK/c-Si tandem cells show great potential to become highly efficient solar cells for future PV market.	c-Si cells and PSK/c-Si tandem cells

Table 4. *Cont.*

Region of Interest	Reference	Description	Focus
PV technology	[8]	The construction of solar PV cells, types of PV systems, and solar tracking systems are discussed.	PV cells, PV systems and solar tracking systems
	[63]	Manufacturing costs for popular PV technologies are discussed.	PV modules, costs
	[70]	The strategies, impacts and treatments associated with alkali elements doping in CIGS solar cells are discussed.	Alkali element, CIGS solar cells
	[81]	Systematic review of ML-based studies is conducted on PV parameter estimation conducted between 2020 and 2022.	PV system parameters, optimization
BIPV technology	[12]	BIPV technology evolution and frontiers are identified through patent co-citation analysis and SNA, of which results provide reference for researchers and overcome limitations of previous methods.	BIPV technology evolution
	[9]	The latest technology level of BIPV are present, analysing variables and making generalizations and inferences.	BIPV systems and BIPV applications
	[64]	BIPV integrates solar panels into building envelopes, enabling renewable energy generation and contributing to smart cities. PV glass replaces architectural glass, providing power generation, transparency, heat insulation and cost considerations.	BIPV applications
	[77]	A novel monitoring system which can accurately detect shading and other faults is developed.	Artificial Neural Network (ANN) technology, BIPV technology
	[86]	Aesthetically appealing BIPV systems and their applications are discussed in the green energy building environment.	The aesthetic of BIPV
	[80]	Primary energy-related characteristics of BIPV modules and systems are discussed.	BIPV modules and systems, sustainability and economic feasibility
	[92]	Performance of two steady-state PV module temperature models are analyzed specifically for BIPV rainscreens and curtain walls.	BIPV, performance and assessment
	[38]	A BIPV/T design method is proposed based on a well-established building practice in order to address the lack of design standardization in the field.	Design standardization in BIPV/T systems

Table 4. *Cont.*

Region of Interest	Reference	Description	Focus
PVT technology	[97]	The combined application of phase change material (PCM) in photovoltaic-thermal (PVT) systems.	PCM, PVT
	[94]	A comprehensive overview of hybrid PVT collectors and their wider systems is performed, assessing energy and carbon mitigation potential. It covers experimental and computational studies, identifies performance enhancement opportunities, pathways for innovation, and implications for solar generation systems.	Recent developments of research projects for performance enhancement and assessment.
	[96]	The experiment investigated the effect of inserting Al_2O_3, CuO and MWCNT into the PVT system on the improvement of efficiency.	Nanoparticles on the PVT systems
	[101]	The utilization of PCM wall in combination with solar thermal systems significantly improves building energy efficiency.	Coupling, PCM, solar energy
	[102]	The evaluation focused on the thermal performance of a PVT collector that incorporated a twisted absorber tube and PCM enhanced with nanoparticles.	PVT collectors

Solar energy is an intermittent source of energy because its availability depends on weather and geographical factors. Storing solar energy for use during cloudy days or at night remains a challenge. Although researchers have been working on energy storage devices to address the intermittent nature of solar energy, many issues still need to be perfected. Despite the decrease in the price of solar energy systems, they are still relatively expensive compared to conventional energy sources, which hinders the widespread acceptance and use of solar energy technologies. The lack of government support and relevant policies may also constrain the promotion and application of solar energy technologies. Furthermore, maintenance and recycling issues when implementing this technology need to be consider so as to achieve wider promotion and better development of this technology.

6. Conclusions

Solar energy has begun playing an increasingly important role in the protection of the environment as technology has advanced over the past few decades. Due to the significant role that buildings play in overall energy consumption, the application and promotion of solar building systems contribute to the solution of energy and environmental problems. The following conclusions have been drawn.

Integrating solar thermal into buildings can provide a clean and renewable energy alternative for buildings. It can significantly reduce dependence on traditional energy sources and help mitigate environmental impacts.

Effective building performance simulation can reduce energy consumption and carbon emissions, improving building quality and productivity. It can also be a driver of innovation and technology development.

At present, considerable research has been devoted to PV modules. They have evolved significantly in terms of performance, shape and color to accommodate various PV building envelope alternatives within the past few decades.

The rapid development of BIPV systems has been driven primarily by improvements in three key areas: the efficiency of solar cells and modules, the reduction in manufacturing costs, and the realization of a levelized cost of electricity. The lowest price of crystalline silicon (c-Si), which dominates the current PV market, was the ($0.25–$0.27/W) in 2020.

Simulation and optimization techniques play a critical role in the analysis of building integrated photovoltaics (BIPV). Simulation work has increased in academic research due to recent technological advances. These advances have made the analysis and design of BIPV systems easier and more cost-effective.

The integration of photovoltaic and solar thermal technologies enables the simultaneous generation of electricity and heat. This significantly improves the overall efficiency of solar energy use compared to photovoltaic or solar thermal systems operating alone.

The stability of perovskite solar cells remains a significant challenge, and further research is required to advance improvements in this area.

It is essential to integrate energy storage tightly with solar installations in buildings. Future efforts should focus on advanced battery technologies, smart energy management and IoT technologies for real-time monitoring and optimization. Ultimately, realizing the full potential of sustainable solar technologies in buildings will depend on addressing these issues.

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