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Review

Advancements in Solar Panel Technology in Civil Engineering for Revolutionizing Renewable Energy Solutions—A Review

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Abstract: Globally, solar energy has become a major contributor to the rapid adoption of renewable energy. Significant energy savings have resulted from the widespread utilization of solar energy in the industrial, residential, and commercial divisions. This review article comprises research conducted over the past 15 years (2008–2023), utilizing a comprehensive collection of 163 references. Significantly, a considerable focus is directed towards the period from 2020 to 2023, encompassing an extensive investigation into the latest developments in solar panel technology in civil engineering. The article examines the incorporation of solar panels into building designs and addresses installation-related structural considerations. In addition, the present review examines the applications of solar panels in terms of innovative infrastructure development applications of solar panels, such as photovoltaic parking lot canopies and photovoltaic noise barriers, which contribute to improved energy efficiency. It also emphasizes their role in water management systems, including water treatment plants, water pumping and irrigation systems, energy-efficient solar desalination technologies, and promoting sustainable water practices. In addition, this study examines how solar panels have been incorporated into urban planning, including smart cities and public parks, thereby transforming urban landscapes into greener alternatives. This study also examined the use of solar panels in building materials, such as façade systems and solar-powered building envelope solutions, demonstrating their versatility in the construction industry. This review explores the diverse applications of solar energy, which promotes sustainable practices in various industries. Owing to the ongoing research, solar energy holds great promise for a greener and cleaner future.

Keywords: solar energy; renewable energy; building integration; infrastructure development; energy efficiency; agrivoltaic

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1. Introduction

The construction sector is undergoing a shift towards sustainability, with the integration of solar panels leading the way in this transformation. Solar energy has emerged as a pivotal force, reshaping the landscape of buildings and charting a path toward a more eco-friendly and energy-efficient future. The present review-type paper examines the significant influence of solar panels on the construction industry [1], focusing on their advantages, challenges, and potential to shape a more sustainable built environment. The integration of solar panels into the construction industry has gained significant traction owing to their capacity to transform solar energy into clean electricity. As concerns about climate change and environmental degradation intensify, architects, developers, and policymakers are increasingly turning to solar energy as a reliable and renewable power source that significantly reduces greenhouse gas emissions [2]. One of the primary benefits of solar panels in the construction industry is their ability to generate electricity onsite. By capturing sunlight and converting it into usable energy, solar panels enable buildings to satisfy a portion or all of their electricity requirements. This reduces the reliance of the building on traditional grid electricity, lowers utility costs, and increases energy independence. In addition, solar panels allow buildings to contribute back to the grid through a process known as "net metering". Solar-panel-generated excess energy can be returned to the grid, allowing buildings to earn credit or compensate for the energy surplus they supply [3]. Building-integrated photovoltaics (BIPVs) and building-applied photovoltaics (BAPVs) have emerged as revolutionary developments in pursuing sustainable energy solutions. These ideas surpass the limitations of conventional solar panel applications, integrating solar technology seamlessly into architectural designs and structures. BIPVs involve the intrinsic integration of solar panels into building elements; whereas, BAPVs focus on retrofitting solar panels onto existing structures; they offer distinct avenues for harnessing solar energy in the built environment [4].

This increases the self-sufficiency of buildings and promotes a more resilient and decentralized energy system. In addition to economic welfare, the incorporation of solar panels into the construction industry has significant environmental benefits. By utilizing solar energy, structures can significantly reduce their carbon footprints, mitigate air pollution, and conserve finite fossil fuel resources. This transition to cleaner energy sources is consistent with global efforts to combat climate change and the transition to a future with reduced carbon emissions [5]. The widespread adoption of solar panels in the construction industry depends on overcoming certain obstacles. Cost-up-front and installation complexities are two of the most common obstacles that prevent building owners from adopting solar energy. However, as technology advances and economies of scale improve, the long-term cost-effectiveness of solar panel installations has increased, making them an increasingly attractive investment [6].

Hosseinnia et al. [7] proposed a two-step method for an optimal solar-assisted ground source heat pump (SAGSHP) for integrating buildings. The first is a dynamic pinch analysis that targets energy and determines equipment sizes based on the dynamic demands of buildings, resulting in multiple energy-efficient daily design candidates. Second, a concluding design for the entire year is proposed by computing the total annual cost (TAC). The investigation of various daily optimum designs (DODs) for a Canadian multifamily test building demonstrates significant energy and cost savings, with 55.9% and 79.2% reductions in annual electricity consumption for the September and March DODs, respectively, compared with conventional cases. Figure 1 depicts the general process for generating solar power from residential buildings.

Dezhdar et al. [8] examined the energy of solar and wind methods of renewable sources for heating, electricity generation, cooling, and heating. It considers multiple components, including wind turbines, heat pumps, reverse osmosis, fuel cells, photovoltaic/thermal panels, hydrogen tanks, and battery storage. A performance analysis of six Iranian cities determined the best location for the system based on factors such as fuel cell power, heating capacity, solar panel angle count, cooling, and wind turbine count. The suggested system reduced supply and demand variations, offering USD 674,278.4 per hour as the cost life cycle and generating power for a thermal comfort of 225,694.8 kWh for residential units. Alshibil et al. [9] suggested a hybrid solar collector design, combi-photovoltaic/thermal (PV/T), which combines water and air as working fluids to address the waste heat from classical PV modules. The comparison parameters included the sustainability index, exergy efficiency, solar cell surface temperature, and waste heat. The results showed that the combi-PV/T module reduced waste heat by 77.5%, lowered the surface temperature of the solar cells by 30.6%, and exhibited a higher exergy efficiency and sustainability index than the classical PV module.

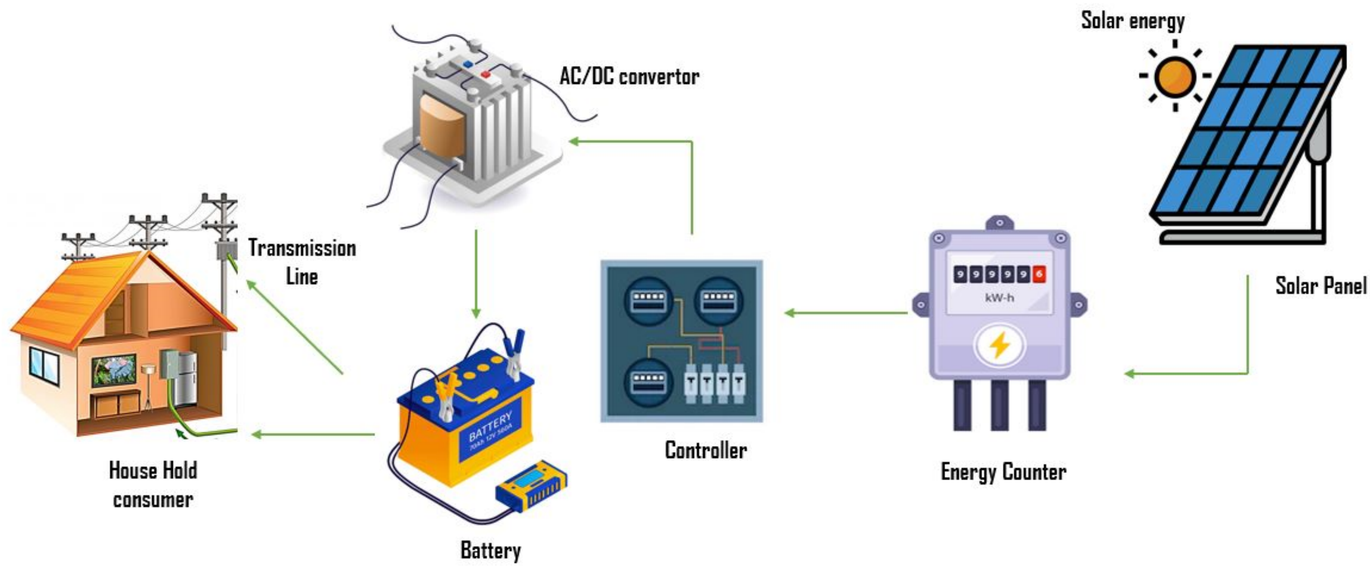

Figure 1. General procedure for residential solar power generation.

Yang et al. [10] analyzed solar energy resources in China. The authors discussed three types of utilization methods: photovoltaic (PV), photothermal, and gathering light, which are recommended for solar-powered residential buildings (SPRBs). Active SPRBs have been highlighted owing to their flexibility and intelligence. This paper proposes a building-integrated solar energy (BISE) design to achieve harmony between appealing and technology-promoting energy conservation and sustainable development in residential buildings.

Kim et al. [11] proposed and evaluated a two-stage approach to identifying suitable sites for PV panels on the South Korean national highway network. The authors aimed to enhance computational efficiency while maintaining estimation accuracy by using both low- and high-resolution maps with different raster cell sizes. The selected candidate sites from both cases resulted in significant solar energy potential, demonstrating the practicality of the proposed approach in identifying the optimal locations for PV systems on a broader scale. Venugopal et al. [12] explained "Future Sustainable Roads for Electric Mobility", focusing on a multi-disciplinary approach to address energy transfer and conversion techniques. The impact is demonstrated through lab-scale experiments theoretical examination, and simulations. Models of the loss and thermal properties of the self-healing asphalt were developed and contactless charging and solar integration were studied.

The present review includes a financial feasibility case study for a forthcoming Dutch highway with proposed developing modules. Vivar et al. [13] investigated a SolWat hybrid system, which was evaluated using real wastewater from secondary treatment, incorporating solar water disinfection and PV energy generation. Over a year, four seasonal experiments demonstrated that after 4 h of treatment, complete bacterial inactivation was not achieved for *E. coli*, *Enterococcus faecalis*, and *Clostridium perfringens*. However, the attained inactivation levels permit water reuse for numerous applications.

Bouhadjar et al. [14] demonstrated the viability of a low-cost water treatment approach to address the high fluoride concentrations in the groundwater in rural Tanzania. A small PV-powered nanofiltration (NF) plant equipped with a spiral-wound NF90 membrane resulted in more than 98% fluoride removal. The treated water consistently met the World Health Organization (WHO) recommended standard fluoride concentration of less than 1 mg/L, proving its suitability for local communities. The solar PV system operates autonomously, producing approximately 240 L/h of permeate, with a recovery rate of approximately 12%. Mohammed et al. [15] suggested that a power supply design for single-phase induction motors (SPIMs) powered by PV cells was successfully simulated using MATLAB SIMULINK. The power supply design utilizes a cascade boost (CB) DC/DC converter with a fuzzy logic controller (FLC) to achieve maximum power-point tracking (MPPT). A five-level inverter was integrated to deliver a stable AC voltage to drive the 1 hp SPIMs. The simulation outcomes demonstrate the efficiency of the system and its potential to power SPIMs for irrigation purposes, focusing on temperature and humidity.

The present paper comprehensively reviews the revolutionary impact of solar panels on the construction industry. Through an analysis of recently published scientific articles, this study highlights the importance of solar energy in combating climate change and highlights technological advances that improve efficiency and cost-effectiveness. This review article examines how solar panels are being creatively integrated into energy to improve architecture and urban planning. It investigates their innovative use in managing water systems, such as treatment plants and desalination, even supplying energy to transportation infrastructure. In addition, the review describes how solar panels are reshaping the aesthetics of buildings and cities by becoming integrated into building materials, thereby adding a sustainable touch to contemporary designs. Unlike previous review articles, this one examines solar panels' many uses beyond energy generation. Earlier reviews briefly discussed the use of solar panels in building designs; but, this work shows how they can become construction materials, improve city development, and go green. Unlike previous studies, this review examines how solar technology can be used in water system management, road construction, and transportation systems. This study investigates the potential for solar panels to enhance various aspects of life, shedding light on their capacity to improve sustainability by addressing frequently overlooked factors.

2. Types of PV Technologies

Exploring the landscape of PV innovation, various developed PV technologies should be examined. They mostly involve efficiency-focused mono-Si, cost-effective poly-Si, mono-PERC, and ingenious half-cut solar cells designed to improve performance.

2.1. Monocrystalline Silicon (Mono-Si) Solar Cells

Mono-Si is a pioneering technology in PVs, utilizing single-crystal ingots to achieve exceptional energy conversion efficiency. Sun et al. [16] used statistical distribution law to study monocrystalline silicon solar cell conversion efficiency and proposed a forensic algorithm to distinguish natural and computer-generated images. Electrochemical etching for porous silicon preparation is also introduced. The authors of the study verified statistical methods and provided references for related research using processing approaches, mathematical methods, statistical methods, and experimental techniques [16]. Boulmrharj et al. [17] examined Morocco's transition to renewable energy sources (RES), particularly solar energy, to reduce fossil fuel and electricity imports. Three silicon-based grid-connected PV systems in El Jadida, Morocco, were compared in Mediterranean climates. The final yield, performance ratio, and capacity factor favored polycrystalline silicon and monocrystalline silicon systems over micromorph tandem systems [17].

2.2. Polycrystalline Silicon (Poly-Si) Solar Cells

Poly-Si utilizes multiple silicon crystals to provide a viable alternative for solar energy generation, embracing cost-effectiveness without sacrificing its potential. Tariq et al. [18] examined the mechanical behavior of polycrystalline silicon solar cells (PSSCs) in PV modules. Using the finite element (FE) method, they used a Voronoi-tessellation scheme and a mean-field homogenized scheme to predict the homogenized response. This study compared heterogeneous and homogeneous modeling and investigated the deterioration of stiffness caused by existing microcracks. The homogenized FE solution represents a progressive failure in solar cells in an accurate and computationally efficient manner [18].

According to Kazem et al. [19], dust accumulation in PV modules can result in significant yield loss. The researchers collected and analyzed dust from five locations in North Al Batinah, Oman. A total of 5 g/m^2 of contamination on monocrystalline modules decreased the power by 12%, 6%, 6%, 7%, 3%, 4%, and 4%, respectively. The degradation of the polycrystalline modules was 5%, 4%, 4%, 1%, 2%, and 2%. The study suggests periodic cleaning intervals ranging from 10 to 15 days for polycrystalline and monocrystalline modules, respectively [19].

2.3. Monocrystalline Passivated Emitter and Rear Cell (Mono-PERC)

Mono-PERC improves light capture through its reflective rear surface, resulting in a new phase of increased efficiency through cutting-edge design. Es et al. [20] predicted that the passive emitter and rear cell (PERC) concept would dominate the future of the PVs industry. Pilot lines, such as the GUNAM PV line, connect laboratory-proven concepts with mass-produced goods. The authors focus on standard PERC solar cells with a p-type base and Al_2O_3 rear passivation to demonstrate how loss analysis can be applied in an industrially relevant environment [20]. Lunardi et al. [21] performed an environmental analysis comparing monocrystalline Al-BSF and PERC solar modules. Using life cycle assessment (LCA) methods, they calculated global warming, human toxicity, freshwater eutrophication, ecotoxicity, abiotic depletion potential, and energy payback time. Compared to Al-BSF, PERC technology slightly improves environmental impacts while electronic and upgraded metallurgical grade silicon results in lower impacts [21].

2.4. Half-Cut Solar Cells

The efficiency dynamics of solar cells are redefined by half-cut solar cells, which revolutionize the conventional approach by significantly reducing shading losses. Researchers have identified a potential pathway for enhancing output efficiency and minimizing energy loss by dividing cells by half and optimizing their connections. Shukir et al. [22] investigated the influence of solar radiation, including infrared, visible, and ultraviolet rays, on the performance and effectiveness of solar panels. Infrared rays overheat panels; whereas, ultraviolet rays destroy the cells. During summer, high temperatures can decrease power and voltage. Shade can also threaten the durability and safety of solar panels. This article proposes using solar panels with half-cut cells to reduce losses caused by high temperatures and the effect of shade on panel safety and productivity [22]. Vedat Kiray et al. [23] discussed barriers to self-generating energy in residential houses, including location, slope, strength, and exposure to shade on roofs. Solar tracking systems improve efficiency but are not aesthetically pleasing. The article suggested a dual-axis sun tracking system and an aesthetically pleasing gazebo to solve these issues. A design study examined the dimensions of a movable platform/roof and calculated the annual energy collected by PV panels using a simulation program known as the “PV performance tool” [23]. Table 1 displays a comparative analysis of different studies categorized according to their settings: Computational Research, Field Research, and Experimental Research. These study settings serve to emphasize the focus of each study.

Table 1. Comparative analysis of PV technologies in different study settings.

S. No.	Source by Authors	Types of PV Technologies Used	Study Setting	The Primary Focus of the Study
1	Sun et al. [16]	Mono-Si	Computational Research	Validation of statistical methods for monocrystalline silicon solar cell efficiency and developing a forensic algorithm to differentiate between natural and computer-generated images.
2	Boulmrharj et al. [17]	Mono-Si, Poly-Si	Field Research	Analysis of silicon-based grid-connected PV systems in Morocco's transition to renewable energy sources, focusing on the performance advantages of polycrystalline and monocrystalline silicon over micro morph tandem systems.
3	Tariq et al. [18]	Poly-Si	Computational Research	Mechanical analysis of PSSCs in PV modules using finite element methods, comparing heterogeneous and homogeneous modeling to predict changes in stiffness due to microcracks
4	Kazem et al. [19]	Poly-Si, Mono-Si	Field Research	The effect of dust accumulation on PV modules in North Al Batinah, Oman, and the resulting power loss analysis, recommending periodic cleaning intervals for both polycrystalline and monocrystalline modules.
5	Es et al. [20]	Mono-PERC	Experimental Research	The application of loss analysis to standard PERC solar cells with a p-type base and Al_2O_3 rear passivation in an industrially relevant environment, with particular emphasis on the role of pilot lines in bridging laboratory concepts with mass production.
6	Kiray et al. [23]	Half-Cut	Field Research	Exploration of challenges to the residential self-generation of energy, with the proposal of a dual-axis Sun-tracking system integrated with an aesthetically pleasing gazebo as a solution, supported by a design study and energy calculations using the "PV performance tool".

3. Degradation of PV Modules

In the field of solar technology, understanding the degradation of PV modules is crucial. Various factors affect the efficiency and performance of solar panels over time, necessitating a comprehensive examination of degradation processes to ensure prolonged and optimal energy production. Khan et al. [24] investigated the stability of PV modules in non-ideal environments. Temperature and humidity were found to degrade optoelectric and material properties. This study examined the performance of c-Si PV modules installed on a concrete slab for 4000 h in a humid-heat stress-testing chamber. Their results indicated that the performance retention of the PV modules mounted on a concrete slab was 93.2%, which was 5% greater than that of the modules without a concrete mount [24]. Khan et al. [25] studied 3200 h of the effect of damp-heat stress on PV degradation in low-humidity regions. They discovered that PV modules installed on concrete had a 1.9% efficiency loss, 5.6% less than that of the PV module used as a benchmark. However, the series resistance increased by 60% and 43%, indicating that PV modules can perform better in regions with low humidity after concrete slab installation [25].

4. Solar Panels in Building Construction

Solar panels used in building construction are revolutionizing the use of renewable energy in power structures. By integrating solar technology into the design of structures, clean electricity can be generated and the carbon footprint can be reduced. This transformative strategy represents a major step towards a greener and more environmentally responsible future for the construction industry.

4.1. Integration of Solar Panels in Building Designs

Integrating solar panels into building designs is on the rise, fostering sustainability within the construction industry. Vassilades et al. [26] studied solar energy in integrated buildings by monitoring building-integrated photovoltaics (BIPVs) in terms of single and double solutions of façades. A cavity is formed in the double solution that can be used as a duct of air for building-integrated photovoltaics/thermal (BIPV/Ts) and building-integrated photovoltaics (BIPVs), which results in improving the capacities in the design and enhancing the architecture by the building-integrated solar system (BLISS). Based on climatic conditions, the significance of water and air energy and the cost convenience of the BISS can be evaluated and adopted during the design stage.

Behzadi et al. [27] developed and suggested a model of a solar energy generation-pumped system equipped with panels made of thermal PVs by rejecting the presence of heat pumps and batteries to decrease the amount and make people adopt less expensive energy systems in buildings. The developed model was observed under different heating systems, including ultra-low, low, and current temperatures, and was analyzed using TRNSYS software. The result shows that the productivity during reduced temperature is more efficient, in terms of a huge amount of heat (9118.5 kWh) and electricity (3647.4 kWh), than the other two and the value ranges from 52.3%, to 62.35%, to 74.51% for the existing, low, and ultra-low temperatures.

Hosseinnia et al. [28] recommended a dynamic approach of targeting the buildings to evaluate the major reuse of heat produced indirectly and directly in a building. The authors presented a group of heat exchangers based on solar PV panels, ground heat exchange, heat pumps (HPs), and energy storage (both electric and thermal energies) and they analyzed them based on the concept of pinch, using the cold and hot composite curve (CC) for 12 days. It has been recommended that this dynamic method leads to increased storage of electric energy, thermal energy storage (TES) volume, and solar PV panels. Allouhi et al. [29] determined that the tri-objective optimization process successfully determined the best design for a residential building in Fez, Morocco. The chosen configuration includes capacity, thermal storage, and thermal collectors of approximately 25 kW PV, 18 m^2, and 1.8 m^3. The resulting objective function values were LCOE = CAD 17.8 per kWh, LOCH = CAD 3.5 per kWh, and REP = 45%. The self-consumption, solar thermal fraction, and self-sufficiency ratios were 69.7%, 90.1%, and 30.6%, respectively. The findings indicate the cost-effectiveness and potential of renewable solar energy systems applicable to other building types and locations, which promotes broader acceptance of solar energy solutions.

4.2. Structural Considerations for Solar Panel Installations

Integrating solar panel installations into buildings safely and effectively requires structural consideration. Engineers carefully evaluate load-bearing capacities and architectural compatibility to optimize solar panel placement and maximize energy capture. Eltayeb et al. [30] offered a study on designing a 3 kW hybrid tree with wind and solar capacities of 1 kW and 2 kW, respectively, intended for installation in Vaddeswaram, Andhra Pradesh. The optimal energy generation was achieved using a two-axis tracking system. The authors explored diverse global energy tree designs and applications, by examining the PV and current-voltage characteristics of solar panels and wind turbine power characteristics. Structural optimizations ensured that the tree could withstand applied loads, resulting in a significant increase in power generation compared to fixed solar panels. Choi et al. [31] recommended a safety assessment for floating PV systems considering different wave angles and wind, analyzing the stress distribution through experiments and numerical simulations (FEA, CFD, and hydraulic dynamics). Wave and wind loads were used by hydraulic dynamics and CFD, validated through the experiments. FEA analyses the stress distribution at various angles, with junctions between floating bodies and solar panels experiencing the highest stress (150–298 MPa). Maintaining the stress below the material yield strength ensures safety during the wind and wave conditions. Designers should follow this procedure prior to field installation.

Khan et al. [32] simulated computational fluid variant (CFX) testing for solar panels and rooftop structural analysis under various wind velocities ($\pm$7.53 to $\pm$45 m/s). Factors of safety (FoSs) and displacement for all elements were computed. The truss showed vulnerability, with a FoS of 0.41 and a 51.6 mm displacement at 7.53 m/s. Failure of the structure's mounting occurred at 15 m/s, with a FoS of 0.72 and a 58.26 mm displacement. Structures of column and channel resisted up to $\pm$25 m/s without exceeding limits, exhibiting FoSs of 15 and 14.27 at +25 m/s, respectively, and deformations of 0.43 mm and 4.59 mm. Meiramov et al. [33] conducted full-scale testing and numerical simulations by analyzing the load-carrying capacity of the solar panel structure, concentrating on a system of poles mounted on a column-to-base connection. This study determined the progress of a non-welding connection feature for better durability. The results showed that proper structural assessment of the connection is crucial for designing reliable structures of paneled solar poles mounted to connect column-base connections.

4.3. Energy Performance and Efficiency in Solar-Powered Buildings

The solar energy performance and efficiency of solar-power buildings exemplify the significant advantages of solar panel integration. Deymi et al. [34] explored a case study in St. Petersburg, Russia, on an integrative system based on the solar wind in a near-zero-energy building. The system aims to satisfy hourly electricity loads, heating, and cooling using an absorption chilled turbine of wind, a solar loop of a parabolic trough, and storage of compressed air energy. The feasibility assessment indicated that the solar system can cover 61% of the yearly heating loads; the required electricity load is supported by almost 99% of the energy storage system. The system contributes to a reduction of 13,859 kg/year in CO_2 emissions and achieves extreme efficiency and monthly energy consumption in December. Economic analysis shows positive net present values after 17, 14, and 12 years, with 5%, 3%, and 1% interest rates, respectively. Sulaiman et al. [35] examined the possibility of using low-GWP refrigerants as replacements for conventional refrigerants. The model evaluates performance based on exegetic and energetic vapor compression cycles with different refrigerants. The prototype unit, powered by PV panels and battery storage, supplies cold air to a connected canopy. R290 and R600a demonstrated potential as suitable replacements, showing improved COP and energy efficiency compared to R134a.

Temiz et al. [36] developed a comprehensive solar energy system with a ground-sourced heat pump for stand-alone residential usage, providing power, heating, cooling, and domestic hot water. The system included different building-integrated PV plant orientations, an anion-exchange membrane electrolyzer, a vertical-oriented ground-sourced heat pump for hydrogen-based energy storage, and proton exchange membrane fuel cells. The study assessed the system in five global cities, determining the required PV capacity for a 20-floor building in Ottawa, Canada, achieving energy efficiencies and overall energies of 10.49% and 18.76%, respectively. Woo et al. [37] determined the system of solar power in advanced residential areas based on the usage of flexible power (ESS Provision) and aesthetics (panel transparency installation type and installation cost). It investigates suitable installation types for multi-unit residential buildings and analyzes consumer preferences and economic value through a choice experiment with Korean consumers. The results emphasize the economic value of transparent solar panel technology and installation type and impact consumer acceptance alongside generation efficiency.

Baniasadi et al. [38] examined a novel solar-geothermal system that provides hot water, electricity, cooling, heat, and desalinated water for a zero-energy residential building. It evaluates the exergy, energy, and exergy-economic aspects to assess an organization's feasibility in meeting energy and water demands. The system integrates solar and geothermal energies, incorporating a PV system, proton exchange membrane (PEM) electrolyzer, desalination system, and the fuel cell of a PEM with a pressure exchanger, with cooling and heating mode efficiencies of 13.27% and 17.25% for energy, and 32.44% and 42.4% for exergy, respectively. Acar et al. [39] evaluated the design of an ideal sizing for an energy system for hybrid solar hydrogen located in Afyon, Turkey, ensuring an uninterrupted and reliable power supply for a zero-energy house. Finding an adequate number of PV panels, fuel cell stacks, storage volume, and an appropriate electrolyzer model and size was crucial for meeting the house's energy demands. The optimal nominally powered electrolyzer significantly affected the efficiency of the system. Abu-Hamdeh et al. [40] associated the energy competence of paraffin wax/graphene and paraffin wax/graphene oxide nanofluids in flat-plate solar collectors for building heating systems. The results revealed that both graphene-based nanofluids exhibited enhanced thermal conductivities compared to paraffin. The solar collector efficiency was also improved using graphene-based nanofluids. In addition to the structural constraints, the operational constraints of the fluid solar collector operation were significant [41].

5. Innovative Applications of Solar Panels in Infrastructure Development

Solar panels are essential to infrastructure development, which results in a sustainable energy environment. The integration of solar technology into PV parking lot canopies and PV noise barriers enhances energy efficiency by employing innovative techniques.

Photovoltaic Canopies and Noise Barriers

Two innovative applications of PV technology are examined here. It is, namely, PV parking lot canopies and PV noise barriers. These inventive solutions not only utilize solar energy but they also serve practical purposes in urban environments. Teng Zhong et al. (2021) proposed a computational framework for estimating the solar PV potential of urban PV noise barrier (PVNB) systems. The framework employed a method of deep learning to identify sites suitable for panel installation. The results indicated that PVNB systems in Nanjing have potential installation capacities of 14.26 MW and 57.24 MW, generating 4662 MWh and 18,010 MWh annually, respectively [42]. Lee et al. [43] conducted research on noise barriers for Singapore's rapid transit railways. They compared the performance of Taipei's subway track noise barriers and vertical noise barriers used by the Singapore Mass Rapid Transit (MRT) system using on-site measurements of housing estates. The results demonstrated that simulated noise mitigation barriers reduced noise levels reaching residential apartments by 5 to 12 decibels, highlighting the need for additional research on noise barriers for elevated railway tracks or viaducts [43]. Vallati et al. [44] explored the use of PVNBs as a solution to limited space requirements in large-scale solar panel implementation. Despite not being a novel concept, the study focused on optimizing the acoustic and energy properties of these barriers [44]. Soares et al. [45] conducted a multi-criteria evaluation of PV noise barriers (PVNBs) in order to assess their energy, economic, and environmental impacts. They compared various design configurations and simulated energy outputs at various U.S. locations and found that PVNBs with shingles performed the best [45]. Iringová et al. [46] designed a PV system for a parking garage in Ilina, optimizing its orientation and layout for maximum efficiency. The system was located on a flat roof, above the electric vehicle charging stations. The optimal PV technology was evaluated for its economic viability, revealing that the system can generate enough electricity for six charging stations and cover the building's energy needs. Figure 2 showcases the integration of solar panels within a noise barrier along a road.

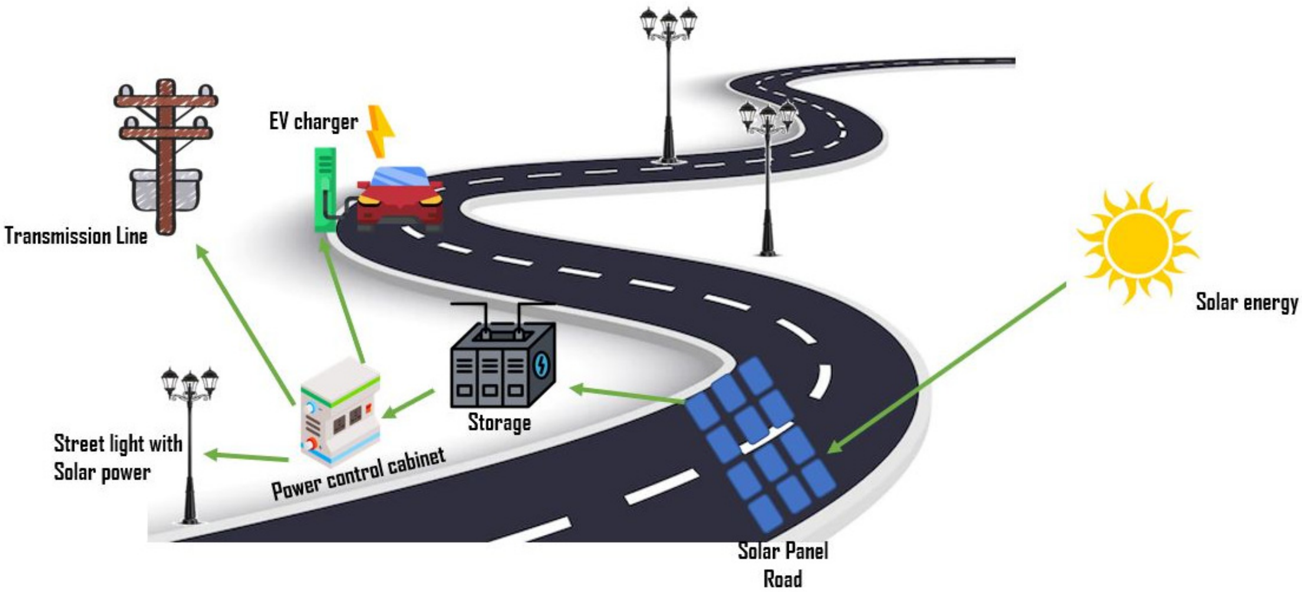

Figure 2. Integration of solar panels in a roadside noise barrier.

Deshmukh et al. [47] investigated the viability of solar PV canopies for incorporating electric vehicle (EV) charging stations into retail parking infrastructure. According to the study, Walmart supercenters could potentially deploy 11.1 GW of solar canopies, which would provide over 346,000 EV charging stations. This model could be adopted by any store, resolving issues with community pricing and increasing store selection and revenue. There is a need for more precise quantification in the future. Abdolahzadeh et al. [48] studied dust deposition on PV surfaces and discovered that small variations in tilt angle do not significantly affect dust deposition behavior. However, dust particle size has a substantial effect on deposition. Duo-pitch electric vehicle parking lots (EVsPLs) offer better performance against dust deposition while mono-pitch EVsPLs are more effective for smaller particles. The study provides a fresh perspective on selecting the optimal parking lot structure based on environmental conditions, particularly in regions with high dust concentrations. Rudge [49] focused on the possibility of solar canopies in Connecticut, a state with a zero-carbon electric sector goal. The study employed geospatial methods to evaluate the viability of large parking lots in the state, revealing 8416 sites with the capacity to generate 9042 GWh of electricity. This accounts for 37.0% of Connecticut's current electricity consumption. The study highlights the potential for solar canopies to contribute to Connecticut's energy portfolio and recommends policies to encourage their adoption. The methodology can be replicated at multiple geographical scales.

6. Solar Panels in Water Management Systems

Solar panels are instrumental in revolutionizing water management systems that use renewable energy sources. Their integration in water treatment plants, water pumping and irrigation systems, and energy-efficient solar desalination technologies promotes sustainable water practices and addresses water scarcity challenges. As solar-powered solutions evolve, they offer a promising path toward efficient and environmentally conscious water resource management.

6.1. Solar-Powered Water Treatment Plants

Solar-powered water treatment plants are emerging as a viable means of meeting the growing demand for clean water. These plants reduce their reliance on conventional power sources by utilizing solar energy, resulting in more eco-friendly water-purification practices. Ruiz-Aguirre et al. [50] discussed the combination of pilot-scale H_2 production and water decontamination or disinfection. The combination of solar-to-hydrogen (STH) and TiO_2-CuO for conversion was investigated and the highest STH conversion reached 0.9%. Moreover, 25 mg L^{-1} of imidacloprid was completely degraded (>99%). The synergetic consequence of the anoxic conditions, TiO_2:CuO and solar radiation, caused a significant reduction (>5 Log) in the concentration of *E. coli* in less than 10 min, highlighting the potential of this approach for safe wastewater reuse. Hu et al. [51] investigated H_2 generation with decontamination or disinfection of water using a TiO_2–CuO mixture for solar-to-hydrogen adaptation. Experiments were conducted in a 25-L solar pilot plant to optimize the catalyst dose, semiconductor proportion, and sacrificial agent concentration. The best conditions achieved 0.9% STH conversion and 25 mg L^{-1} imidacloprid degradation. The anoxic conditions, TiO_2:CuO and solar radiation, significantly reduced the *E. coli* concentration. This study demonstrates the potential of safe wastewater reuse for hydrogen production. Further research on Cu toxicity and inactivation kinetics is needed.

Shumiye et al. [52] discussed integrating solar and geothermal energy for power generation and water purification via boiling and reverse osmosis. The objective was to enhance energy efficiency and cost-effectiveness. The designed hybrid power plant in Ziway, Ethiopia, demonstrates promising potential, producing 44 MW of power and treating 100 m^3/day of water. The system effectively addresses green energy and clean water shortages by combining selective components and advanced technologies. Salmerón et al. [53] implemented a pilot-scale hybrid eco-engineered water treatment system, utilizing efficient electrocatalysis to produce H_2O_2 at an air-diffusion cathode, generating OH through Fenton's reaction with an added Fe^{2+} catalyst. The system effectively degraded the model pesticides using a boron-doped diamond anode and photocatalysis. The optimization of key parameters resulted in a H_2O_2 mass production rate of 64.9 mg min^{-1}, 89.3% current efficiency, and 0.4 kWh m^{-3} of energy intake; meanwhile, the SPEF process removed over 50% of pesticides in just 5 min, showing promising potential for wastewater treatment applications.

Alrawashdeh et al. [54] suggested a mathematical model for producing desalinated water using the multistage flashing-brine recirculation (MSF-BR) technique driven by solar energy. A solar power plant with a 30 MW capacity generated 6.5 kg/s of superheated steam, where 15 MW is allocated to influence the plant of MSF-BR desalination. The remainder was supplied to the grid. The MSF-BR desalination plant consisted of 24 evaporation stages, with a top brine temperature of 110 °C and a blowdown brine salinity concentration of approximately 69,439 ppm. Berruti et al. [55] determined the effectiveness of a solar water photochemical process by harnessing the combined power of peroxymonosulfate (PMS) and natural solar radiation for treating urban wastewater. The PMS/solar process performance was evaluated by monitoring the inactivation of naturally occurring bacteria and degradation of contaminants of emerging concern (CECs). These findings suggest that solar treatment could be a promising, sustainable, and cost-effective solution for reclaiming and reusing urban wastewater, particularly in regions with ample solar radiation. Figure 3 displays the utilization of solar panels to purify water.

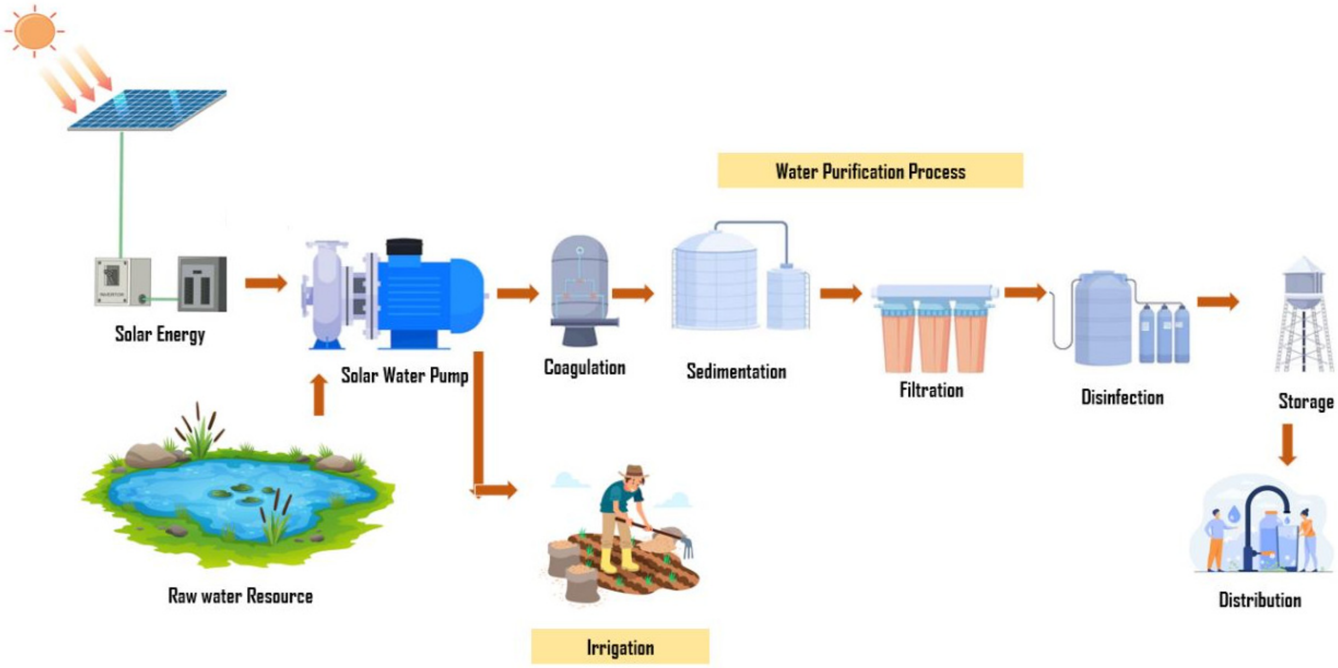

Figure 3. Solar panel utilization for water purification.

Andronic et al. [56] investigated wastewater treatment for potential reuse utilizing innovative materials with photocatalytic and adsorption properties. TiO_2, Cu_2S, and fly ash were combined to create substrates for removing pollutants from wastewater. Characterization techniques, including X-ray diffraction and scanning electron microscopy, offer valuable insight into the properties of these substrates. The photocatalytic activity was assessed with model pollutants, such as phenol, imidacloprid, and dichloroacetic acid, under different solar irradiation conditions, achieving impressive removal and mineralization efficiencies of 90%, 56%, and 66%, respectively, after specific time intervals. Xiong et al. [57] studied a 3D solar evaporator called PPy-PFBs, utilizing industrial polyester fiber bundles (PFBs) coated with polypyrrole (PPy). The solar evaporator emulates plant transpiration, drawing water via capillary action and keeping it at seven times its mass, making it salt resistant. With an exposure height of 6 cm, the matrix-arranged PPy-PFBs achieved an impressive 3.77 kg m^{-2} h^{-1} water evaporation rate, with a remarkable energy conversion efficiency of 155.77%.

6.2. Solar Panels for Water Pumping and Irrigation Systems

Integrating solar panels into water and irrigation pumping systems makes water resource management more sustainable and efficient. Vishnupriyan et al. [58] experimented with an optimal tilt angle and orientation to maximize solar energy utilization in water-pumping applications in remote areas. This study considered four different tilt angles (8°, 15°, 30°, and 45°) using a single-axis tracking system. By analyzing the performance using the PVsyst simulation software, it was found that a 30° tilt angle provided the highest solar radiation and achieved the best performance, with a 58% performance ratio. This information is critical for enhancing the efficacy of solar PV water pumping systems in such regions. Ramli et al. [59] developed a solar-powered portable water pump integrated with an IoT-controlled irrigation system. The system uses moisture, temperature, and humidity sensors to transmit real-time data to a Blynk IoT cloud. Farmers can easily access and manage water pumps by using user-friendly mobile applications. The integration of IoT technology has shown significant improvements, achieved higher water usage efficiency, and reduced operational costs by 30%. Practical testing and evaluation of the system have been successfully conducted, paving the way for future enhancements and automation.

Wanyama et al. [60] determined that a solar-powered control system, the Smart Irri-Kit, utilizes soil moisture sensor feedback for real-time irrigation scheduling. Field tests at Makerere University Agricultural Research Station Kabanyolo showed that the Smart Irri-Kit achieved efficient irrigation scheduling with no noteworthy variance from the gravimetric method for soil moisture detection. Integrating solar power into the Smart Irri-Kit enhances its autonomy and reduces its operational costs. Future research will explore incorporating weather parameters and advanced communication capabilities for remote monitoring and control, making the Smart Irri-Kit a promising solution for promoting efficient and sustainable agricultural practices.

Hilali et al. [61] inspected the potential of solar pumping methods, benefiting the Meknes region, with an average of 4.7 $kW \cdot m^{-2} \cdot day^{-1}$ of solar irradiation, respectively. Embracing PV energy satisfies irrigation needs, reduces greenhouse gas emissions, and minimizes energy expenses. The use of solar energy technology through direct or indirect coupling techniques is effective and eco-friendly and fosters sustainable agricultural practices. Further exploration can focus on practical implementation and innovative control strategies to enhance the efficiency of solar water pumping systems. Ashraf et al. [62] assessed the viability of implementing a solar-powered irrigation system (SPIS) in the UIB region of Pakistan. Based on the slope index, the results indicate that approximately 92.5% of the HKH range is highly suitable for harnessing solar energy. Additionally, approximately 13.3% of the area exhibited high suitability based on aspect, with 25.3% showing medium suitability. This study underscores the potential of SPISs as a nature-dependent remedy for the sustainable waste management of agriculture, emphasizing the importance of water conservation technologies and enhancing water-use efficiency.

Kumar et al. [63] investigated the importance of a solar-powered irrigation system for conserving electricity and water in Indian villages. Integrating solar energy technology with sprinkler systems can significantly reduce water consumption and energy use, leading to cost-effectiveness and environmental benefits. Surplus energy can be stored for other electrical needs, thereby promoting sustainable socio-economic development in rural Indian communities. Overall, implementing solar-powered irrigation in Indian villages has the potential to bring about positive changes to agriculture, water management, and energy conservation. Abhilash et al. [64] developed a solar tracking system for agricultural irrigation to optimize solar energy utilization. The system uses silicon-based solar panels and employs solar tracking to align with the sun's beams, enhancing energy generation and battery-charging efficiency. This study emphasizes the importance of storing solar energy in batteries to ensure a continuous power supply despite variations in solar irradiance throughout the day. The implementation of this automated solar tracking approach can significantly improve the sustainability and cost-effectiveness of agricultural water management.

Yavuz [65] proposed and analyzed a pump for agricultural irrigation known as the solar thermoelectric generator-assisted water pump (STEGWP). It highlights the design and parameters of solar thermoelectric generator cells (STEGCs) and compares their power output and cost with those of traditional photovoltaic (PV) panels. The proposed STEGWP system shows promising potential as an alternative for reducing energy costs in isolated regions. With further improvements in the utilization of quality materials, STEG systems could become viable for enhancing irrigation efficiency and sustainability.

Kumar et al. [66] discussed the evaluation in terms of the techno-economic elements of a solar-tree-dependent irrigation pump for sustainable agriculture in rural Indian areas. It highlights the data collection on the water requirements for various crop stages and estimates the CO_2 mitigation values based on electricity harvest and lifetime. The cost of the system is projected to be USD 3430 and this research suggests the potential for clean energy adoption in agriculture. Overall, this study emphasizes the viability and benefits of utilizing solar-powered irrigation systems to promote sustainable agricultural water practices management. Huang et al. [67] address sewer system planning limitations, like non-quantifiability, fuzzy objectives, and decision-making variable uncertainties.

Multi-objective, nonlinear, mixed-integer, and compromise-fuzzy programming determine decision-making variables and provide a framework for optimal planning. The study found that a compromise-fuzzy-based MOP method can build a regional sewer system plan that meets effluent standards while maximizing the in-plant establishment value and minimizing costs [67,68].

6.3. Energy-Efficient Solar Desalination Technologies

Energy-efficient solar desalination technologies have revolutionized sustainable water desalination techniques. These innovative solutions address freshwater scarcity and offer greener alternatives to conventional desalination techniques that utilize solar energy. Wilson et al. [69] experimented with a low-cost and efficient 3D solar steam generator (ISSG) design for seawater desalination. Utilizing readily obtainable materials, such as diesel soot, PVA sponges, chopsticks, and air-laid paper, the generator achieved an impressive evaporation rate of 3.81 kg m^{-2} h^{-1} under one sun illumination. The proposed design offers a promising solution to address global water scarcity, with the DSp-PVA-3D-6 configuration demonstrating a stable and durable performance for continuous desalination operations, producing freshwater at a rate of approximately 2 L m^{-2} h^{-1} in outdoor experiments. Future work will aim to enhance the evaporation rates and water transportation mechanisms. Ahmed et al. [70] discussed the importance of desalination in arid regions, the energy demands of desalination systems, and the potential for integrating solar power into this technology. The study emphasizes the advantages of this integration, such as reduced dependence on fossil fuels and a cleaner environment. This review highlights the need for further research and development to achieve sustainability and address the challenges associated with renewable-energy-based desalination systems.

Li et al. [71] discussed a unique BiOI-FD-CuO interface evaporator, combining a superhydrophobic BiOI floating layer and a CuO polyurethane sponge. It achieved efficient solar desalination and sewage purification with a remarkable photothermal evaporation rate of 2.37 kg m^{-2} h^{-1}, thereby addressing the challenges of pollutant degradation and salt crystallization. This innovative design offers practical solutions for large-scale desalination and wastewater treatment applications and provides effective and sustainable solutions to environmental issues. Menon et al. [72] reread the potential of renewable-energy-based desalination to shift towards a more sustainable approach that highlights solar energy as a capable solution for the production of decarbonizing water and evaluating the water cost of water for various solar desalination configurations compared to fossil-fuel-driven plants. The analysis also indicated a positive outlook for desalination as solar generation and storage costs will decrease by 2030.

Tunsound et al. [73] examined the development of electro spun composite-membrane evaporators for solar desalination and steam generation. The composite membranes achieved a remarkable evaporation rate of up to ~79% for saline water concentration (21.00 wt% NaCl) and reached a maximum rate of 2.42 kg m^{-2} h^{-1} at 1.35 sun. Additionally, the membranes demonstrated outstanding reusability, with a water mass variation of over 90% after 10 cycles. These findings present a promising approach to efficient solar-driven freshwater generation and desalination. He et al. [74] investigated solar interfacial-heating desalination (SIHD), which showed great potential for addressing freshwater scarcity. However, managing high-salinity brine and optimizing water production remains a key challenge. This review covers recent developments in the handling of high-salinity brine during SIHD and categorizes various strategies. It also discusses the principles, comparative analysis, and optimization techniques for enhancing water production, while highlighting the tasks and future research prospects in interfacial-heating solar desalination.

Wijewardane et al. [75] reviewed advancements in solar desalination technology, focusing on inventions, innovations, and their potential for commercialization to address clean water scarcity. With an estimated two-thirds of the global population being impacted by water scarcity by 2025, solar desalination offers a sustainable approach to tackle this challenge. Interfacial solar evaporation systems have attracted significant research interest owing to their efficiency in utilizing solar energy for water production. Ongoing efforts aim to overcome these challenges and optimize the scalability and cost-effectiveness of these innovative solar-driven solutions. Burhan et al. [76] developed a common platform using long-term ratings (LTR) and standard solar energy (SSE) to compare three practical solar harvesters. The comparison considers the efficacy of each system despite variations in the optical and work cycles. For instance, in the case of solar-powered seawater desalination, the SSE required per m^3 for stationary PV, concentrated PV (CPV), and concentrated solar power (CSP) systems are 6.49, 2.36, and 2.99, respectively. This approach compares solar technologies based on their true system potential and efficiency.

Elhenawy et al. [77] experimented by integrating a system to determine desalination using solar energy into hybrid water that combines the technologies of membrane distillation (MEE-MD) and thermal desalination. The expertise was established using the multi-effect evaporation (MEE) and air-gap membrane distillation (AGMD) structures. Outdoor testing revealed that the hybrid MEE/MD configuration outperformed the unconnected multi-consequence evaporation unit by 45%. The proposed hybrid system can produce 159.84 m^3 of fresh potable water annually at USD 5.37/m^3 and reduce carbon dioxide emissions by 189 tons annually. He et al. [78] reviewed the integration of solar photovoltaic-thermal (PVT) technology with desalination processes to improve efficiency and productivity. The combined use of PVT panels and desalination offers a practical and cost-effective solution, potentially reducing expenses by up to 20% compared to current methods. This approach aims to enhance solar energy efficiency and enable operational independence for off-grid applications.

7. Solar Panels in Sustainable Urban Planning

Solar panels are being increasingly incorporated into sustainable urban planning initiatives worldwide. Smart cities and public parks are increasingly adopting solar technology, paving the way for urban landscapes that are greener and more energy efficient. Incorporating solar panels into urban planning reduces the carbon footprint and encourages the adoption of renewable energy sources for a more sustainable and environmentally conscious future.

7.1. Solar Energy in Urban Development Strategies

Solar energy has driven the development of eco-friendly cities. Solar panels can optimize energy use, reduce greenhouse gas emissions, and clean cities. Li et al. [79] determined how the urban form affects solar radiation in Nanjing using two-hundred samples from eight block types. Urban density negatively affected solar radiation; whereas, the newly proposed BSR parameter was significantly correlated with building density and sky visibility. Certain layouts performed better in different seasons, with the U-shaped type having the highest annual average PV utilization potential of 143 kWh/m^2, and both FAR and BSR significantly influenced PV utilization (r^2 of 0.94 and 0.83, respectively). Kaleshwar et al. [80] evaluated the performance of solar energy in five different urban build forms (UBFs) based on local climatic zones (LCZs) in Nagpur, India. Using indicators related to density, open spaces, buildings, streets, and vegetation, digitized 3-D models and solar simulations were employed using the Grasshopper and Ladybug plugins. This study shows that the UBF significantly affects the probability of solar energy. The procedures used can aid in creating urban solar maps, providing valuable insights for decisionmaking and planning for retrofitting solar panels in precise urban settings. Guillén-Lambea et al. [81] suggested a practice to determine the self-sufficiency of energy in urban areas using the energy self-sufficiency urban module (ESSUM) concept in Zaragoza, Spain; geographical information systems (GIS), LiDAR point clouds, and cadastral data were utilized to determine the self-sufficiency capacity. The results indicate that 21% of the available rooftop area can achieve total independence of domestic hot water (DHW) while dedicating the balance of the area on the rooftop to photovoltaic (PV) can influence self-sufficiency electricity by 20%, resulting in significant CO_2 emission reduction (12,695.40 t CO_2eq/y) and energy hoards (372,468.5 GJ/y). It is justified to install solar panels, even in buildings with historical value, as they reduce operational charges and pay for the preservation of structures through this new energy source [82].

Liu et al. [83] adopted the Grasshopper platform to analyze a multi-objective urban form design optimization framework in Jianhu, China, considering the minimum building energy consumption, maximum solar potential, and sunlight hours. The Ladybug Tools plugin was employed for performance simulation, revealing correlations between urban form factors and building energy consumption (e.g., BD, OSR, SC, and PAR) and rooftop PV energy generation (e.g., FAR, BD, AF, OSR, SC, PAR, and SVF). Future research should consider different functional blocks, address simulation time issues, and incorporate microclimate and landscape layout factors. Cantoni et al. [84] conducted interviews and population surveys in Cape Town, Burkina Faso, Ouagadougou, and South Africa; this fieldwork-based study used a hybrid theoretical framework to analyze electricity access in peripheral areas. The research highlights the importance of the technological design, planned scale, and scope of solar energy projects in determining their benefits for local communities, providing valuable guidance for policymakers and renewable energy companies to address energy justice issues. Kumar [85] conducted a spatial variability analysis of solar energy resources in southern India. Using geostatistical models and time series studies with Meteosat satellite-derived datasets from the NREL, the region was classified into five suitability classes for solar energy resources. The results show an average annual GHI of 690.051 GWh/m^2 and DNI of 617.580 GWh/m^2, indicating ample solar potential for future urban applications, supporting sustainable energy resources, and contributing to infrastructural development in the area.

Jo et al. [86] determined the global and local effects of climate change caused by buildings in urban areas. This study introduced a new methodology using remote sensing data and building energy simulations to evaluate the potential benefits of installing reflective roofs. The results show that 73% of the buildings in the study area can benefit from cool roof systems, leading to an annual electricity reduction of 4.3% (7830 MWh), peak electrical demand reduction of 555 kW, and annual reductions of 3823 tons of CO_2, 5.29 tons of NO_x, and 3.52 tons of SO_2 emissions. This study underscores the potential economic and environmental advantages of implementing cool roof systems for sustainable urban development. Xie et al. [87] evaluated the impact of urban morphology on building energy consumption and solar energy generation potential for university dormitory blocks in Wuhan, China. The authors of the research classified block types and analyzed the correlations between urban morphology and energy performance indicators (EUI, SEGI, and NEUI) for 55 blocks. The results demonstrated that different block types could lead to a 12.25% difference in the EUI and a 35.85% significant difference in the NEUI with PV panel deployment, offering valuable guidelines for enhancing building energy conservation and clean energy policies at the block scale in Wuhan and similar regions. Ranalli et al. (2018) [88] investigated the challenges of increasing distributed solar energy capacity in urban areas. A spatial decision-support system (SDSS) workflow was proposed to aid stakeholder planning and communication. The workflow generates quantified results for economic and technical parameters, facilitating informed decisionmaking in the renewable energy sector. With the potential to identify suitable deployment sites, encourage policy development, and foster data-based decisionmaking, SDSSs offers valuable support for sustainable urban energy planning.

7.2. Solar Panel Applications in Smart Cities

Solar panels are indicators of environmental responsibility within the imagined landscapes of smart cities that convert urban areas into renewable energy centers. These solar energy options open the door to cleaner, smarter, and more resilient urban environments when integrated into smart infrastructure. Current practices, regulations, and urban development guidelines in many countries do not provide a sufficient foundation for implementing a smart city model [89]. Integrating solar vehicles within the framework of smart cities is a visionary step. By utilizing solar panels as a power source, these vehicles contribute to sustainable transportation and conform to the eco-friendly ethos of contemporary urban landscapes, fostering a symbiotic relationship between renewable energy and urban mobility [90]. Kappagantu et al. [91] analyzed the barriers to implementing rooftop solar PV systems in the Puducherry smart grid pilot project involving 5000 electricity consumers. The results indicated that installing rooftop solar power for these consumers would establish a 5 MW capacity, support power generation for the Puducherry Electricity Department, reduce losses, fulfill a 5 MW renewable power obligation (RPO), and benefit from the net metering feature of smart meters. Puducherry's commitment to solar energy and a favorable environment for energy innovation may exemplify India's transition to renewables. Byrne et al. [92] evaluated solar cities using an assessment method to estimate the solar electric potential of overlooked rooftop spaces. An illustrative case study conducted in Seoul, South Korea, representing a significant portion of the country's population and economic activity, reveals that the widespread deployment of rooftop-based PV systems could supply nearly 30% of the city's annual electricity consumption. Moreover, on a typical day, 66% of Seoul's daylight-hour electricity needs can be met by distributed solar power systems, indicating a considerable potential for reducing pressure on the city's electricity grid.

Abu-Rayash et al. [93] developed an integrated solar energy system in a small city with 5000 homes, achieving overall exergy and energy efficiencies of 49.2% and 53.4%, respectively. This method consumes intense solar power, PV thermal technology, organic Rankins, and absorption refrigeration to offer electricity, cooling, and heating solutions. The CSP farm had the highest exergy destruction rate of 46%. Simultaneously, electricity production from PV and organic Rankine systems contributed significantly to environmental impacts, representing the highest impact potential in categories such as global warming and acidification. Hsiao et al. [94] recommended using robotic fiber spinning and graphene silk materials to create solar panels of graphene silk thin films. Studies have revealed that feeding silkworms with an aqueous solution containing graphene doubles the efficiency since the carbon nanotubes increased the durability of the spit silk and the carbonized silk's conductivity by approximately 10 times. This biologically autonomous solution addresses the pollution problem of traditional solar panels at smart bus stops and offers promising opportunities for sustainable infrastructure development. Dispenza et al. [95] designed, validated, and realized a solar-powered hydrogen fueling station in Capo d'Orlando, Sicily. This station features a 100 kW rooftop PV plant and a 300 kWh battery energy storage system, providing energy to an on-site hydrogen production plant. The hydrogen fueling station, with subsystems for electrolysis-based hydrogen production, compression, high-pressure storage, and automotive dispensing, produces 6.64 Nm^3/h of 99.995% pure hydrogen. The successful results from the initial test campaign demonstrated the promising potential of this smart city application for achieving sustainable transportation solutions. Figure 4 illustrates the application of solar panels in smart cities.

Calvillo et al. [96] lead an inclusive evaluation of energy-related planning and operation models, categorizing them into four main interventions: transport, generation, storage, and facilities. Promising trends have been identified, such as the increasing presence of distributed generation (DG) with energy storage and renewable sources, the adoption of energy-efficient facilities with advanced control systems, and the growing utilization of microgrids and smart grid paradigms. These advancements signify the potential of smart cities to integrate sustainable and efficient energy systems.

Varghese [97] determined the concept of smart cities in India by focusing on the proposed city of Dholera in Gujarat. The government's intention to attract foreign direct investment and upgrade infrastructure for development was evident. However, the lack of elaboration on rural areas and the potential infringement of constitutional freedoms raises concerns. The first smart city's initial challenges highlighted the uncertainties in scaling up 100 smart cities. Considering the country's existing deficiencies, exploring indigenous solutions, such as Dr Abdul Kalam's smart villages, may offer a more inclusive approach to addressing wider-ranging problems effectively. Modern solar micro installations cannot store a large amount of surplus energy, a solution could be energy storage systems for energy storage [98].

Figure 4. Utilizing Solar Panels in Smart cities.

Behzadi et al. [99] introduced a smart building energy system incorporating PVT panels and a heat storage tank to increase renewable energy utilization, reduce energy costs, and enhance reliability. A thorough thermodynamic analysis was performed on a real case study house in Esbjerg, Denmark, to assess the feasibility and efficiency of the system. The PVT panels generate 3647.4 kWh of annual electricity with 14% overall energy efficiency, achieving a yearly energy utilization factor of 0.61 and effectively meeting the domestic hot water demand while compensating for the building's energy costs.

Mosannenzadeh et al. [100] conducted empirical research on 43 European communities implementing smart energy city projects; this study provides a systematic classification and analysis of 35 barriers in various aspects, such as policy, administrative, financial, and technical. The prioritization of these barriers, using a novel multidimensional methodology, reveals key obstacles, including fragmented political support, lack of cooperation among partners, insufficient external financial support, and a shortage of skilled personnel. The findings can aid policymakers in successfully understanding and addressing these barriers to implementing smart energy city projects. Ghadami et al. [101] conducted an experiment in Mashhad, Iran, utilizing machine learning tools to assess electrical energy consumption with a remarkable 99% accuracy in forecasting, employing artificial neural network (ANN) and statistical analyses. This study presented innovative dynamic strategies based on expert knowledge to promote citizen participation in renewable energy generation. Prioritized motivational approaches include optimizing costs through energy sharing, implementing an energy coin system, reducing electricity costs, and offering valuable insights for smart city development in short- and long-term planning.

Mukilan et al. [102] explored power generation in a residential building using PV sensors and piezoelectric transducers integrated into floor tiles. Machine learning models, including the ARIMA time series, support vector machine (SVM), and k-nearest neighbor

(KNN), were used to analyze and predict the sensor performance, with a validation accuracy of 99.5% achieved by the ARIMA model. Despite some manufacturing, installation, and maintenance limitations, these energy-harvesting tiles offer an innovative and sustainable approach to power generation. Guo et al. [103] examined a peer-to-peer (P2P) energy trading strategy as a key to addressing peak electricity costs in residential areas. Three interconnected buildings incorporating solar panels and a hydrogen source engaged in P2P transactions to optimize energy consumption and reduce billing. The results indicate the usefulness of the planned system, with the risk-averse model generating 30 kW (18 kW in the risk-neutral model) of solar power, showcasing the potential benefits of renewable energy resources. Additionally, minimal variation was observed in hydrogen charging, discharging, and fuel cell electricity generation between the risk-averse and risk-neutral strategies, emphasizing the significance of the trading model of P2P in enhancing energy efficiency and resource utilization.

Ashwin et al. [104] investigated a smart bin equipped with an HC-SR04 Ultrasonic Sensor and TowerPro SG90 Servo Motor, which offers an automated solution for waste collection and segregating dry and wet household waste in smart cities. The smart bin operates efficiently by using solar panels producing 800 W of energy per day and a $LiFePO_4$ battery for storage, reducing 20% of the main electricity consumption. This waste management advancement benefits smart city dwellers by ensuring a cleaner environment and sustainable disposal. Yao et al. [105] introduced a multi-objective robust optimization framework to maximize EVs' economic and environmental assistance and integrate low-carbon electricity in smart cities. This method addresses uncertainties and reflects the benefits of numerous stakeholders in smart charging and discharging systems. The proposed strategy has positive outcomes, including enhanced clean energy utilization, cost savings, and load regulation. This shows its potential to foster sustainable and efficient energy management in smart city environments.

Mosannenzadeh et al. [106] developed a 5 W + 1 H model integrated with a literature review and expert knowledge. This study defined smart energy city development both theoretically and practically. This study presented a comprehensive conceptual framework outlining spatiotemporal scales, stakeholders, principles, objectives, and domains. It also offers practical answers and methodology for eight interventions, highlighting the significance of integrating smart energy solutions with sustainable approaches for successful city development. Yang et al. [107] incorporated distributed thermal energy resources into smart thermal grids (STGs) to improve efficiency and intelligent management. Integrating renewable resources and thermal energy storage (TES) in district heating (DH) technologies, a solar DH system with centralized and distributed TES significantly enhances overall efficiency, reducing heat losses, energy consumption, and greenhouse gas emissions. Optimization studies are recommended to ensure the cost-effective integration of distributed solar energy systems into a larger infrastructure.

Bandyopadhyay et al. [108] studied the impact of various circulated energy methodologies on the peak grid load, energy consumption, and residential sector emissions. The optimization framework considered lithium-ion batteries, solar panels, smart thermostats, and the storage of ice-cold thermal energy. The findings suggest that investing in solar panels and smart thermostats can effectively minimize the overall annual expenditure and environmental footprint. However, high capital costs and policy disincentives hinder the economic viability of storage systems for residential customers. Conversely, LIBs are beneficial for mitigating demand charges and controlling peak loads. Abas et al. [109] researched SlugCam, a solar-powered wireless smart camera network suitable for outdoor applications, such as video surveillance and environmental monitoring. Its energy efficiency is achieved through hardware optimization and adaptive software operation, leading to extended unattended deployment periods and low network bandwidth requirements. The open-source design and versatile functionality of SlugCam make it a promising solution for future outdoor video monitoring needs, as demonstrated through extensive power characterization and real-world deployments.

Sohani et al. [110] examined the effect of meteorological parameters on the photocurrent and thermal voltage of a 320 W polycrystalline solar panel, showing a 200% increase in solar radiation impact within the range of 500–1500 W m^{-2}. Furthermore, ambient temperature influenced the thermal voltage of the diode by 9.36% when changing from 27 to 47 °C. The photocurrent was the most significant parameter in reducing CO_2 emissions, with 18.0% smaller and 14.6% greater CO_2 savings observed for photocurrent values 20% inferior and 20% more developed than the base circumstance, respectively, representing a 32.6% variation within the range. Qing Li et al. [111] assessed the degradation mechanism of perovskite solar cells (PSCs) to address their instability. They discovered that a halide diffusion equilibrium affects the performance of the device. The study found that diffused halides can contaminate the transport layer, reducing the efficiency of PV cells. In response, a strategy was developed to achieve halide diffusion equilibrium, resulting in an efficiency of 23.13% and a stable power output under continuous one-sun illumination [111]. Zhao et al. [112] improved organic solar cell power-conversion efficiency (PCE) by increasing the charge-carrier diffusion length (LD) in an organic bulk heterojunction (BHJ). They added F1, a fullerene liquid crystal, to the active layer to improve charge-carrier transport and energetic disorder. The PM6:Y6: F1 ternary OSCs had a 15.23% PCE with an active layer thickness near 500 nm [112].

7.3. Solar-Powered Public Spaces and Parks

Solar-powered public spaces and parks are illuminated by environmentally friendly architecture, embracing nature's abundant energy while illuminating urban parks. Stock et al. [113] demonstrated that climate change mitigation, rural electrification, and solar park development in India cause social friction, particularly in Gujarat Solar Park, where marginalized populations bear disproportionate burdens. This study examines how the socio-material accumulation of water and electrical infrastructure unevenly distributes surreptitious burdens across differently positioned peasants, posing threats to food security and exacerbating water scarcity.

Obaideen et al. [114] highlighted the impact of energy supply and demand on the social, economic, and environmental aspects. In response, decision makers are adopting sustainable development goals (SDGs) to guide policies towards sustainability. The given study emphasizes the allocation of solar energy themes within the SDGs. It analyzes its contributions, particularly in the Mohammed bin Rashid Al Maktoum (MBR) Solar Park in the United Arab Emirates, which has mitigated 6.5 million tons of carbon dioxide and achieved several SDGs.

Sekyere et al. [115] investigated a 20 MW solar PV plant located in the southern part of Ghana, near the Gulf of Guinea, which was analyzed using both PVsyst simulation and monitored data from 2018. Based on the monitored data, the plant delivered 26,480 MWh of energy to the grid; whereas, the simulations projected 29,154 MWh annually. The findings provide valuable insights into performance statistics, with a 72.8% to 80.2% performance ratio and a 15.1% to 16.6% capacity factor. The system efficiency ranged from 11.39% to 12.32% and the carbon emission savings reached 12,181 metric tons in 2018. These results can guide future large-scale solar projects in coastal tropical regions, including Ghana's southern part. Golroodbari et al. [116] conducted a techno-economic analysis that evaluated the viability of combining an offshore floating solar farm with a Dutch offshore wind farm in the North Sea. By using cable pooling to optimize cable capacity, the anti-correlation between solar and wind resources minimizes curtailment issues. The findings demonstrate the potential benefits of integrating solar and wind systems in terms of technical efficiency and economic returns, with optimally combined capacities that depend on meteorological conditions and cost factors.

For over a year, Wei et al. [117] deployed a prototype solar-powered air monitoring system called the Village Green Project (VGP) on a school rooftop in Hong Kong. It recorded approximately 330,000 1-min observations (data completeness of ~62%) of ozone, PM2.5, and meteorological parameters, exhibiting good performance for a 1-h resolution with

R^2 values of 0.74 for PM2.5 and 0.76 for ozone when compared with the nearby Hong Kong Environment Protection Department (EPD) station. The combination of the VGP and nonparametric trajectory analysis (NTA) models successfully identified local pollution sources in urban areas, demonstrating the potential for effective air quality monitoring and source identification. Mohamed et al. [118] evaluated the economic viability of Benban Solar Park, a 1600 MW AC grid-connected PV project in Benban, considering its annual electricity output of 3.8 TWh annually. The analysis showed an economically feasible electricity cost of USD 8.1 per kWh with a 10.1-year payback period at a 12% interest rate. Moreover, solar parks will mitigate nearly 1.2 million tons of greenhouse gas emissions annually. This investigation suggests that agrivoltaic systems are potential movement directions for the project's feasibility.

Chen et al. [119] distinguished the viability of consuming radiating solar-produced electricity in Qingdao, China as a supporting authority for electric buses, considering 547 bus routes and 28,661 street-view scenarios. The findings indicate that electricity from solar radiation contributes to approximately one-eighth and one-fifth of a bus's overall electricity usage per kilometer on sunny and cloudy days, respectively. The proposed framework offers insight into the feasibility of integrating solar power into electric bus fleets, thereby supporting effective planning decisions for extensive urban areas at diverse locations and times. Stock et al. [120] examined Gujarat Solar Park and Kurnool Solar Park in India. This study investigated the resistance to land acquisition and agrarian system transformations. Various forms of resistance 'from below,' such as protests, blockades, and lawsuits, challenge the impact of solar park development on livelihoods. While corporate social responsibility efforts attempt to appease discontent, they fail to address the underlying political claims and resistance persists. Carlisle et al. [121] examined public support for large-scale solar developments in six Southern Californian counties (Inyo, Kern, Riverside, San Bernardino, San Luis Obispo, and Ventura). Findings from a 2013 telephone survey (N = 695) revealed that visual impact and proximity to different types of land significantly influenced the support. Preferences for buffer sizes and proximity contrasts depended on the type of land considered, highlighting the complexity of the factors shaping support for solar facilities.

7.4. Solar Panels and Urban Agriculture

The presence of solar panels creates a specific microclimate, thus altering the living conditions of the vegetation [122]. Changes in the species spectrum of vegetation induced by the microclimate are particularly evident in solar parks established in agricultural landscapes [122]. According to Dupraz et al. [123], society must face the choice of increasing energy or food demand. Therefore, they posed the question of whether land should be divided into areas designated for crop cultivation and those for energy production. Alternatively, we should attempt to find a way to combine food production and energy generation on the same land. The answer might lie in the agrivoltaic, combining crop cultivation and solar panels. Thomas et al. [124] focused on solar parks and mega solar projects to accelerate renewable energy integration while mitigating the socio-economic and environmental impacts on local livelihoods. By incorporating agrivoltaics, the analysis identifies potential income improvements of 8% to 83% through medicinal plants, poultry, and beekeeping, providing sustainable solutions for societal implications and energy transitions. These findings emphasize the significance of considering agrivoltaic as a self-healing mechanism that promotes environmental and social benefits in solar projects.

Agrivoltaic farms have been established in Italy (capacity 800–1500 kWp), the USA (capacity 550 MWp), and China (capacity 700 MWp) [125]. Solar panels create a persistent shade that most cultivated crops can adapt to, primarily due to the lower water losses observed under the panels than in traditional agriculture [126]. Agrivoltaic farms produce rosemary, oregano, savory, thyme, legumes, chili peppers, tomatoes, potatoes, etc. [127]. The water use efficiency of traditional agrosystems is 157% lower than in agrivoltaic systems. Carefully selecting crops for agrivoltaic can also enhance economic efficiency [128,129].

These results indicate that combining solar panels with crop production can increase land utilization efficiency [130]. Nowak et al. [131] called for collaboration between botanists and engineers in solar projects to preserve biological diversity and promote the trend of ecovoltaics. An additional benefit of vegetation within solar installations is carbon sequestration [132]; however, as noted by Lambert et al. [133], several ecosystem functions in solar parks are limited, including carbon sequestration.

The unavailability of food triggers another urban trend, urban agriculture, which contributes to food security [134]. Implementing urban agriculture holds architectural and urban potential regarding the functional use of green spaces, enriching public areas, and increasing green zones within dense urban environments [135]. The pressure of regional food availability can lead to the application of agrivoltaic technology in urban agriculture. The primary benefits of this combination include improved water management, employment opportunities, enhanced local food security, and increased energy independence. This will promote self-sufficiency in cities and urban neighborhoods.

8. Solar Panels in Construction Materials

Incorporating solar panels into building materials represents a revolutionary step towards sustainable building practices. Façade systems and solar-powered building envelope solutions demonstrate the seamless integration of solar technology into the fabric of buildings, generating clean electricity while preserving aesthetic appeal.

8.1. Solar-Active Façade Systems

Solar-active façade systems exemplify an innovative and eco-aware approach to building design. By incorporating solar panels into the exterior of buildings, these systems efficiently harness solar energy while enhancing the aesthetic appeal and green credentials of the architectural design. Vassiliades et al. [136] studied the effects of integrating the active solar energy method on prevailing façades in Thessaloniki, Greece and in Naples, Italy to examine thermal comfort in public spaces. The physiological equivalent temperature was used to evaluate street-level thermal conditions before and after integration, utilizing the Envi-MET software. The research aims to suggest the most feasible combination of urban practices and building integration strategies to enhance thermal conditions in public spaces in these coastal cities. Tariq et al. [137] presented a novel recommendation system for integrating a solar chimney with PCM-based passive energy storage in buildings, exemplified by a digital twin generation process. The results indicate that the optimized configurations vary based on the climatic zone, with ventilation rates ranging from 2.19 1/h to 4.9 1/h and energy efficiencies from 37.6% to 40.33%. This study highlights the significance of digital data engineering and its impact on global solutions for energy-efficient building design.

Giovanardi et al. [138] analyzed different building typologies as potential applications for the UST collector, optimizing the collector field to match the specific heat load profiles. Using TRNSYS software (TRNSYS 16), the authors evaluated the innovative thermal façade component's thermal behavior and the energy potential in a combined system. The researchers concluded that its low cost, modularity, and easy installation make it a promising technology for building transformation, despite the lower energy quality owing to the unglazed collector's low output temperature. Noaman et al. [139] demonstrated the integration of passive solar design strategies (PSDSs) with active solar cooling technology (ASCT) in a façade. The results showed that passively designed façades can reduce cooling claims by 43–65.70% and integrating sloped solar thermal collectors at a tilt angle of 30° proved to be the greatest efficient choice for most orientations, requiring a façade width ratio of 74–84.30% to meet cooling demands. However, vertical STCs cannot satisfy the cooling demands in this context. Vanaga et al. [140] discussed dynamic solar façade systems with energy storage to meet building cooling and heating demands. The consequences designate that the suggested solar façade module reduces the energy demand throughout the cooling season related to the reference triple-glazed window. However, further enhancements are required to optimize performance throughout the heating season. This underscores the significance of integrating passive and active solar design strategies to create sustainable and energy-efficient buildings.

Tariq et al. [141] determined the sustainability of low-budget social houses in Mexico, where over 100,000 houses were built in 2021, without strict adherence to energy codes. A novel integrated sustainability framework that considers energy, economic, environmental, and social aspects was proposed. The results demonstrate that intelligent integration of a double-façade architecture with advanced air conditioning systems can achieve up to a 48% increase in thermal comfort while reducing CO_2 emissions by approximately 5668.59 kg/year. These findings highlight the need for government regulations to promote sustainable building practices in social housing projects. Li et al. [142] suggested an integrated active solar thermal façade (ASTF) system by investigating its thermal performance, achieving 44.60% and 45.30% heat collection efficiencies on sunny and cloudy summer days and 55% and 35.50% efficiencies on sunny and cloudy winter days, respectively. The ASTF system demonstrates the compensations of active energy supply and passive energy saving, making it a promising solution for hot summer and cold winter regions.

Yongga et al. [143] presented a solar thermal façade system to minimize building energy usage while ensuring indoor comfort in hot summer and cold winter regions. Tests conducted under various weather conditions demonstrated significant reductions in indoor air temperature of 8.9 °C during cooling and increases of 8.0 °C during heating compared to stagnation conditions. These findings highlight the potential of this innovative solar façade system to contribute to energy-saving building designs and create pleasant indoor environments. Liang et al. [144] investigated an innovative active solar building façade system that generates domestic hot water and electricity. Utilizing PV/thermal modules as opaque ventilated façades significantly reduces the heat transfer into the building envelope by 40% and achieves an average PV conversion efficiency of 9%. With a coefficient of performance of 3.1, the system demonstrates promising potential for enhancing the thermal properties of buildings and providing sustainable energy solutions.

Italos et al. [145] assessed the energy recital of a residential apartment building in Limassol, Cyprus, before and after energy renovation, incorporating a double-skin façade and active solar energy systems. Through digital energy simulations, the proposed systems' impact on cooling, heating, and artificial lighting loads was examined, resulting in an impressive 83.5% reduction in energy consumption from 94,321 kWh to 15,563 kWh, annually. Integrating these innovative systems has proven to be a cost-efficient solution for refurbishing buildings in the southeastern Mediterranean region.

8.2. Solar-Powered Building Envelope Solutions

Solar-powered building envelope solutions have redefined energy-efficient building designs by integrating solar panels seamlessly into roofs and walls. These innovative solutions optimize energy capture, reduce a building's environmental impact, and embrace sustainable design at the innovation frontier. Wang et al. [146] investigated phase change materials (PCMs) proving that building energy efficiency has rapidly advanced. However, static PCM-built envelopes lack heat storage and flexibility, which results in low efficiency. Innovative adaptive dynamic building envelopes integrated with PCMs (ADBEIPCM) address this issue by utilizing rotating, moving, flipping, and controlling vents to efficiently store solar energy, release heat, reduce building loads, and enhance comfort. Future research should focus on developing novel PCMs with high strength and stability, AI-based control strategies, and bionic technology-powered ADBEIPCMs using renewable energies to improve further building energy efficiency. Luo et al. [147] transformed a building envelope into a multifunctional component that controls the heat flux and provides additional heating/cooling energy. Integrating PV and thermoelectric modules with energy storage explores five different systems (S1–S5). These systems exhibit significant energy savings, with an average 30% reduction in annual power consumption, offering promising opportunities for sustainable building design.

Elghamry et al. [148] evaluated the influence of solar cells integrated into a building envelope on the power generation, energy consumption, comfort conditions, and CO_2 emissions within a building. Different positions, orientations, and locations were analyzed in New Borg El Arab, Alexandria, and Egypt. The findings show that solar cells on the façade and roof can reduce energy ingesting by approximately 15% and 40%, respectively, and that a south-facing cell on the roof generates the highest annual power. A cell fronting south also affords contented interior situations and a north-facing cell on the façade yields the lowest CO_2 emissions.

Zhou et al. [149] determined that a building envelope design featuring a dynamic Trombe wall with a PCM was introduced to harness passive solar energy for heating buildings efficiently. The pioneering multi-panel solar collector storage wall allows the independent rotation of a panel to optimize solar irradiation utilization. The experimental results demonstrate that this new envelope is 20% more thermally efficient than a companion envelope with a static Trombe wall, resulting in potential energy savings from nonrenewable sources over the building's design life.

Vakilinezhad et al. [150] conducted an in-depth analysis of TC and RM coatings combined with passive strategies on the surfaces of residential buildings. The results revealed that the thermal behavior and energy performance depend highly on the climatic conditions and insulation thickness. In Ahvaz's hot, arid climate, the retroreflective coating on south-facing surfaces reduced cooling loads by approximately 26%, surpassing the winter heating demand. In Shiraz, a hot-semi arid climate, the combination of retroreflective and thermochromic coatings resulted in an 18% reduction in cooling or heating loads, leading to an overall 14% decrease in energy consumption. These findings highlight the significance of tailored coating applications for optimizing energy efficiency in different climate regions.

Qiu et al. [151] emphasized the importance of a passive solar design in achieving energy efficiency for office buildings in hot and humid climates. By integrating data mining techniques and parametric energy simulations, this study identified the glazing system, window-to-wall ratio, and coating on the roof as the top three critical enterprise parameters, with significance notches of 0.12970, 0.4858, and 0.3197, respectively. These findings offer valuable guidance for architects and policymakers to prioritize energy-saving measures and achieve sustainable design principles for office buildings in locations such as Guangzhou. The advanced simulation-built data mining technique can also be extended to additional building categories and weather conditions for energy-efficient designs.

Weerasinghe et al. [152] studied the growth of solar building envelopes, or building-integrated PV (BIPV), which has been important in Asia and Europe; meanwhile, in Australia, it has been rather neglected. A machine learning model using real BIPV and building-attached PV (BAPV) data, particularly in Australia, could guide stakeholders in making informed decisions for investment, policymaking, and research to promote BIPV implementation and achieve greenhouse targets.

Li et al. [153] introduced a solar building integrating photocatalysis and TCES, achieving the double purpose of space heating and formaldehyde degradation with a thermal efficiency of 66%. The system simultaneously demonstrates significant potential for space heating and the purification of air, with an impressive formaldehyde degradation rate of 8.9425 μg/s.

Li et al. [154] established the reaction kinetics for thermochemical sorbents, intending to develop models for numerical simulations. A solar building envelope united the photocatalysis and energy storage of thermochemicals and achieved an impressive total efficiency of approximately 81% under 600 W/m^2 solar radiation, demonstrating promising integration possibilities. Gholamian et al. [155] suggested a hybrid solar-based energy system incorporating phase change materials (PCMs) to combat the building division's substantial energy ingestion and discharge. By integrating PCMs, the system achieved a remarkable decrease of 27% in the demands of cooling and heating, improving the overall productivity of the plant by cost for unit product by 28.54%, exergy efficiency by 13%, usage of fuel by 18.42%, and in terms of fuel consumption, respectively. This approach shows promise for curbing energy usage and enhancing building sustainability.

Winkler et al. [156] and Vaverková [129] indicated an important problem related to the location of PV farms in open areas and cities, regarding fire hazards in terms of both the installations themselves and the vegetation occurring on these facilities. Appropriate plant management is necessary in this regard.

9. Environmental Impact

Solar energy systems generate power without noise or chemicals. However, the associated land use can degrade the habitat. Solar cell manufacturing is harmful, and solar thermal plants can strain water resources. Battery disposal and energy-intensive solar system construction are also important environmental issues. Sustainable and environmentally responsible solar energy implementation requires technologies, guidelines, and impact assessments to mitigate these impacts [157].

Tsang et al. [158] examined the cradle-to-grave impacts of organic PVs versus conventional silicon solar cells. According to research, organic PVs have a smaller environmental footprint and shorter energy and carbon payback times than silicon. The study also discovered that the advantages extend beyond the panel manufacturing process, with the cradle-to-grave impacts for long-term and short-term uses being 55% and 70% lower than those of silicon devices, respectively. A study by Oteng et al. [159] examined the environmental effects of monocrystalline and multicrystalline silicon solar panel waste modules in Australia. The research determined that mandatory product stewardship scenarios have a global warming potential of -1×10^6 kgCO_2eq for mono c-Si solar modules and -2×10^6 kgCO_2eq for multi c-Si solar modules. However, the collection and recycling of most multi-c-Si panels are ineffective. This research provides the first framework for life cycle assessment in policy and transportation-related analyses.

10. Architectural and Economic Impact

Incorporating solar panels into buildings provides substantial long-term financial benefits, such as reduced energy costs, employment opportunities during installation and maintenance, and increased property values [160]. This integration can stimulate local economies and make properties more appealing to prospective buyers, increasing resale values [161].

A study conducted by D'Adamo et al. [162] evaluated Italy's PV market, focusing on subsidies introduced for plants with a capacity above 20 kW. The authors used a discounted cash flow methodology to determine critical variables like insolation, plant size, self-consumption share, investment cost, and electricity purchase price. Break-even point analysis revealed profitability in most cases and half of the alternative scenarios, consistent with investments aiming to increase the self-consumed energy share [162]. Zeraatpisheh et al. [163] investigated the financial viability of PV systems in three buildings. They used EnergyPlus to simulate these structures and compare various solar system sizes. The results indicate that demand charge tariffs do not justify using PV systems, even considering maintenance costs. The profitability index for all three structures falls between 0.2 and 0.8 and larger systems are less cost-effective when demand charges are present [163].

11. Future Trends and Challenges

The future of solar panels in the construction industry exhibits promising trends and presents numerous challenges. Advancements in solar panel technology, seamless integration with building design, and improved energy storage solutions are among the trends anticipated to drive widespread adoption. To fully utilize the potential of solar energy and create a sustainable built environment, it is necessary to address issues related to initial costs, grid integration, and aesthetics:

(i) Solar panel technology is likely to continue to advance for solar panels utilized in the construction industry. Solar panels will become more accessible and cost-effective for building owners and developers owing to efforts to improve solar efficiency, reduce manufacturing costs, and enhance energy-storage capabilities;

(ii) The seamless integration of solar panels into building designs is an important future trend. As architects and engineers integrate solar solutions earlier in the construction planning process, buildings can maximize solar energy capture while maintaining aesthetically pleasing designs;

(iii) For buildings to store excess solar energy, advancements in energy storage technologies, such as improved battery systems and grid-scale storage solutions, are essential. In addition, integrating smart grid technologies and advanced energy management systems will optimize the flow of electricity, thereby improving energy efficiency;

(iv) Numerous building owners, particularly in the commercial and industrial sectors, continue to find the initial cost of solar panel installation prohibitive. Innovative financing options and cost-competitive solar technologies are required to overcome this challenge;

(v) Integrating solar panels into the design of a building while preserving architectural aesthetics is challenging. Future trends will concentrate on creating solar panel options that are visually appealing and adaptable, allowing them to blend into a variety of architectural styles;

(vi) A method to reduce the competitive pressure between solar energy production and food production is explored. One of the trends is considering agrivoltaic in urban agriculture or using solar panels in vertical farming systems that produce food outside of agricultural land.

12. Conclusions

In pursuit of sustainability and a greener future, this review article proposes the widespread adoption of solar panels in the construction industry. The most significant conclusions drawn from the discussion are as follows:

(i) Solar energy has emerged as a major contributor to the worldwide adoption of renewable energy. Its exponential growth and applications in numerous industries, including construction, have demonstrated its critical role in combating climate change;

(ii) Solar energy systems provide eco-friendly power generation without noise or chemical emissions; but, environmental challenges, such as land use and manufacturing impacts, must be addressed. Adopting mitigating measures, such as technological advancements, guidelines, and impact assessments, is essential for sustainability;

(iii) According to new research, organic photovoltaics have several environmental advantages over silicon cells, including faster energy and carbon payback. Product responsibility is essential for the management of solar panel waste modules. These findings highlight the need for eco-conscious decisions and robust policies for the sustainable integration of solar energy in urban environments;

(iv) Incorporating solar panels into buildings presents a compelling long-term financial proposition, including reduced energy costs, employment opportunities during installation and maintenance, and a significant increase in property values. These advantages not only have the potential to stimulate local economies but could also increase the desirability of properties, thereby increasing their resale values;

(v) The comprehensive studies conducted underscored the importance of assessing the financial viability of solar panel installations. While one study demonstrates the profitability of such systems under various circumstances, another advises against employing them when demand charge tariffs are in place. These insights highlight the significance of well-informed decision-making when undertaking solar panel integration projects, balancing both financial incentives and constraints for a sustainable and economically sensible future;

(vi) Solar energy is becoming more accessible to building owners and developers as solar panel efficiency and cost-effectiveness continue to improve. This enables buildings to generate electricity on-site, promoting energy independence and reducing reliance on traditional grids. However, it also paves the way for smarter energy distribution and consumption, improving overall energy efficiency. In addition, solar panel integration plays a crucial role in reducing buildings' carbon footprints, mitigating air pollution, and conserving finite fossil fuel resources, aligning with global environmental preservation efforts;

(vii) Although there are many advantages, issues still need to be resolved before solar panels can be widely used in the building industry. These issues include high upfront costs, difficult grid integration, and aesthetic concerns.

In conclusion, this review article demonstrates that solar panels are no longer a futuristic concept but a practical solution that enables the construction industry to reduce its carbon footprint, achieve energy independence, and pave the way for a greener and more sustainable world. The adoption of solar energy is a shared responsibility for shaping a better future for future generations.

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