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REVIEW PAPER

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DEVELOPMENT OF ADVANCED SOLAR PANEL TECHNOLOGIES IN BUILDINGS – A REVIEW

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ABSTRACT

In recent years, the global energy landscape has been undergoing a significant transformation, with renewable energy sources gaining prominence. Among these, solar energy has emerged as a leading 'green energy' option, particularly in India, which is at the forefront of this renewable energy revolution. This article focuses on the increasing relevance of solar energy, underlined by the widespread adoption of solar power in various sectors, including residential, commercial, and industrial. The centrepiece of this solar energy boom is the solar panel, primarily installed on commercial buildings, which harnesses solar energy and converts it into electrical power. These panels are composed of a network of solar cells, each crafted from layers of silicon, phosphorous, and boron, meticulously arranged to optimise energy absorption and conversion. The paper delves into the technological progress in the field of solar panel systems, emphasising their growing integration in different types of buildings. It discusses how these advancements not only enhance energy efficiency but also contribute significantly to the development of a more sustainable and environmentally friendly energy future. The article presents a comprehensive overview of the current state of solar panel technology and its potential implications for shaping a greener energy landscape.

Keywords: solar panel, passive buildings, green energy, sustainability, renewable energy

INTRODUCTION

In recent years, solar energy has emerged as a notable renewable energy source. This surge in popularity is evident in the increasing adoption of it by residential, commercial, and industrial sectors, driven by its environmental sustainability (Vaverková et al., 2022; Vijayan et al., 2023). Often referred to as photovoltaic energy, solar power has seen a significant rise in installations, with a record 760 GW reached globally in 2020, including 139 GW added in that year alone. This growth coincides with advancements in solar technology and a shift in focus from traditional energy sources like coal and oil. Zander (2021) conducted a study in Darwin to analyse the usage patterns and the effectiveness of feed-in tariffs (FITs) in promoting domestic solar power production. The study aimed to identify barriers to solar panel adoption despite attractive incentives and to determine the average installation cost under the FIT scheme. A survey involving 652 respondents revealed that the primary deterrents were high installation costs, decreasing efficiency and storage capacity over time, and a 10% annual decline in interest in purchasing solar

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panels. The research indicated that an average FIT of 14.40 cents per 1 kWh was necessary, contrasting with the current subsidised rate of approximately 9 cents per 1 kWh (inclusive of goods and services tax), which falls short in offsetting additional battery expenses. The study also found that 40% of users with a 30% reliance on solar energy and 17% with a 60% dependence might discontinue using solar power if the existing policies were not revised. Solar panels have become increasingly significant in the construction industry due to their ability to provide sustainable and cost-effective energy solutions. Their integration into building designs, known as building-integrated photovoltaics (BIPV), not only reduces the carbon footprint of buildings but also enhances their aesthetic appeal. Solar panels contribute to the energy efficiency of buildings, lowering operational costs and increasing property value. Additionally, their use in construction aligns with global trends towards green building practices and helps in meeting environmental regulatory standards. This adoption signifies a critical step towards a more sustainable and eco-friendly construction sector.

Tarsitano, Ciancio and Coppi (2017) presented a study exploring the use of solar-powered absorption systems for air conditioning in residential buildings, emphasising the shift from non-renewable energy sources. The research involved a selected group of households to evaluate the efficacy of this technology in terms of energy savings, return on investment, and reduction in carbon emissions. The results of the study indicated that these solar-driven absorption air conditioning systems not only surpassed the performance of traditional methods but also contributed positively to environmental sustainability by utilising a limitless source of clean energy. Teodorescu and Vartires (2016) described the use of photovoltaics combined with thermal structures for domestic constructions with the help of TRANSOL software and EN 15316-4-3:2014 methods for simulation. In the beginning, solar voltaic usage was measured for domestic hot water (DHW) preparation and electrical and thermal requirements. The evaluation was performed on a combined structure of DHW and heating for its properties and solar fractions. The analyses were strictly made using TRANSOL and EN 15316-4-3:2014 standards (European Committee for Standardisation [CEN], 2014) and later compared with each other to get an optimal value. Saleheen Salema, Islam, Sarimuthu and Hasanet (2021) conducted a detailed study to validate the effectiveness of a goal-oriented prototype in the real-time operation of a 232.5 kWp grid-connected photovoltaic (GCPV) system, aimed at establishing a sustainable infrastructure for business operations in Malaysia. This research involved a comprehensive analysis to assess the performance and viability of the GCPV system in an actual business setting, demonstrating the practical application and scalability of solar energy solutions in enhancing the energy infrastructure within the region. The study underscores the potential of PV systems in contributing to the renewable energy landscape, particularly in commercial and industrial applications, by providing a reliable source of clean energy.

Oh and Son (2020) introduced a novel approach to designing community solar photovoltaic (PV) service plans for commercial buildings, aiming to achieve a harmonious balance between benefit, equity, and fairness. Utilising the Lagrangian relaxation and dual ascent methods, they iteratively found the optimal solution that enhances fairness in service distribution by up to 51% compared to strategies focused solely on maximising benefits. This methodology allows for a detailed breakdown of the advantages and equitable aspects of various service models, providing valuable insights for the development of community PV services that are both efficient and fair. This research highlights the importance of considering equity in the deployment of renewable energy solutions, ensuring that the benefits of solar energy are accessible and distributed fairly among all stakeholders. Sivaram, Premalatha and Arunagiri (2021) explored an innovative integration of passive solar energy techniques with PVs within the context of the CMS solar-powered greenhouse program. Their study introduced a solar still, a device designed to achieve multiple functions including air ventilation, energy generation, and water purification, all within a structural model. This model significantly reduced the airflow inside the structure by 30% during peak sunlight hours, aligning with the ANSI/ASHRAE Standard 62.1-2010 for indoor air quality and utilising GRIHA software to demonstrate its commercial feasibility. They further developed this method by adjusting the ductwork to utilise the thermal energy captured by the solar still to enhance air ventilation. This approach not only showcases the multifunctional benefits of incorporating solar energy into building designs but also emphasises the system's adaptability and potential for commercial application. The physical layout and satellite view of Monash University Malaysia, where this system was presumably tested or exemplified, are provided to illustrate the practical implementation of these concepts and are depicted in Figure 1.

Fig. 1. Monash University Malaysia's physical layout and satellite view

Source: Saleheen et al. (2021), CC BY-SA 3.0.

Liu, Yue, Lu and Li (2021) explored the impact of dust accumulation on PV panels in Wuhan, China, examining both the origins and development of dirt particles as well as their effects on the panels' efficiency. The study found that dust primarily originates from industrial emissions and urban pollution, including materials like sand, stone mortar, and dolomite, transported through the air and deposited on the panels. This accumulation of dirt reduces the panels' ability to transmit light, thereby decreasing their efficiency. The findings underscore the necessity for developing effective and sustainable methods for cleaning PV panels to maintain their performance.

Sheps, Golovinsky, Yaremenko and Shchukina (2021) investigated a novel passive solar panel technology that enhances energy generation by using thermal collection on the outer walls of buildings, specifically under the climatic conditions of central Russia. This approach allows for the conversion of absorbed solar energy into usable power, significantly improving a building's energy efficiency. The study also introduced a simplified computational model for analysing heat transfer dynamics in passive solar panels. By applying the principle of superposition of thermal waves, the research offers insights into optimising the thermal management of buildings to maximise solar energy utilisation. This advancement in passive solar technology presents a promising avenue for enhancing the sustainability and performance of energy systems in buildings.

Noorollahi, Khatibi and Eslami (2021) conducted a study to explore the feasibility of replacing natural gas with solar and wind energy at a national level, employing simulation techniques. The findings highlighted that all the methods investigated resulted in a significant reduction of carbon dioxide emissions, primarily due to the decreased consumption of natural gas. The study revealed that employing heat pumps to generate electricity from solar or wind sources led to an increase in the average total cost by approximately 127% and 326%, respectively. However, the use of solar thermal collectors was found to reduce the average total cost by about 13%. Given the existing natural gas infrastructure in Iran, the study concluded that the adoption of solar thermal collectors presents a viable and efficient alternative.

RESIDENTIAL BUILDINGS

In the context of residential buildings, solar panels play a pivotal role in promoting sustainable living and energy independence. They not only reduce electricity bills but also contribute to a greener environment by harnessing renewable solar energy. Sim and Suh (2021) conducted a study to assess the economic impact of integrating solar cells and ground source heat pumps (GSHP) in residential campus buildings in Korea. Recognising the significant energy-saving potential in these structures, the research aimed to optimise the life cycle cost (LCC) using DesignBuilder and EnergyPlus simulation tools. The study encompassed a comprehensive evaluation of various costs and impacts associated with the use of solar cells and GSHP. For practical insights, a residential case study in Korea, where seven experimental prototypes were examined, was selected. The analysis of these models provided a framework for the adoption of energy-efficient solutions tailored to specific conditions, highlighting the feasibility and benefits of such integrated systems.

Application

Fikru (2020) demonstrated the factors of reducing bills for consumers with domestic photovoltaics in four US states with the help of prototypes. The analysis was made through the prototypes considering their state situation, local rules, and the building's properties. The observation showed that higher savings were achieved with favourable policies to locate solar cells in areas with a greater potential for photovoltaic penetration, and areas with zip codes encouraging small-scale installations have much more savings during summer. The outcomes reveal that liberal policies to promote the use of solar panels are most effective. In conclusion, various factors that have an impact on electrical savings were discussed. Wang, Zheng and Cheng (2021) reported a testing method for the adoption of solar power to prepare hot water on a large scale, considering its environment-friendly approach in the domestic houses of China. The solar hot water system (SHWS) can reduce the dependence on conventional energy sources by 20%. An adaptability calculation prototype was prepared to find eight stable and six dynamic energy, and environmental impact characteristics. The observation showed that the primary focus subjects are solar radiation, solar fraction, installation area, payback period, and water supply temperature. Only a 25% change in the analysis index has little or no impact on the final result. The energy-economic-environment adaptability analysis method is the most trustworthy. The result also gave many vital points to encourage the adaptability of renewable sources of energy. Figure 2 illustrates an unglazed transpired solar collector system in operation.

Panagiotidou, Aye and Rismanchi (2021) investigated the optimal cost and zero-total emission goals for multi-residential optimised retrofitted buildings. The aim was to help achieve the greenhouse gas (GHG) goals of the European Union under the European Green Deal. An optimisation method with multiple targets was created to reduce GHGs and life cycle prices. A building was chosen to analyse the model in four climatic areas in Greece. The outcomes revealed that optimal retrofit is at par with required market trends like the solar thermal receiver and air-to-air heat pumps and covered the insulation with a 60–96% reduction in GHG production depending on the envelope layer. With the improvements in factors like photovoltaic-thermal systems, cooling systems, heat pumps, and facade-combined photovoltaic structures, a promising future with net-zero GHG emissions is anticipated. Alsabbagh (2019) reported the general outlook on photovoltaics on residential buildings on an island. The research was conducted to improve the natural renewable power plan by integrating solar panels to encourage renewable power. An online study included 764 answers collected from questionnaires from the general public. The response showed that the majority are happy with the solar cell equipment but are reluctant to adopt it because of its high cost, lack of proper knowledge, and shorter lifespan. The paper describes the role the government still needs to play to make this project a success. Li, Mojiri, Rosengarten and Stanley (2021) proposed a suburban demand-side administration with the help of a combined thermal depository and solar-driven heat pump. The aim is to find solutions to connection overload and voltage issues when extra solar--generated current is passed to the mainline. An Australian building was chosen to find hourly domestic boiler and thermal loads for a year under a simulation of the building's power. The data were collected and compared with electric sub-meters to find the average heat storage capacity, heat pump requirement, and export of solar structures. The outcomes reflect around a 45% reduction in temporal shifts, an 84% increase in hot water loads and air-conditioning, and a reduction in grid electricity demand by 76% when using a 5-kW photovoltaic structure. The conclusion was that this suggested method efficiently addresses damages in the electricity grid due to photovoltaics without compromising electricity requirements.

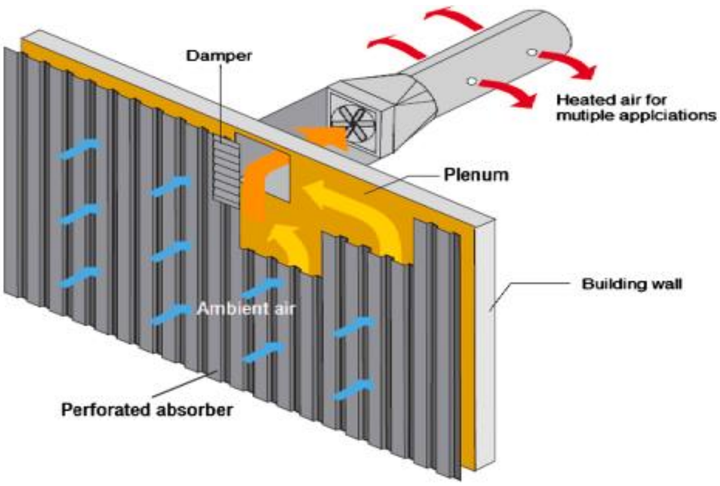

Fig. 2. An unglazed transpired solar collector system in operation

Source: Saini, Paolo, Fiedler, Widén and Zhang (2021), CC BY-SA 3.0.

Panagiotidou, Aye and Rismanchi (2020) described a method of solar-powered boiler systems for Mediterranean places among medium-rise domestic constructions. The limited roof availability of these houses was aimed to be addressed with solar-powered boiler systems at par with present electric boilers. A proper analysis was made on S4 combined heat pump boiler and solar cells, S3 electrical backup solar PV/T boilers, S2 backup thermal solar water boilers, and S1 solar PV water boilers. The outcomes were compared with net LCC and yearly electricity from the power grid for 20 years. The S3 and S4 showed higher current production but were subjected to a high-cost setup, while LCC was found to be minimal, with S2 in colder places and S3 in hotter areas.

Zander (2020) prepared a report on new opportunities for household solar cells in Australia. Past usage and future prospects of using solar cells were considered to find the possible reluctance to use them, with 1,126 people in Australia being chosen for an online questionnaire. The answer revealed that 65 out of 100 people with no previous solar panels were eager to adopt it despite past or future trends. Most renters and homeowners are unsure about using solar PVs because of their uncertainties in maintenance, adoption costs, and future profits. However, they are aware of its environment-friendly aspects. The conclusion was that a uniform system must be regulated to provide proper profit benefits to consumers to provide the much needed and cheaper source of electricity, especially in city areas.

Abd-ur-Rehman, Sulaiman, Mehmood, Shakir and Umer (2018) demonstrated the importance of manufacturing clean energy through photovoltaics and the possibilities of power savings in the suburban houses of Saudi Arabia. A modified International Energy Conservation Code (IECC) building was chosen to simulate its energy outcomes, storage, and usage methods. The products showed 27% less power used by appliances, 46% less for ignition, 37% less for a room heater, and 56% less for cooling in the IECC compared to an average house. Further, when solar boilers and solar cells connected to the power grid were added secondarily, a 76% reduction in the bill was seen.

The paper concluded that with lucrative subsidies by the government, this innovative source could be appropriately utilised, and all its prospects can be explored.

Asrami, Sohani, Saedpanah and Sayyaadi (2021) studied the eminent way to use solar cells in suburban constructions. The environmental impact, economic aspects, and energy were considered to compare the three frameworks of full feed-in and grid connection with or without batteries. Each framework was further explored using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and the NSGA-II (Non-Dominated Sorting Genetic Algorithm II). The proposed method was evaluated in a suburban house situated in Teheran. The outcomes showed the entire feed-in process to be most effective, with $0.15 per 1 kWh of levelised price, a payback time of 7.3 years, and a massive 78.6% improvement in performance ratio; however, it has inevitable setback to human health (0.023 DALY), the ecosystem (0.101 species per year) and destruction of resources ($487 per year).

Chahartaghi and Baghaee (2020) investigated the economic and practical aspects of integrated heating, cooling, and power systems established on amalgamated micro gas turbines (MGT) for suburban constructions. A simulation of the combined cooling, heating, and power (CCHP) model on MGTs was made to collect the early function of the cycle in reality. Solar cells were included to boost the MGT's heat cycle, parabolic solar dishes, heat-saving vapour generation, auxiliary boiler, and microturbines in the system. The observation was made by changing the number of system parts. A levelised cost of electricity (LCoE) was also found for the best performances, and the economic situations were also evaluated. In the end, the LCoE of the system was differentiated from the LCoE of the solar cell structure.

Saini et al. (2021) demonstrated an evaluation of the practical-economic condition of an exhaust air thermal pump structure based on porous transpired solar receivers situated in colder areas. All parts and systems were strictly examined for varied solar collector sizes. An algorithm was made to control airflow inside an unglazed transpired solar collector (UTSC), and a comparison was made from traditional flow control. The TRNSYS model was used to procure the exhaust air heat pump (EAHP) maximisation of multi-storey constructions, and the UTSC model was used to collect data about energy and capabilities. The outcomes revealed that the UTSC is a better method to control airflow for improving periodical performance with huge savings. Wu and Skye (2021) devised a review system of successful net-zero power-consuming buildings throughout the world. The net-zero energy building (NZEB) with renewable power sources of wind, biomass (with a combined heat and power system), solar thermal, and photovoltaics were examined. Energy storage options, hydrogen storage, district cooling/heating systems, and electrical grids were reviewed. The power efficiency and future independence were checked. Modern envelope design buildings, heating, ventilation, and air conditioning (HVAC) systems, and new boiler systems were proposed along with other adaptability features that can be considered according to climate conditions. This paper provides detailed information about the improvements in net-zero power-consuming houses and some measures to encourage their adoption.

Zakeri, Cross, Dodds and Gissey (2021) explored strategies to maximise profits from household-owned solar panels and storage batteries. Their study focused on the growing adaptability and advancements in photovoltaic (PV) technologies, propelled by various government and non-government initiatives, which have opened up new revenue streams for homeowners through excess energy generation. The research proposed several policies aimed at enhancing the financial returns from PV investments. These included dynamic retail pricing to capitalise on domestic storage capacity, a feed-in tariff bonus, and an energy storage policy that offers rewards when additional electricity is supplied to the grid. By integrating a national energy system model with a cost-optimising consumer model, the effectiveness of these policies was assessed. The findings indicated that the PV self-consumption model could yield up to a 70% return on investment, while the energy storage policy could offer up to a 40% return, assuming a one-third reduction in costs and without the need for additional facilities. The study concluded that dynamic electricity pricing and optimal storage deployment are crucial for maximising financial returns from solar energy investments. Qiu, Kahn and Xing (2019) described the calculated recoil effects of domiciliary applications of solar panels. Two hundred seventy-seven houses with solar panels and 4,000 ordinary houses were chosen around Phoenix

(Arizona) to take hourly data from them using their electricity meter and solar generation meter. These houses were studied adequately for four years (2013–2017). The results showed that, with an increase of 1 kWh of solar energy creation, the household consumes 0.18 kWh more than the average total consumption. The findings thus showed an 18% solar recoiling effect with an additional annual income of $972 because of the usage of solar panels.

Experimental studies

Sharma (2021) prepared research on general users' perception of using personal solar water boilers in the city of Phoenix. The study was conducted to find the market capabilities of solar boilers in the US and the possible reasons for their usage/non-usage. The survey focused on collecting data on solar boiler awareness, family income, and educational status to target future consumers. The survey revealed that people with family incomes above $60,000 and higher qualifications are users of solar boilers and are ready to accept other eco-friendly solar cell-powered technologies. 70% of people were found to be aware of the importance of photovoltaic cells. This research thus proved essential to ventures selling solar water heaters in the USA to find potential users and frame their marketing strategy. Bandyopadhyay, Leibowicz and Webber (2021) discussed the apex grid impact of load, grid power usage, and discharge in suburban houses using various pairs of distributed power technologies at different price levels. Some places using intelligent thermostats, chilled thermal power vaults, Li-ion batteries, and solar cells were chosen to apply a functional framework for reducing current charges, operational prices, and amortised capital for one year. The observation showed that the only obstacle to the acceptance of energy and environment-friendly solar cells is the higher price of storage units. Furthermore, pricing mechanisms decide the popularity of the two storage units among houses. In the end, the suggestion to use an efficient apex load control mechanism with lucrative returns for promoting storage units among households with demand charges was proposed.

Rosato Ciervo, Ciampi and Sibilio (2019) conducted a study on a novel centralised hybrid solar district heating system, integrating solar power with seasonal borehole thermal energy storage. This study, leveraging dynamic transient system simulation software TRNSYS over a five-year period, assessed the system's potential to reduce primary energy use, carbon dioxide emissions, and operational costs when compared to conventional heating systems. The inclusion of photovoltaic thermal (PVT) collectors, notable for their ability to generate both electricity and heat, showed a significant impact on reducing the system's carbon footprint and energy consumption. Specifically, the use of PVT collectors led to a notable decrease in carbon dioxide emissions, energy supply costs, and operational costs over five years, attributed to the enhanced median temperature at the PVT collectors' entry point, albeit with a slight reduction in their electrical efficiency. This approach exemplifies how integrating renewable energy sources with advanced thermal storage technologies can offer a sustainable and cost-effective alternative to traditional district heating solutions. Pinamonti and Baggio (2020) examined the effectiveness of solar-assisted heat pump (SAHP) systems paired with energy storage solutions across a variety of applications, including both heating and cooling, within three buildings of differing energy performance levels. They found that increasing the temperature of the thermal storage by 10°C in combination with solar thermal (ST) collectors proved beneficial across all cases studied. The use of solar thermal collectors emerged as the most favourable strategy, characterised by reduced energy demand and cost efficiency. The findings of this investigation are particularly relevant to specific climatic conditions, suggesting that the applicability and performance of SAHP systems can significantly benefit from integration with solar thermal technologies, highlighting a sustainable approach to managing a building's heating and cooling needs. Qiu, Wang and Xing (2021) leveraged a unique and previously untapped dataset detailing customer-specific electricity needs and the deployment of solar panel systems. Their study focused on three key areas, including an empirical assessment of the impact of deploying solar panels in non-residential settings. They found that the reduction in electricity purchases from the grid was significantly less when compared to the generation of solar power, highlighting the efficiency and environmental benefits of solar energy adoption. The concept of "solar rebound effects" was introduced as a crucial metric for assessing the environmental advantages of solar power utilisation.

Krarti (2021) explored the energy efficiency of dynamic overhangs combined with photovoltaic (PV) arrays on windows in U.S. residential buildings, specifically analysing their impact in Golden, Colorado. The study revealed that dynamic overhangs could reduce energy demand by up to 6% without PV arrays and by over 35% when integrated with PV panels, based on monthly calculations. These dynamic overhangs, especially when used with PV arrays, offer significant energy savings by adjusting to solar exposure, thereby enhancing the overall energy performance of homes. This approach suggests that incorporating dynamic overhangs with PV technology can significantly reduce a home's energy requirements, offering a sustainable solution to energy consumption challenges in residential settings.

COMMERCIAL BUILDINGS

For commercial buildings, the integration of solar panels is a strategic move towards energy efficiency and corporate responsibility. These installations not only significantly cut down energy costs but also demonstrate a commitment to sustainable practices, enhancing the company's public image. Suhail, Akhtar and Kirmani (2021) discussed the economic analysis of a 26 kW PV method and demonstrated the economic comparison between a grid-connected PV process and a stand-alone PV method. Solar power is a pure and consistent source of power, and its atmosphere--friendly nature provides it an edge over the other renewable sources of power. The performance of the PV method is higher in January and December, while it is lower from April to July. The current evolution in PV methods is advantageous for meeting the power required, particularly in metropolitan areas. Behzadi and Arabkoohsar (2020) described a novel creation of intelligent building energy systems. In the system, photovoltaic thermal (PVT) panels are connected to a heat storage tank to provide a large portion of the structure's heat and electricity requirement. With such a method, not only may the share of reusable power in the national power matrix safely rise, but also the building will profit from the cheap, eco-friendly power flows generated by itself. The outcomes show that the process provides the total annual domestic hot water demand and creates 402.8 m^3 of hot water at 40°C to be sold to the regional district heating system.

Mendecka, Tribioli and Cozzolino (2020) conducted research on the environmental impact of a standalone solar-based polygeneration power system, which includes a photovoltaic array, battery storage, a unitised regenerative polymer electrolyte fuel cell, and a diesel generator as backup. The study highlighted the minimal initial but significant lifecycle environmental impact of the regenerative fuel cell. The findings suggest potential improvements in system design to reduce reliance on batteries and diesel generators, thereby enhancing the sustainability of the building operation and usage phases. This research underscores the critical role of construction and operational phases in influencing both the energy supply and demand, despite the minimal contribution from the end-of-life phase.

Christiaanse, Loonen and Evins (2021) examined the economic feasibility of solar panel installations on rooftops from the perspective of manufacturing companies and the availability of structural frameworks. They developed a two-tier optimisation model to streamline the design process for rooftop PV systems. This model enables high-level adjustments to design parameters, aiming to cut costs or adjust priorities in lower-tier optimisations. Such adjustments, which focus on reducing installation costs and optimising energy imports from the grid, hinge on the demand profile of the building. The innovative approach of modifying PV system design parameters not only maximises energy efficiency in smaller structures but also significantly boosts potential energy export, tripling the maximum energy intake from the grid. This methodological shift promises enhanced energy output with optimised costs, marking a step forward in the integration of solar energy into urban infrastructure. Drissi, Ling and Mo (2020) explored the development of an innovative core-shell phase change material (PCM) known as AGGSpcm, designed to capture and store solar energy within the structural envelope of buildings for heating and cooling purposes. By enhancing the concentration of microencapsulated PCMs (mPCMs) within the AGGSpcm or selecting a PCM with an optimal phase change temperature, the study achieved improved thermal storage and release efficiency. The results demonstrated significant enhancements in thermal performance and energy savings within concrete structures through the use of PCMs. The utilisation of these materials in construction contributes to substantial energy conservation, as illustrated by the integration of the solar energy system into a building's design, depicted in both schematic and photographic formats. This approach not only optimises the building's energy efficiency but also represents a forward step in sustainable architectural practices. Figure 3 shows the solar energy system integrated into a building, which is illustrated schematically and photographed.

Mendecka et al. (2021) developed a concept for a hybrid renewable power plant incorporating a novel integration of photovoltaic panels with unitised solid oxide fuel cells powered by bio-gas. This approach enables the power plant to operate entirely on renewable energy, assuming the bio-gas digester produces between 6,000 to 9,500 standard cubic meters per year and the system's battery storage starts the year fully charged. This innovative design represents a significant step forward in sustainable energy solutions, offering a blueprint for achieving 100% renewable energy operation in power generation. El-Bayeh Alzaareer, Brahmi, Zellagui and Eicker (2021) introduced a new multi-criteria decision-making algorithm that prioritises efficiency over the traditional Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This algorithm, based on a rank weight system, speeds up the selection process of solar panels by evaluating various criteria. The findings challenge the assumption that the most expensive solar panels are automatically the best choice, or that the cheapest options are the least desirable. By employing this refined decision-making process, stakeholders can make more informed choices regarding solar panel selection, emphasising the balance between cost and performance without assuming a direct correlation between price and quality.

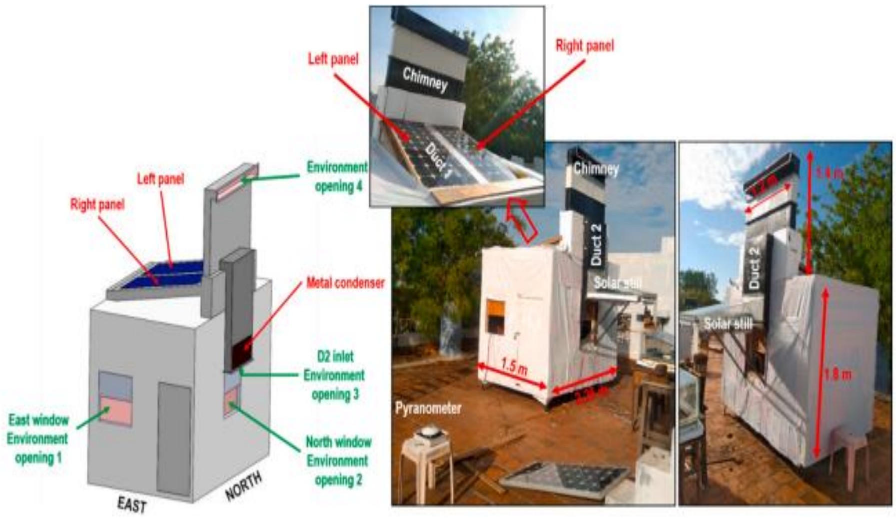

Fig. 3. The solar energy system integrated into the building

Source: Sivaram et al. (2021), CC BY-SA 3.0.

Elghamry Hassan and Hawwash (2020) conducted a parametric analysis on the impact of integrating solar cells within the building envelope, focusing on generated power, energy consumption, temperature regulation, and carbon dioxide emissions. Utilising design-builder software and validated through experimental data, the study found that solar cells positioned within windows had the least effect on light transmittance, while those oriented northward minimised carbon dioxide emissions most effectively. Installing solar cells on the façade and roof was shown to significantly reduce annual energy consumption by approximately 15% and 40%, respectively, compared to buildings without such installations. Bre, e Silva Machado, Lawrie, Crawley and Lamberts (2021) undertook a comprehensive investigation to assess the accuracy of solar radiation data incorporated into Typical Meteorological Year (TMY) databases for various Brazilian locations. This study highlighted how the quality of solar radiation data influences the selection of months for TMYs and, consequently, the outcomes of Building Performance Simulations (BPS). Their analysis revealed that commercial buildings are more susceptible to inaccuracies in weather data than residential buildings, especially concerning cooling load forecasts. By comparing the global horizontal irradiation data from the latest Brazilian TMY databases with satellite-derived data, the research underscored the critical importance of accurate solar radiation models in influencing TMY compilations and, by extension, building energy simulations.

INDUSTRIAL BUILDINGS

In the realm of industrial buildings, the integration of solar panels is increasingly recognised as a vital strategy for enhancing operational efficiency and advancing environmental sustainability. These systems provide a dependable and economical energy source, crucial for meeting the substantial energy demands typical of industrial operations.

Aly, Chokwitthaya and Poche (2017) explored the impact of aerodynamic features on the performance of solar panels mounted on gable roofs. Their study specifically focused on how various panel configurations could mitigate wind-induced forces on buildings, while maintaining aesthetic appeal and functionality for widespread application. Findings indicated that solar panels significantly reduce wind uplift on flat roofs and that strategically combining panels can lower wind pressures on buildings with minimal structural enhancements, ensuring reliable power supply, especially during power outages. Ayodele, Ogunjuyigbe and Nwakanma (2021) investigated the feasibility of meeting Ibadan's growing electricity needs through rooftop solar PV systems. Using advanced mapping technologies and GIS, they assessed the potential rooftop area suitable for solar installations, considering factors like shadowing to minimise energy loss. The study estimated that Ibadan could generate approximately 6.6714 TWh of solar energy annually, highlighting a significant potential for solar energy to contribute to the city's power supply with an estimated capacity of 1,734.8 MWp.

Pakere Lauka and Blumberga (2018) examined the integration of photovoltaic thermal (PVT) systems into district heating networks in European climates. This research aimed to identify the most effective ways to utilise surplus solar energy for heating purposes, balancing solar power generation against the energy and heating needs of buildings. The analysis showed that converting excess electrical energy into heat is economically viable, particularly when electricity prices are lower than those of district heating, offering a cost-effective method to enhance energy efficiency and sustainability in industrial settings.

These studies collectively underscore the critical role of solar energy technologies in transforming industrial buildings into more energy-efficient and sustainable infrastructures. By leveraging solar power, industrial facilities can significantly reduce their environmental footprint while ensuring energy security and operational efficiency.

ADVANCED TECHNOLOGY AND RECENT TRENDS IN SOLAR PANELS

This section explores groundbreaking advancements in solar panel technology, underscoring the enhancements in efficiency, cost-effectiveness, and versatility for architectural integration. These innovations represent significant strides in harnessing renewable energy more effectively.

Tian et al. (2021) conducted an examination of 13 different membrane materials, analysing their thermal and optical properties using the Perkin Elmer LAMBDA™ 750 spectrophotometer. The study addressed how these materials affect the indoor thermal environment, particularly focusing on their ability to absorb and transmit solar radiation. A model was developed to calculate the internal solar heat gain, providing insights into how different levels of light transmittance and absorptivity impact indoor thermal comfort. Yemenici and Aksoy (2021) undertook both practical and numerical studies to assess the impact of wind direction and panel tilt angles on solar panel efficiency. Their findings revealed that the optimal tilt angle for minimising wind load while maximising energy capture varies significantly with wind direction. This research highlights the importance of considering environmental factors in the placement and orientation of solar panels to enhance their performance and durability.

Xu et al. (2021) developed a multi-dimensional analysis to evaluate solar power potential at the urban block level, utilising a clustering algorithm to categorise blocks based on morphological parameters. Their findings indicate a substantial variation in solar power potential across different block types, with building density identified as a key factor influencing this potential. As building density increases, so does the achievable solar power, demonstrating the impact of urban design on renewable energy generation capacity. Together, these studies illuminate the path forward in solar panel technology, emphasising the need for a nuanced understanding of environmental interactions and urban planning in maximising solar energy utilisation.

THE CURRENT IMPACT OF SOLAR PANELS

This section examines the broad-ranging effects of solar panel implementation in today's context. It addresses how solar panels are influencing energy policies, environmental conservation, and economic dynamics, signifying a major shift towards more sustainable and responsible energy use globally. Salehi, Jahanbakhshi, Golzarian and Khojastehpour (2021) suggested the connection between reducing the solar panel's temperature and variation in its energy and efficiency in discussions with general controlling situations and the ones furnished with thermoelectric modules. The process evolved in this study was made from two main parts known as cooling units and solar panels. The results reveal that utilising a thermoelectric module with a heater could enhance the efficiency and energy of solar panels by 10.50% each. The outcomes of this study showed that the industrial design of solar panels with a process to decrease excess heat from solar radiation could be helpful in increasing total efficiency via reducing extra heat and enhancing the panels' efficiency. Gupta, Dubey, Kumar and Mehta (2021) proposed an innovative approach to harnessing solar energy, focusing on the utilisation of the full spectrum of solar irradiation. They detailed the development and application of a hybrid solar photovoltaic and thermal (SPVT) system. This system uniquely combines a transparent solar panel with a primary Fresnel lens to concentrate sunlight efficiently. Their research found that using a red filter in the semi-transparent solar panel yielded better results than a blue filter, enhancing both the electrical output and thermal energy for domestic hot water production. This dual-functionality approach not only improves the efficiency and cost-effectiveness of solar energy systems but also contributes to the sustainable development goals by providing a more comprehensive and resilient energy solution.

Dermentzis, Ochs and Franzoi (2021) reported on a four-year monitoring project of two newly constructed multi-family apartments in Innsbruck, designed with the ambition of achieving net-zero energy building (NZEB) status. The primary objective for these NZEBs was to annually match the buildings' electrical energy consumption with the energy produced by on-site PV systems, thereby achieving a balance between energy demand and supply. This balance aims to reduce both the buildings' heating requirements and thermal losses, underscoring the importance of optimising the buildings' energy efficiency. The study highlighted the necessity of managing and reducing thermal losses and energy consumption as critical steps toward realising the NZEB goal. It demonstrated that achieving NZEB status requires careful planning and integration of additional PV panels and other energy-saving measures to ensure that the buildings operate efficiently and sustainably.

Wu et al. (2022) explored an innovative approach to solar energy generation by examining the integration of solar cells into building designs and the broader implications of such systems on energy production. Their research delved into the architectural incorporation of solar panels and the optimisation of solar energy output, utilising an extensive array of data sources and creating a supportive framework for the analysis. Solar energy, recognised for its environmental benefits and sustainability, stands out as a flexible and scalable source that overcomes geographical limitations and can be directly integrated into the local power grid through inverters. The study aimed to address several challenges facing solar energy deployment, including issues related to system integration, capacity limitations, efficiency concerns, and the need for more comprehensive monitoring mechanisms. By focusing on these areas, the research contributes to enhancing the reliability, effectiveness, and scalability of solar energy solutions (Wu et al., 2022).

CONCLUSIONS

Solar energy is a free, clean, and sustainable source of energy. Energy usage per individual is increasing at an alarming pace. Energy prices are also reaching new highs. Buildings are being built with an eye on energy efficiency. The objective is to reduce energy consumption and to increase the use of alternative solar energy, which has many advantages.

– Solar-powered buildings are very effective in conserving energy in a variety of ways. By using cutting-edge solar energy technologies, buildings may save up to 35–45% on their energy use. Additionally, you may become a net-zero energy building owner if you generate more energy than you use. Without question, solar -powered buildings that make effective use of technology use less energy.

1. Solar-powered buildings increase the efficiency of the heating and cooling system by 25% through the appropriate installation of a modern HVAC system. Solar-powered energy-efficient buildings may decrease the operating costs of a highly efficient solar water heater by 90%.
2. When low-emissivity window glazing is used, it helps to decrease the demand for space cooling by about 35%. A light-coloured roof lowers the warmth of the roof since it absorbs less than 50% of the solar radiation.
3. When energy-efficient lighting and appliances are utilised, a solar building may decrease its energy consumption by 15–25%. With the continuous advancement of construction technologies, achieving better energy efficiency in buildings is becoming simpler.

Authors' contributions

Conceptualisation: S.K., D.S.V., P.D. and A.S.; methodology: S.K., D.S.V., P.D. and A.S.; validation: S.K., D.S.V., P.D. and A.S.; formal analysis: S.K., D.S.V., P.D. and A.S.; investigation: S.K., D.S.V., P.D. and A.S.; resources: S.K., D.S.V., P.D. and A.S.; data curation: S.K., D.S.V., P.D. and A.S.; writing – original draft preparation: S.K., D.S.V., P.D. and A.S.; writing – review and editing: E.K., W.S. and Ł.W.; visualisation: S.K., D.S.V., P.D.; supervision: S.K., D.S.V., P.D. and A.S.; project administration S.K., D.S.V., P.D. and A.S.; funding acquisition: S.K., D.S.V., P.D. and A.S.

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ROZWÓJ ZAAWANSOWANYCH TECHNOLOGII PANELI FOTOWOLTAICZNYCH W BUDYNKACH – PRZEGLĄD

STRESZCZENIE

W ostatnich latach globalnie obserwuje się dynamiczny wzrost wykorzystywania energii odnawialnej. Indie również rozwijają się jako światowy lider w produkcji tego typu energii. W ciągu ostatnich kilkudziesięciu lat energia słoneczna nabrała ogromnego znaczenia jako źródło tzw. zielonej energii. Jej wykorzystanie wzrosło, w miarę jak coraz więcej właścicieli domów, przedsiębiorstw i jednostek przemysłowych decyduje się na korzystanie z tej proekologicznej formy energii. Panele fotowoltaiczne na budynkach komercyjnych pozyskują czystą energię odnawialną ze słońca i przekształcają ją w energię elektryczną, która jest wykorzystywana do zasilania urządzeń elektrycznych. Panele fotowoltaiczne składają się z wielu oddzielnych ogniw słonecznych złożonych z warstw krzemu, fosforu i boru, ułożonych w siatkę. W artykule omówiono postępy w technologii paneli fotowoltaicznych przeznaczonych do montażu na budynkach mieszkalnych, komercyjnych i przemysłowych.

Słowa kluczowe: panele fotowoltaiczne, budynki pasywne, zielona energia, rozwój zrównoważony, źródła odnawialne