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Editorial

Advances in the Design and Application of Solar Energy in Buildings: From Solar Potential to Integrated Energy Systems

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1. Introduction

Buildings remain one of the key sectors in the global energy transition. According to the International Energy Agency, they account for approximately 30% of global final energy demand, with residential buildings responsible for around 70% of energy consumption within the building sector [1]. In developed economies, a substantial share of this demand is associated with space heating and domestic hot water production. Consequently, the integration of solar energy into buildings must address not only electricity generation but also their thermal energy requirements. At the same time, the role of buildings within the energy system is undergoing a fundamental transformation. Rather than functioning solely as passive energy consumers, buildings are increasingly becoming energy producers, storage assets, and flexible participants in electricity networks. In this context, simply increasing the installed area of solar collectors or photovoltaic (PV) modules is no longer a sufficient design objective.

The importance of solar energy integration is further reinforced by evolving regulatory frameworks. The recast European Energy Performance of Buildings Directive (EPBD) establishes zero-emission buildings as the standard for all new public buildings from 2028 and all new buildings from 2030 [2,3]. New buildings are expected to be designed to facilitate the effective use of solar energy, while electricity generated by PV systems can be consumed by building services, heat pumps, and electric vehicles, stored for later use, or exported to the electricity grid [2]. These requirements encourage a more integrated approach to building design, in which renewable energy generation, energy efficiency, storage, and interaction with the wider energy system are considered together.

The concept of a solar-powered building has therefore evolved considerably. Early research focused primarily on maximizing the amount of solar radiation captured through appropriate collector orientation, inclination, and surface area. Subsequent advances in building-integrated photovoltaics (BIPV), photovoltaic–thermal (PV/T) technologies, energy storage, and heat pumps progressively expanded the boundaries of the systems under investigation. Today, the central question is no longer simply how much solar energy a building can generate, but also when that energy is available, how closely generation matches instantaneous demand, and how surplus energy can be stored, converted, or exchanged with the electricity network. Studies of PV-assisted air-source heat pump (PV-ASHP) systems demonstrate that supply–demand matching is highly sensitive to the temporal resolution adopted and that annual energy balances may conceal substantial mismatches occurring at the hourly scale [4]. This highlights the need to move beyond conventional annual energy assessments toward more dynamic approaches that account for the temporal relationships among energy generation, consumption, and storage.

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These developments also emphasize the importance of spatial considerations. The solar energy potential of a building is influenced not only by the characteristics of individual collectors or PV modules but also by roof and façade geometry, building orientation, shading, urban morphology, and interactions with the surrounding built environment. Furthermore, maximizing the theoretical solar potential does not necessarily lead to the most effective overall energy solution. The actual benefits depend on building demand profiles, the availability of storage and energy conversion technologies, control strategies, and the technical constraints of local distribution networks. Solar energy integration must therefore be addressed across multiple spatial and temporal scales, from individual building components to entire building complexes and their interactions with the wider energy infrastructure.

Against this background, the Special Issue Advances in the Design and Application of Solar Energy in Buildings was established to explore recent developments in solar technologies and their integration into the built environment. Its scope encompassed building-integrated photovoltaics, solar thermal systems, energy storage, phase change materials (PCMs), hybrid energy systems, modeling and simulation, smart control, techno-economic and environmental assessment, and net-zero energy buildings. The Special Issue ultimately brought together six research articles, addressing complementary aspects of solar energy utilization at different scales. Their contributions range from the effects of urban morphology on solar energy potential and the automated assessment of rooftop PV installations to balcony-mounted photovoltaics, the integration of distributed PV into low-voltage networks, thermal stratification in solar storage tanks, and the combined optimization of daylighting and energy performance in building retrofits.

Taken together, these contributions illustrate a broader transition in the design and application of solar energy systems in buildings. The focus is gradually shifting from maximizing the performance of individual technologies toward optimizing the interactions among solar resource availability, building energy demand, energy storage, system operation, and grid constraints. This transition also calls for greater attention to life-cycle environmental impacts, economic performance, and resilience under future climatic conditions. Accordingly, this Editorial synthesizes the principal findings of the six contributions, identifies their shared implications and limitations, and discusses emerging research directions. Particular emphasis is placed on the need to progress from component-level optimization toward the dynamic, multi-objective design and operation of integrated building energy systems.

2. Contributions of the Special Issue

The first group of contributions addresses the spatial conditions governing solar energy utilization. Ye et al. extended conventional PV potential assessment from individual buildings to the scale of entire building complexes. Using 18 idealized models of science and technology industrial parks in the Yangtze River Delta region, the authors combined solar irradiation and PV generation modeling with simulations of building energy demand and urban heat island effects. The indicators of Net Energy Use Intensity (NEUI) and Potential Utilization Ratio of Renewable Energy (PURRE) enabled them to assess the trade-offs among urban morphology, energy demand, and potential renewable energy generation. The minimum NEUI was 72.09 kWh/(m^2·a), compared with a maximum of 85.93 kWh/(m^2·a). Under the conditions examined, compact circular or courtyard-type configurations, with a building density of approximately 35–40%, an average height of around 17–18 m, and a relatively low shape factor, proved advantageous.

This study is particularly significant because it demonstrates that solar-oriented design should begin well before the selection of PV modules or solar collectors. Urban morphology simultaneously determines the surface area available for solar installations, shading conditions, and building energy demand. However, the PURRE indicator employed in

this study represents a measure of potential utilization, based on the assumption that all generated solar energy can be used. Distinguishing between theoretical potential and actual utilization is therefore essential and leads directly to one of the major challenges for future research: matching energy generation and demand over time.

At the scale of individual building surfaces, Błaszczak-Bąk et al. developed a low-cost method for automatically acquiring rooftop geometry using a commercially available DJI Air 3 unmanned aerial vehicle (UAV), photogrammetry, and three-dimensional modeling. Their Model Analysis Tool (MAT) enables the automatic determination of parameters such as roof area, azimuth, and inclination, as well as the estimation of potential PV capacity and energy generation. For the study area, the estimated PV capacity ranged from 0 to 37 kWp, while annual electricity generation was approximately 24–38 MWh. On average, MAT produced estimates approximately 11% higher than those obtained using PVGIS. The authors also highlighted the need for further improvements in shading and seasonal modeling, together with validation using larger datasets.

This approach illustrates a broader transformation in solar mapping, from manual assessments of individual buildings toward automated analyses of large building stocks. Developments in geographic information systems (GIS), LiDAR, and deep learning are further accelerating this transition. However, recent city-scale research indicates that simplifying façade geometry, particularly by neglecting the actual window-to-wall ratio, can introduce substantial errors into estimates of façade solar energy potential [5].

Another way to increase the surface area available for PV installations is to utilize façade elements. Polański et al. investigated the potential for installing photovoltaic modules on balconies in large-panel prefabricated residential buildings in Poland. Under the assumptions adopted, the conservative estimate of installed capacity was approximately 0.6 GW, corresponding to annual electricity generation of around 390–480 GWh. Module inclination proved particularly important: for south-facing installations, changing the module position from vertical (90°) to a tilt angle of 70° increased the potential energy yield by 24.37%.

The significance of this study extends beyond electricity generation alone. Balcony-mounted photovoltaics represent a retrofit solution that makes use of existing building surfaces, particularly where conventional rooftop PV installations are constrained by the limited roof area available per dwelling. At the same time, the authors emphasized that local shading, balcony structures, orientation, and legal requirements prevent the development of a single universally applicable installation model for the entire building stock.

Increasing the available PV capacity, however, introduces a further level of complexity. Kowalak et al. examined an existing residential development comprising 32 multi-family buildings and investigated the consequences of PV deployment under Polish regulatory conditions. In the scenario without PV installations, the transformer operated within acceptable limits. By contrast, extreme PV deployment scenarios resulted in significant voltage and overloading problems, with transformer loading reaching approximately 117% and 180% of rated capacity in the scenarios analyzed.

Considered together, studies lead to a fundamental system-level conclusion. The physical feasibility of installing additional PV modules on a building does not necessarily imply that the corresponding generation capacity can be integrated into the electricity network without difficulty. As PV penetration increases, the principal constraint may shift from the availability of building surfaces to the hosting capacity of the distribution network. Under these conditions, energy storage, power control, demand response, and coordination with heat pumps become as important as the efficiency of the PV modules themselves.

Solar energy use in buildings is not, however, limited to electricity generation. Król and Kupiec investigated thermal stratification in a water storage tank used in a solar domestic hot

water system. Their multi-node model enabled the analysis of both short-term variations in operating conditions and annual system performance under the climatic conditions of Kraków, Poland. The authors found that increasing the number of nodes beyond $N = 10$ did not significantly affect the results and that, under typical domestic hot water operating conditions, the degree of stratification had only a limited influence on annual performance indicators. Nevertheless, stratification had a considerably stronger effect on the short-term stabilization of domestic hot water temperature, particularly during autumn and winter.

This finding has broader methodological implications. The level of model detail should be selected according to the research question being addressed. A perfectly mixed storage model may be adequate for certain annual energy assessments of small solar thermal systems, but it may be unsuitable for investigating instantaneous temperatures, thermal comfort, or control performance. This distinction is particularly relevant to the development of digital twins and model predictive control (MPC), where excessive model complexity can hinder real-time operation, whereas excessive simplification may fail to capture important system dynamics [6].

The sixth article extends the discussion toward multi-objective building retrofitting. Forastiere et al. proposed a building information modeling–building energy modeling (BIM–BEM)-based parametric framework and applied it to three existing food-retail buildings in Italy. The study investigated 27 configurations involving skylight geometry and orientation, glazing type, PV installations, and LED lighting with Digital Addressable Lighting Interface (DALI) controls. In the best-performing configurations, lighting energy consumption was reduced by up to 60%, while the environmental impact indicator improved by approximately 15–20%.

This contribution demonstrates why building components should not be optimized independently. Increasing daylight availability can reduce the need for artificial lighting, but it can also affect solar heat gains and cooling demand. Similarly, PV modules and skylights compete for the same roof area. A solution that performs best according to one indicator may therefore be suboptimal from the perspective of the building as a whole. This approach naturally leads toward multi-objective building design and digital twin-assisted operation.

3. Cross-Cutting Findings

The first overarching finding of the Special Issue is the importance of geometry at every spatial scale. Urban block morphology, roof orientation, balcony geometry, and skylight configuration directly influence the availability and utilization of solar energy. Nevertheless, maximizing solar exposure through geometric design is only an initial step. In an integrated energy system, it must be considered alongside energy demand profiles and building use patterns.

The second finding is the need to distinguish between potentially available, generated, and actually utilized energy. This distinction becomes particularly important at high levels of PV penetration. Recent studies of hybrid solar systems coupled with heat pumps show that supply–demand matching indicators may appear favorable when calculated on an annual basis while exhibiting substantial fluctuations at daily or hourly resolutions [4].

The third finding concerns the growing importance of system dynamics. Thermal stratification in a storage tank may have only a limited effect on the annual solar fraction while remaining important for instantaneous domestic hot water temperatures. Similarly, high annual PV generation does not eliminate short-duration grid overloads. Annual energy indicators expressed in kWh should therefore be complemented by time-resolved metrics addressing peak power, self-consumption, flexibility, and the quality of energy supply.

The fourth finding relates to the progressive expansion of system boundaries. An optimal PV module does not automatically result in an optimal building, just as an optimally

designed building does not necessarily ensure optimal grid operation. As the share of renewable energy increases, the focus must therefore shift from component optimization to building-system optimization and ultimately to building-to-grid optimization.

The fifth finding is the need for multi-objective assessment. Energy performance, cost, carbon footprint, comfort, architectural quality, climate resilience, and grid impacts may favor different design solutions. Particularly in BIPV applications and architectural retrofits, solutions should be evaluated using multiple performance indicators rather than annual solar energy yield alone.

4. Research Gaps and Future Directions

The six contributions to this Special Issue highlight important advances in the design and application of solar energy systems in buildings, while also pointing to challenges that extend beyond the scope of the individual studies. Several emerging technologies and approaches, including photovoltaic–thermal (PV/T) systems, solar-assisted heat pumps, phase change materials (PCMs), seasonal thermal energy storage, solar-driven cooling, advanced energy management, and demand response, are not extensively represented in the collection. This should not be interpreted as a lack of research activity in these fields. Rather, recent studies demonstrate their growing importance and reveal opportunities for closer integration with the spatial, thermal, and electrical aspects of building design addressed in this Special Issue.

One of the principal research challenges is to establish a stronger connection between solar resource assessment and the actual energy needs of buildings. Although advances in geographic information systems, three-dimensional modeling, and deep learning have improved the assessment of rooftop and façade solar potential [7], maximizing annual solar irradiation or electricity generation does not necessarily result in optimal building performance. The effectiveness of solar installations also depends on the temporal distribution of demand, building function, occupancy patterns, and the availability of energy storage. Future research should therefore combine high-resolution solar resource models with realistic, time-resolved demand profiles. Moreover, the orientation, geometry, and distribution of solar technologies should be optimized for specific building types and climatic conditions rather than solely according to conventional rules for maximizing annual solar exposure. Such an approach would enable a more comprehensive assessment of trade-offs among PV generation, daylight availability, heating and cooling demand, and architectural constraints.

A closely related challenge concerns the integration of solar technologies with heat pumps and energy storage systems. Recent investigations of PV-assisted air-source heat pumps and other hybrid configurations have demonstrated the potential to improve energy performance while highlighting the importance of matching energy generation and demand across different timescales [8]. Similarly, studies of PCM-based storage and PV/T systems indicate opportunities to improve the utilization of solar energy for heating and cooling applications [9,10]. Nevertheless, PV systems, heat pumps, and storage devices are still frequently assessed or sized as separate components. Future research should place greater emphasis on their simultaneous optimization, considering interactions between electrical and thermal energy flows, operating strategies, and the flexibility provided by different storage technologies.

The temporal dimension becomes particularly important when seasonal variations in solar availability and thermal demand are considered. Short-term storage can shift energy consumption over hours or days, but it cannot fully address the mismatch between high solar availability in summer and substantial heating requirements in winter. Recent research on solar-assisted borehole storage, pit thermal energy storage coupled with PV/T collectors, and adsorption-based thermal batteries demonstrates promising approaches to longer-term

energy storage [11–13]. Further investigations should assess the technical and economic feasibility of these solutions under different climatic conditions and building or district energy demand profiles. Long-term experimental validation is also needed to establish appropriate levels of modeling detail and to evaluate storage performance under realistic operating conditions.

Advanced control represents another essential direction for improving the performance of integrated solar building systems. Model predictive control (MPC) enables operating decisions to be informed by forecasts of weather conditions, energy demand, and electricity prices. For example, economic MPC has been reported to reduce daily operating costs by up to approximately 27% compared with rule-based control in a building energy system incorporating PV, a heat pump, thermal storage, and an electric vehicle [14]. Experimental investigations have also demonstrated the potential of predictive control to reduce operating costs and emissions while maintaining acceptable indoor conditions [6]. However, control strategies should not be considered independently of system design. The optimal capacity of storage devices, heat pumps, and solar installations depends partly on how these components are operated. Integrating equipment sizing and control optimization could therefore improve overall performance while reducing the need for system oversizing.

Digital twins offer a complementary means of connecting design models with actual building operation. By integrating building information modeling (BIM), building energy modeling (BEM), sensor measurements, and operational data, digital twins can support continuous performance assessment, fault detection, and adaptive control. Recent approaches to continuous model calibration, including methods capable of handling incomplete or noisy sensor data, illustrate the potential of this concept [7]. Nevertheless, the practical application of digital twins requires a careful balance between model accuracy, computational complexity, and data availability. As also suggested by the investigation of thermal storage modeling in this Special Issue, the appropriate level of model detail depends on the intended application. Future research should therefore focus on computationally efficient, continuously calibrated models that can support reliable real-time decisions throughout the building life cycle.

The increasing penetration of distributed photovoltaics also creates challenges that cannot be resolved at the individual building level. As demonstrated by Kowalak et al., the technical feasibility of installing PV systems does not guarantee that the corresponding generation capacity can be accommodated by the local electricity network. Voltage constraints, transformer loading, and limited hosting capacity may restrict further deployment, particularly in densely populated residential areas. Future solar building design should consequently incorporate grid interaction from the earliest planning stages. Coordinated operation of PV systems, flexible heat pumps, thermal storage, batteries, electric vehicle charging, and smart inverters could reduce peak electricity exports and improve the utilization of locally generated energy. This calls for a transition from building-level energy optimization toward coordinated building-to-grid strategies, supported by time-resolved assessments of self-consumption, peak demand, and operational flexibility.

Environmental and economic performance must also be considered over the entire building life cycle. Although solar technologies can substantially reduce operational energy consumption and associated emissions, their overall environmental benefits depend on manufacturing processes, material selection, system durability, maintenance requirements, and end-of-life management. Recent parametric assessments of PV and BIPV systems have demonstrated the importance of embodied environmental impacts [15], while studies combining life-cycle assessment and life-cycle costing have highlighted the need to consider environmental and economic criteria together [16]. This perspective is increasingly relevant in light of the recast Energy Performance of Buildings Directive, which introduces

requirements for reporting the life-cycle global warming potential of new buildings [17]. Future research should therefore integrate operational energy performance, embodied carbon, life-cycle costs, component replacement, and circularity within multi-objective optimization frameworks.

Finally, the resilience of solar energy systems under changing climatic conditions requires greater attention. Design solutions optimized using historical weather data may perform differently under future conditions characterized by higher ambient temperatures, increased cooling demand, and more frequent extreme weather events. Recent investigations have also highlighted complex interactions between rooftop PV installations, building cooling requirements, and thermal conditions during heatwaves [18]. Future studies should therefore evaluate solar building systems using projected climate scenarios and explicitly consider their ability to maintain acceptable indoor conditions and essential energy services during extreme events or electricity supply disruptions. This is particularly relevant for hybrid systems in which solar electricity generation, heat pumps, cooling technologies, and energy storage interact dynamically.

Taken together, these research directions point toward a common objective: the development of integrated, adaptive, and resilient solar building energy systems. Achieving this objective will require interdisciplinary approaches that combine architectural and urban design, renewable energy technologies, thermal and electrical storage, predictive control, grid integration, and life-cycle assessment. Particular emphasis should be placed on experimentally validated models, realistic operating conditions, and performance indicators that capture both short-term dynamics and long-term outcomes. The next generation of solar-powered buildings should therefore be designed not merely to maximize renewable energy generation, but to coordinate energy production, conversion, storage, consumption, and exchange in a manner that improves overall system performance across different spatial and temporal scales.

5. Conclusions

The six articles published in the Special Issue Advances in the Design and Application of Solar Energy in Buildings address different yet complementary aspects of solar energy utilization in the built environment. Their contributions encompass the morphology of urban building complexes, automated rooftop assessment, balcony-mounted photovoltaics, technical constraints on PV integration in multi-family buildings, thermal energy storage, and integrated architectural and energy retrofitting.

Considered collectively, these studies demonstrate a progressive expansion of the boundaries of the design problem. Optimization begins with solar resource availability and geometry, but ultimately leads to questions concerning energy demand, storage, transient dynamics, building operation, and grid constraints. Maximizing the energy generated by an individual component therefore cannot be equated with optimizing the performance of the entire system.

The next stage in the development of this field is likely to be characterized by closer integration between electrical and thermal energy systems. PV and PV/T technologies will increasingly operate alongside heat pumps, batteries, and short- and long-term thermal energy storage. Their operation will be coordinated through predictive control and digital twins, while performance will be assessed not only in terms of annual energy balances but also through self-consumption, grid flexibility, comfort, resilience, cost, and life-cycle carbon emissions. This transition is further reinforced by new requirements concerning zero-emission buildings, solar energy integration, and life-cycle GWP.

The central research challenge is therefore no longer simply to increase the amount of solar radiation that a building can capture. Rather, it is to coordinate energy generation, de-

mand, storage, conversion, and exchange across both time and space. From this perspective, the future of solar energy in buildings can be understood as a transition from optimizing solar resource utilization to optimizing a dynamic energy system in which buildings play an active role.

Conflicts of Interest: The author declare no conflict of interest.

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