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Integrated Photovoltaic–Phase Change Material and Hybrid Renewable Energy Systems: A Literature-Based Review

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Abstract

The increasing demand for reliable and sustainable energy has accelerated research into photovoltaic (PV) systems, hybrid renewable energy configurations, thermal energy storage, and multifunctional building-integrated solar technologies. This paper presents a literature-based analysis of 25 studies supplied as references for the development of an integrated renewable-energy concept involving PV generation, phase change material (PCM) thermal management, hybrid solar–wind operation, and energy management. The reviewed literature indicates that elevated PV temperature is an important limitation because thermal accumulation can reduce electrical performance, while PCM-based thermal storage can absorb excess heat and moderate temperature variation. Enhanced heat-transfer approaches, including porous fins, nanoparticle-enhanced PCMs, and improved flow arrangements, are reported as promising routes for overcoming the relatively low thermal conductivity of conventional PCMs. The literature also demonstrates that combining solar and wind resources can improve renewable-resource utilization and reduce the effects of intermittency, particularly when storage and intelligent control are included. Transparent photovoltaic technologies provide an additional pathway for integrating generation into windows and building envelopes. Based on these findings, an integrated PV–PCM and hybrid renewable-energy architecture is proposed as a suitable direction for further experimental investigation. Because the supplied material consists primarily of literature summaries rather than original experimental measurements, the results and discussion in this paper are presented as a comparative literature synthesis and not as newly measured performance data.

Keywords

Photovoltaic system; Phase change material; PV thermal management; Hybrid renewable energy; Solar–wind system; Transparent photovoltaic; Thermal energy storage; Energy management; Sustainable energy

1. Introduction

The transition toward low-carbon energy systems requires technologies that can generate electricity efficiently while maintaining reliability under variable environmental conditions. Solar photovoltaic technology has become an important renewable-energy option because it can convert incident solar radiation directly into electrical power and can be implemented from small distributed installations to large energy systems. However, PV performance is strongly affected by operating temperature. Under high solar irradiance, part of the absorbed solar energy becomes heat, increasing module temperature and contributing to a reduction in electrical conversion performance. The literature supplied for this study therefore places substantial emphasis on thermal management and on methods of recovering or storing otherwise unused heat [9,14,23,24].

Phase change materials offer a passive means of thermal regulation. During a phase transition, a PCM can absorb a substantial amount of thermal energy while maintaining a relatively stable temperature. When incorporated with PV modules, the PCM can store excess heat during periods of strong solar radiation and release it later. This can moderate temperature peaks and potentially improve the operating environment of the PV module. The reviewed studies further show that PCM performance is closely related to melting temperature, latent heat, thermal conductivity, geometry, and heat-transfer enhancement [12,14,15,23].

A second major direction in the literature is the integration of multiple renewable resources. Solar generation varies with irradiance and time of day, while wind generation depends on local wind conditions. Combining complementary resources can reduce the dependence on a single intermittent source. Studies of hybrid solar–wind systems and wider renewable-energy systems emphasize appropriate capacity sizing, storage, control, and resource assessment as important design variables [2,3,5,8,19,20,24,25].

Another emerging area is transparent photovoltaic technology. Transparent PV systems can convert portions of incident light into electricity while allowing daylight transmission, creating opportunities to integrate renewable generation into windows, facades, and other building surfaces. The literature identifies efficiency, transparency, durability, cost, and scalability as continuing challenges [1,22]. A multifunctional window can therefore be viewed not simply as a building component but as an energy interface capable of combining daylighting, electrical generation, thermal management, and potentially thermal storage.

The 25 supplied studies collectively indicate that future renewable-energy systems will increasingly depend on integration rather than isolated technologies. PV generation, PCM-based thermal regulation, hybrid solar–wind generation, thermal storage, and intelligent energy management can be combined to improve utilization of available renewable resources. The purpose of this paper is to synthesize the supplied literature, identify the major technical approaches, compare their reported contributions, and formulate a methodology and component architecture suitable for future experimental development.

2. Literature Analysis

2.1 Photovoltaic and transparent solar technologies

The supplied literature identifies photovoltaic generation as the central electrical conversion technology in many of the reviewed systems. Conventional PV installations can be complemented by new integration concepts in which the generating surface becomes part of a building component. The review on transparent solar panels describes their potential for smart infrastructure and multisectoral applications, while the study on transparent photovoltaic technologies emphasizes their integration into building envelopes, windows, and facades [1,22]. These approaches are significant for applications where roof area is limited but window and facade area is available.

The literature also emphasizes that PV technology cannot be assessed only through electrical conversion. Thermal behavior, durability, material selection, optical transmission, and building integration affect the overall usefulness of a system. Accordingly, transparent PV systems introduce a multi-objective design problem in which electrical output must be balanced with daylight transmission and architectural requirements [1,22].

2.2 PCM-based photovoltaic thermal management

PCM-based thermal management is one of the strongest themes in the supplied studies. The literature describes PCMs as thermal storage media that absorb heat during the phase transition and subsequently release it as conditions change. Their integration with PV modules can reduce thermal peaks and improve temperature stability [12,14,23]. This approach is attractive because it can operate passively and does not necessarily require continuous electrical power for cooling.

A major limitation is the relatively low thermal conductivity of many conventional PCMs. The reviewed research addresses this through structural and material enhancements. Arc-shaped porous fins are proposed to enlarge the effective heat-transfer area and improve heat distribution within the PCM [14]. Nanoparticle-enhanced PCM is investigated for thermal storage tanks, with the supplied review reporting faster heat transfer and improved charging and discharging characteristics [15]. A separate study on MgO-enhanced PCM, metallic microchannels, and thermoelectric generators illustrates a hybrid active–passive strategy for PV cooling [9]. These approaches suggest that future PV–PCM designs should treat PCM selection and heat-transfer enhancement as a coupled design problem.

2.3 PV/T and hybrid thermal systems

PV/T systems attempt to use the thermal energy associated with PV operation instead of treating it solely as a loss. The supplied critical review compares air cooling, liquid cooling, and PCM-based cooling and identifies differences in simplicity, heat-removal capacity, thermal recovery, and system complexity [12]. Liquid systems can provide effective heat removal and useful thermal energy recovery, whereas PCM systems offer passive temperature regulation. Hybrid systems can combine these mechanisms when the additional components and control requirements are justified.

The supplied literature also includes studies involving PV-assisted solar distillation and PV/T-integrated desalination. These systems demonstrate that thermal energy recovered from solar technologies can be redirected to useful processes such as water evaporation, while PV components simultaneously contribute electrical power [4,16,17]. Such work supports the broader concept of cascading energy use, where a single solar input is utilized through multiple conversion and storage pathways.

2.4 Solar–wind hybrid renewable energy systems

Solar–wind hybridization is repeatedly identified as a means of improving renewable-resource availability. Solar and wind generation do not necessarily reach their maximum output at the same time, so resource complementarity can help reduce supply fluctuation. The supplied literature discusses resource complementarity, techno-economic optimization, regional planning, capacity configuration, and energy management as important aspects of hybrid system design [3,5,8,19,20,24].

The literature further shows that hybridization alone does not guarantee reliable operation. Generation capacity, storage size, load profile, transmission or grid interaction, and control strategy must be selected together. Optimization studies indicate that regional renewable-resource characteristics strongly influence the appropriate capacity configuration [19,20]. Therefore, a small prototype should use measured local solar and wind conditions rather than assuming that one fixed configuration is optimal.

2.5 Energy storage and intelligent energy management

Energy storage is a recurring enabling technology in the reviewed literature. Thermal storage through PCMs can regulate PV temperature or store useful heat, while electrical storage can balance differences between renewable generation and load demand. The reviewed hybrid-system studies emphasize the need for coordinated charging, discharging, load management, and system sizing [2,3,5,20,25].

Recent work described in the supplied references also points toward explainable cost-optimized dispatch, digital monitoring, advanced optimization, and intelligent control [2,25]. These developments are relevant to a proposed prototype because a microcontroller-based energy management unit can prioritize renewable sources, monitor battery state, and coordinate the load without requiring a complex full-scale grid controller.

2.6 Sustainability and environmental considerations

Renewable-energy deployment must be considered alongside environmental impacts. The supplied study on large-scale wind and solar development emphasizes strategic site selection, biodiversity conservation, environmental assessment, and land-use planning [13]. This indicates that a technically efficient renewable system should also be evaluated in terms of material use, maintenance, lifecycle impacts, and the location of infrastructure. For building-integrated systems, using existing architectural surfaces may provide an opportunity to reduce additional land requirements while simultaneously serving an energy function.

3. Methodology

This study follows a structured literature-synthesis methodology based on the 25 paper summaries and reference entries supplied for the project. The papers were grouped into five technical themes: (i) photovoltaic and transparent photovoltaic generation, (ii) PCM-based thermal management and thermal energy storage, (iii) PV/T and solar-thermal applications, (iv) hybrid solar–wind renewable-energy systems, and (v) optimization and intelligent energy management. The findings were then compared to identify common design requirements, limitations, and opportunities for integration.

Based on the literature, an integrated prototype architecture is proposed. The architecture consists of a PV generation unit, a PCM thermal-management layer, a small wind-energy unit where site conditions permit, a charge-management stage, an electrical storage unit, sensors, and a microcontroller-based energy-management controller. For a transparent-window implementation, the PV element can be incorporated into or mounted on a transparent/sliding window arrangement, subject to the selected PV technology and required optical transmission.

The proposed experimental evaluation should measure solar irradiance, PV voltage and current, PV surface temperature, PCM temperature, ambient temperature, wind speed, wind-generator output, battery voltage, load power, and total generated energy. Tests should compare a reference PV configuration with PV–PCM thermal management and, where feasible, the complete hybrid configuration. Performance indicators should include electrical power, energy yield, maximum PV temperature, temperature reduction, PCM charging/discharging duration, renewable fraction, and system efficiency.

4. Components Used

Component	Function
Photovoltaic module / transparent PV element	Converts solar radiation into electrical power; the transparent option is intended for building-window integration.
Phase change material (PCM)	Stores thermal energy during phase transition and moderates PV temperature.
Thermal enhancement structure	Fins, porous structures, conductive plates, or similar heat-transfer elements can improve heat spreading through the PCM.
Small wind turbine / generator	Provides supplementary renewable electricity during suitable wind conditions and can complement solar generation.
Charge controller / DC-DC converter	Regulates renewable-source power and provides suitable voltage/current for storage and loads.
Rechargeable battery	Provides short-term electrical storage so that the load can be supplied when renewable generation is insufficient.
Microcontroller	Collects sensor data and implements basic energy-management decisions.
Temperature sensors	Measure PV, PCM, ambient, and other relevant

	temperatures.
Voltage and current sensors	Measure electrical generation, battery condition, and load demand.
Irradiance and wind-speed sensors	Provide environmental measurements for performance analysis.
Electrical load	Represents the intended application and provides a controlled demand for evaluating the energy-management strategy.
Window/sliding frame or prototype enclosure	Provides mechanical support and enables investigation of transparent PV integration.

5. Proposed System Operation

During daylight, the PV element converts solar radiation into electrical energy. Simultaneously, part of the absorbed solar energy raises the PV temperature. The PCM layer receives this excess thermal energy and undergoes phase change when the required temperature is reached, thereby moderating the PV operating temperature. If a wind source is included and sufficient wind is available, the wind generator supplies additional electrical power. The energy-management controller monitors the renewable sources, storage condition, and load demand and allocates available energy according to predefined priorities.

A practical control sequence for a small prototype is: renewable generation first supplies the load; surplus electrical power charges the battery; when renewable generation is lower than the load, the battery supplements the renewable source; and when battery state reaches a predefined lower limit, non-critical loads are reduced or disconnected. Sensor data are logged for comparison of operating conditions. The thermal subsystem is evaluated independently by tracking PV and PCM temperatures so that electrical and thermal effects can be correlated.

6. Results and Discussion

Because the supplied material contains literature summaries rather than a new experimental dataset, the results presented here are synthesized findings from the reviewed studies and should not be interpreted as measurements from the proposed prototype.

6.1 Effect of thermal management on PV operation

Across the supplied literature, thermal management is consistently presented as a key route for maintaining more favorable PV operating conditions. PCM-based systems can absorb excess heat during high-temperature periods, while enhanced geometries and conductive additions are intended to improve the rate at which heat enters the storage medium [9,14,15,23]. The literature therefore supports the expectation that an appropriately selected PV–PCM system can reduce temperature excursions relative to an uncooled reference module. The magnitude of improvement, however, depends on irradiance, ambient conditions, PCM properties, thermal contact resistance, and the duration of the charging process.

6.2 Importance of PCM heat-transfer enhancement

The studies on porous fins and nanoparticle-enhanced PCM demonstrate that PCM selection alone is insufficient when rapid thermal response is required [14,15]. Increasing effective thermal conductivity and heat-transfer area can reduce the thermal resistance between the PV surface and the PCM. This is particularly important for compact prototypes because the available PCM volume and surface area are limited. A practical design must therefore balance thermal performance against manufacturing complexity, weight, cost, and long-term material stability.

6.3 Benefits of hybrid solar–wind generation

The hybrid-energy literature indicates that combining solar and wind resources can improve the temporal availability of renewable power, particularly when the resources show complementary behavior [5,8,19,24]. Optimization studies further indicate that the best configuration depends on resource conditions and the required reliability [3,20]. For a small prototype, the wind unit should therefore be considered a supplementary source rather than assumed to provide

continuous power. Measurement of local wind conditions is necessary before determining whether its contribution justifies the additional mechanical and electrical complexity.

6.4 Transparent PV and multifunctional windows

Transparent PV technologies create an opportunity to use window surfaces for energy generation while retaining daylight access [1,22]. The literature also includes a sliding-window concept combining PV, thermoelectric cooling, and multiple PCMs, showing how a window can be designed as a multifunctional thermal and electrical system [11]. The principal trade-off is that higher optical transparency can be associated with reduced electrical conversion potential, while additional thermal and electrical components increase cost and system complexity. Therefore, the design objective should be multifunctional performance rather than maximum PV efficiency alone.

6.5 Energy storage and control

The reviewed hybrid-system literature indicates that generation and storage should be optimized together [2,3,20,25]. A battery can smooth short-term renewable fluctuations, while a controller can determine when energy is directed to loads or storage. Thermal storage through PCM serves a different but complementary function: it manages heat rather than directly supplying electrical demand. Combining electrical and thermal storage can therefore improve overall utilization of the solar input, provided the added components do not introduce disproportionate losses or cost.

6.6 Research gap identified from the supplied literature

The major opportunity identified from the combined literature is the integration of technologies that are often studied separately. Transparent PV research primarily addresses building integration; PCM studies focus on thermal regulation; solar–wind studies address resource complementarity; and energy-management studies address dispatch and storage. A compact prototype that combines these functions can provide a platform for evaluating electrical generation, thermal regulation, renewable resource complementarity, and energy management within one system. The principal research challenge is to demonstrate that the additional integration produces a net performance benefit after accounting for thermal, electrical, mechanical, and economic losses.

7. Conclusion

The literature reviewed in this paper demonstrates that improving renewable-energy performance requires simultaneous attention to generation, thermal management, energy storage, resource complementarity, and control. PV systems can benefit from thermal regulation because high operating temperatures are an important performance limitation. PCMs provide a passive thermal-storage mechanism, while fins, porous structures, nanoparticles, and other heat-transfer enhancements can improve their effectiveness [9,14,15,23]. Hybrid solar–wind configurations can improve renewable-resource utilization, but their performance depends strongly on local resource conditions, capacity sizing, storage, and control [3,5,8,19,20,24]. Transparent PV technologies additionally provide a pathway for converting building windows and envelopes into energy-generating surfaces [1,22].

On the basis of these findings, an integrated PV–PCM hybrid renewable-energy prototype is a technically relevant direction for future experimental work. The proposed system can combine PV generation, PCM-based thermal management, supplementary wind generation, electrical storage, sensing, and an energy-management controller. Future work should experimentally compare a reference PV module with the integrated configuration under controlled and outdoor conditions, quantify thermal and electrical performance, optimize PCM properties and geometry, and evaluate cost and lifecycle considerations. Such an approach can move the concept from literature synthesis toward a measurable and scalable renewable-energy solution.

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Source note

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