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Research and Reviews in Sustainability

Journal homepage: sustainability-journal.com

Review article

Review of Recent Solar-Powered Cooling Systems

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ABSTRACT

With the increasing global demand for cooling and the rising environmental concerns associated with conventional cooling systems, solar-powered cooling technologies have emerged as a sustainable alternative. This study provides a comprehensive review of recent advancements in solar-powered cooling systems, highlighting the latest technological developments, challenges, and future directions. The paper classifies solar cooling technologies into two primary categories: Solar electric cooling and solar thermal cooling. It discusses various configurations, including PV-assisted vapour compression systems, solar absorption and adsorption cooling system, and hybrid approaches that integrate thermoelectric and thermal cooling mechanisms. The findings indicate that while solar cooling systems offer significant energy savings and carbon emission reductions, several technical, economic, and operational challenges remain. Key issues include the intermittency of solar energy, efficiency limitations of current photovoltaic and thermal conversion technologies, and high initial investment costs. Moreover, the effectiveness of different solar cooling methods varies depending on climatic conditions and building types, necessitating further research on system optimisation and scalability. Future research should focus on improving photovoltaic efficiency through advanced materials such as perovskite-silicon tandem cells, enhancing thermal storage systems, and integrating artificial intelligence-based optimisation for real-time energy management. Besides, hybrid cooling approaches that combine passive and active strategies, along with emerging energy storage solutions, could further enhance the viability of solar cooling technologies. By addressing these challenges, solar-powered cooling systems can play a crucial role in reducing energy consumption in the building sector and contributing to global sustainability goals.

ARTICLE INFO

Article History:

Received: 02 January 2026

Revised: 04 February 2026

Accepted: 15 February 2026

Keywords:

HVAC system
Solar electric cooling
Solar thermal cooling
Hybrid cooling systems
Energy efficiency

Article Citation:

Zheng, T., Jarimi, H., & Su, Y. (2026). Review of Recent Solar-Powered Cooling Systems. *Research and Reviews in Sustainability*, 2(1), 85–102. <https://doi.org/10.65582/rrs.2026.007>

1. INTRODUCTION

The urgent need for climate action is evident, as failure to increase ambition in new Nationally Determined Contributions (NDCs) could result in a global temperature rise of 2.6–3.1°C this century, leading to severe environmental and economic consequences. Mitigating global greenhouse gas emissions, which reached a record 57.1 GtCO₂e in 2023, necessitates significant reductions, particularly in the power sector, which remains the largest contributor at 15.1 GtCO₂e (United Nations Environment Programme, 2024).

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The building sector accounts for approximately 40% of global final energy consumption (Pérez-Lombard et al., 2008), with a substantial proportion attributed to cooling and air-conditioning (Ürge-Vorsatz et al., 2015). With rising temperatures and urbanisation, the demand for cooling systems in buildings is escalating, leading to an increase in energy consumption and, consequently, higher carbon emissions (Dilshad et al., 2020). The trend underscores the urgent need for the development and deployment of more sustainable alternatives that can reduce energy consumption while meeting the cooling needs of buildings.

One promising solution to mitigate the environmental impact of cooling systems is to enhance building energy performance can be achieved through passive and active strategies, including thermal improvements to building envelopes and advancements in heating, ventilation, and air conditioning (HVAC) systems. Utilising solar energy for cooling applications has gained significant attention due to its potential to reduce CO₂ emissions and mitigate global warming (Amponsah et al., 2014). Despite the growing interest and potential of solar-powered cooling technologies, the field remains underexplored in many areas. Although research has progressed, there is still much to learn regarding the most effective methods for integrating solar energy with cooling systems in buildings. Challenges related to efficiency, cost, and scalability persist, and significant gaps remain in understanding the optimal configurations for different climates and building types. Given these considerations, it is clear that comprehensive research is still needed to fully realise the future directions of solar-powered cooling systems.

This study aims to provide a systematic review of solar powered cooling technologies, synthesising insights from recent literature while highlighting the key areas that require further investigation. By examining various solar cooling systems employed in research and development, this review seeks to enhance researcher's understanding of the challenges and opportunities within the field. As the fundamentals of solar powered technologies have already been extensively summarised in existing literature reviews, this study emphasised the recent application in difference types of solar powered systems. Through this comprehensive analysis, the future innovations in solar cooling technologies will be guided, the global efforts to combat climate change will be contribute by promoting sustainable energy solutions for the building sector.

While the publication timeframe was not rigidly constrained, particular emphasis was placed on selecting literature published between 2020 and 2025 to ensure the inclusion of the most contemporary and state-of-the-art advancements in the field.

2. LITERATURE REVIEW

Solar energy can be utilised to power cooling and air-conditioning systems through two primary methods: electrical and thermal conversion. In the electrical approach, photovoltaic (PV) panels convert solar radiation into electricity, which then powers conventional cooling systems. These systems are commonly referred to as solar electric/vapour compression refrigeration (SE-VCR) systems or solar PV-assisted cooling systems.

In contrast, solar thermal cooling systems utilise thermal energy from solar radiation to reduce electricity consumption, particularly in small-scale applications. These systems employ solar collectors, such as flat-plate, evacuated tube, or parabolic trough collectors, to capture and convert solar radiation into heat. This thermal energy is then used to drive absorption or adsorption chillers, which generate cooling through thermochemical processes. Due to their efficiency in large-scale applications, solar thermal cooling systems are particularly well-suited for district cooling. There are three primary types of solar thermal cooling systems used in building applications: open-cycle, closed-cycle, and thermo-mechanical cycle systems. Figure 1 shows the classification of the solar powered cooling system.

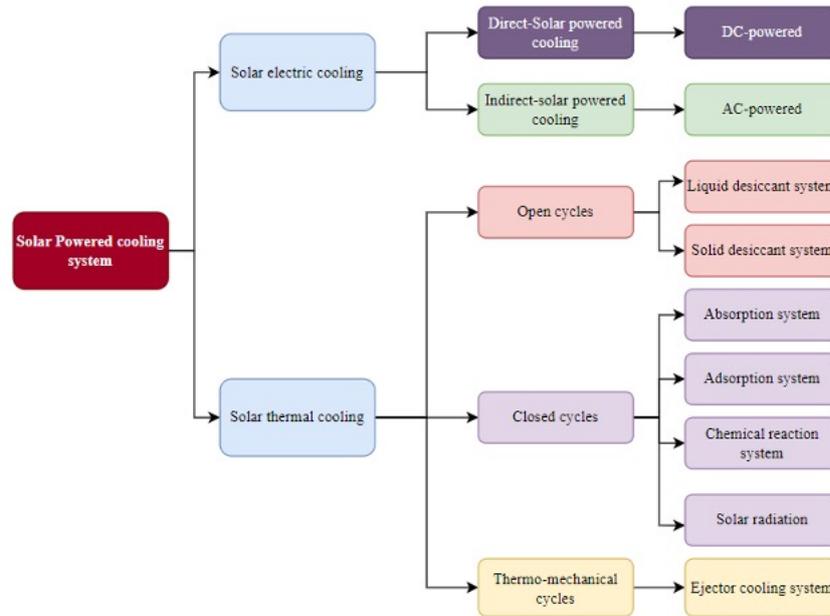


Figure 1. The classification of solar-powered cooling system.

2.1. SOLAR ELECTRIC COOLING SYSTEMS

Li et al. (2021) demonstrated a 3 HP solar direct-drive PV air-conditioning system that incorporated ice thermal storage to capture excess solar energy without the need for batteries (See Figure 2). In the absence of a stable power supply, fluctuations in PV power output could cause the refrigeration compressor to lose power, preventing it from starting or shutting down properly. To ensure continuous and stable operation, an adaptive controller and an appropriately matched compressor were required to align with the power demands of the solar air-conditioning system. For this field experiments, several solar air conditioning prototypes were developed and tested, each featuring different configurations of PV panel capacity, the presence or absence of a maximum power point tracking (MPPT) controller, and various compressor types. The experimental results indicated that the system incorporating a variable-speed compressor and an MPPT controller exhibited reliable operation, efficient ice-making performance, and a substantial improvement in available solar energy utilisation. The highest COP reached 0.289 when the daily cumulative solar irradiance was 18.2 MJ/m². The MPPT controller increased the PV-to-compressor power efficiency (PPE) by 81.7%, reducing power fluctuations and improving compressor startup reliability. The variable-speed compressor outperformed an ordinary compressor, achieving up to 96.24% inverter efficiency compared to 51.22% for a fixed-speed compressor.

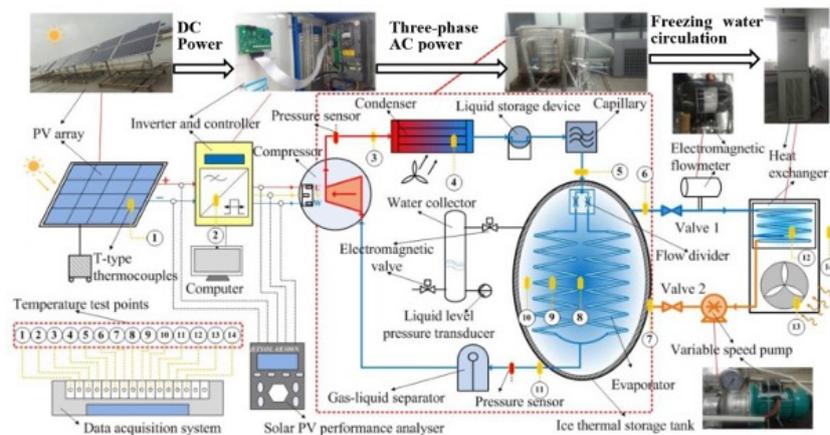


Figure 2. Schematic diagram of the PV-driven air conditioner. Source: (Li et al., 2021).

Du et al. (2021) presented the dynamic performance of a distributed solar PV direct-drive cold storage system designed for off-grid applications in rural and remote areas (See Figure 3). The system consists of a roof-mounted PV array, a DC inverter-driven compressor, cold storage chamber, and a PCM-based cold thermal energy storage (CTES) unit. The innovation lies in the use of direct PV power without battery storage, relying on thermal energy accumulation in the PCM to bridge mismatches between solar availability and cooling demand. A field prototype was developed and monitored under real weather conditions in China. The results show that the system achieved a maximum energy efficiency ratio (EER) of 2.35 and a daily average of 1.75 under varying solar irradiance. The use of PCM allowed the system to continue cooling during non-solar hours with minimal temperature fluctuations, maintaining internal temperatures within 5–15 °C. The dynamic model accurately captured the thermoelectric coupling and was used to predict performance under different seasonal and load conditions. However, limitations include the sensitivity of compressor operation to rapid PV output fluctuations, which can affect system stability in highly intermittent solar environments. Additionally, the absence of electrical storage restricts system autonomy during prolonged cloudy periods. The study suggests incorporating intelligent load-matching controls and improved PCM integration strategies to enhance system reliability and efficiency across broader climatic scenarios.

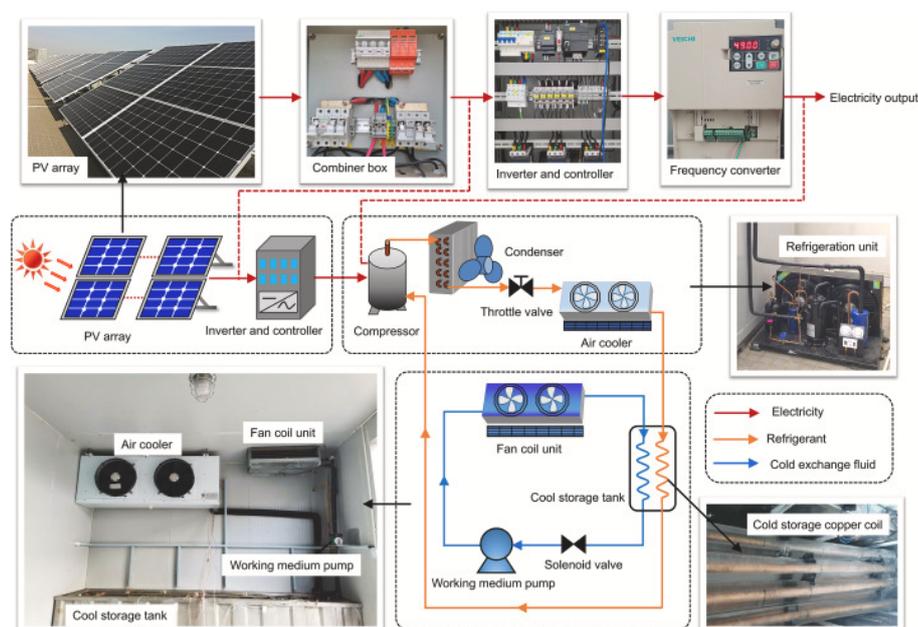


Figure 3. Schematic diagram of the distributed solar PV direct-drive cold storage system.

Source: (Du et al., 2021)

2.2. SOLAR THERMAL COOLING SYSTEMS

2.2.1. OPEN CYCLE COOLING SYSTEM-LIQUID DESICCANT COOLING SYSTEM

Bhowmik et al. (2021) presented an experimental investigation of a solar-assisted thermal liquid desiccant dehumidification system (See Figure 4) that employs a structured packed bed dehumidifier and regenerator using a novel mixed desiccant solution (LiBr + CaCl₂ at an 85:15 mass ratio). The system is thermally driven by evacuated tube solar collectors (ETCs) and operates in a closed loop to ensure continuous dehumidification and regeneration cycles. Key technological innovations include the use of a counter-flow configuration to enhance heat and mass transfer, and a comprehensive instrumentation setup to evaluate performance metrics. The system's dehumidification performance is characterised by a maximum latent heat ratio (LHR) of 0.92 and a thermal coefficient of performance (TCOP) of 1.1. In addition, an Adaptive Neuro-Fuzzy Inference System (ANFIS) was developed to predict performance parameters such as condensation rate, evaporation rate, and effectiveness indices (latent, enthalpy, and sensible), achieving high prediction accuracy with MAPE values of 2.7% and 2.3%. The results highlight that a higher solution-to-airflow (S/A) ratio favours

dehumidification, while a lower S/A ratio enhances regeneration. The system demonstrates effective integration of solar energy for sustainable HVAC applications in hot and humid climates.

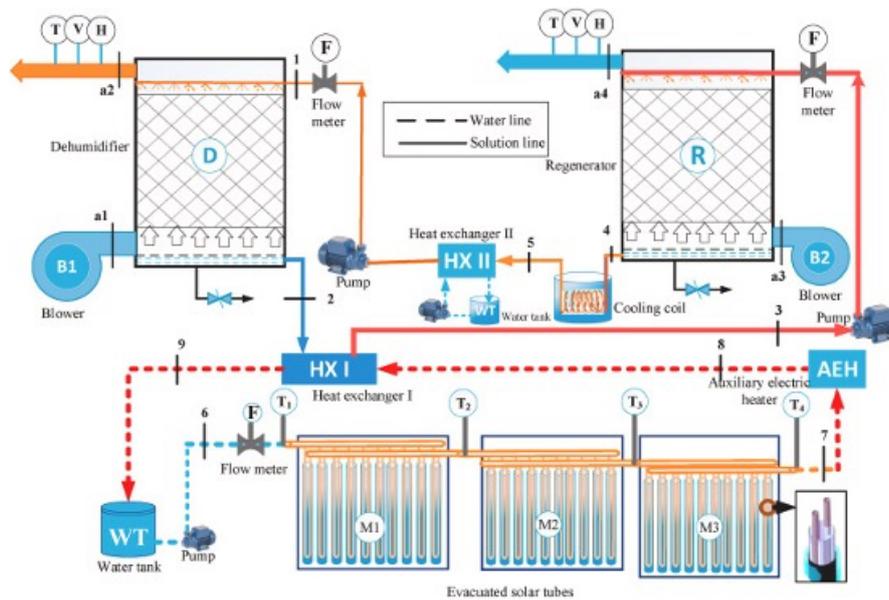


Figure 4. Schematic of the integration of solar evacuated tube collectors for regeneration in a liquid desiccant dehumidification system (T: Temperature; H: Humidity; V: Velocity; F: Flowmeter; D: Dehumidifier; B: Blower; P: Pump; HX: Heat exchanger; R: Regenerator; M: Manifolds; AEH: Axillary electric heater; WT: Water heater).

Source: (Bhowmik et al., 2021).

Zhang et al. (2025) presented an optimised PV/T-assisted desiccant evaporative cooling system (PV/T-DCS) designed for hot and humid urban environments (See Figure 5). By integrating a PV/T system with a liquid desiccant dehumidification and evaporative cooling unit, the system enhances energy efficiency while reducing emissions. The desiccant, lithium chloride, is regenerated using solar thermal energy, reducing the need for conventional power sources. A multi-objective optimisation approach using NSGA-III and Response Surface Methodology (RSM) was applied to balance energy savings, cooling capacity, economic feasibility, and environmental impact. Numerical simulations and performance modelling helped identify the best operational parameters, including air velocity, solution concentration, and recirculation ratio. The results show a 58.1% reduction in energy consumption and a 61% decrease in CO₂ emissions compared to conventional cooling systems, with an effective cooling capacity of 22.9 kW. Under peak conditions, the system achieved a 62.3% energy savings rate and a 64.66% CO₂ reduction. Despite these benefits, the system faces limitations due to its complexity and dependence on solar radiation. Variations in weather conditions impact its effectiveness, and the study does not consider energy storage solutions. Future research could explore ways to simplify the design, improve adaptability across different climates, and integrate energy storage for better reliability.

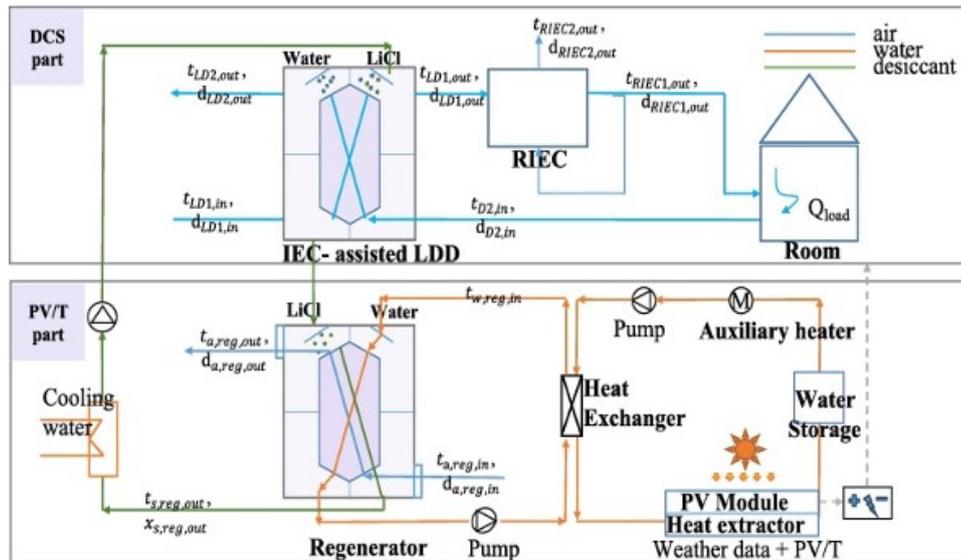


Figure 5. System diagram of liquid desiccant dehumidification and regeneration system. Source: (Zhang et al., 2025).

2.2.2. OPEN CYCLE COOLING SYSTEM - SOLID DESICCANT SYSTEM

Ali et al. (2022) presents an experimental investigation of a hybrid solar-assisted air-conditioning system that integrates a solid desiccant dehumidification unit with an NH₃-H₂O (ammonia-water) absorption chiller (See Figure 6). The system is designed to improve energy efficiency by thermally coupling the desiccant wheel and the absorption chiller: the waste heat from the absorber and condenser of the absorption cycle is recovered to regenerate the solid desiccant. The cooling system operates in two parallel streams—one primarily focused on latent load removal via the desiccant wheel, and the other handling the sensible cooling via the absorption chiller. Solar thermal collectors are employed to drive the generator of the absorption chiller, reducing dependency on fossil fuels. Experimental results indicate that the integrated system can achieve a cooling COP of approximately 0.72, while significantly improving the overall energy utilisation due to heat recovery. The desiccant wheel effectively reduces the latent load on the absorption chiller, allowing the system to perform efficiently even under high humidity conditions. However, the system presents certain limitations: its performance is sensitive to solar irradiance fluctuations, and precise thermal management is required to coordinate heat recovery between the subsystems. The study also notes operational challenges related to desiccant regeneration temperature stability and system control complexity. The authors suggest that optimal integration and advanced control strategies are essential for maximising system efficiency under variable climatic conditions.

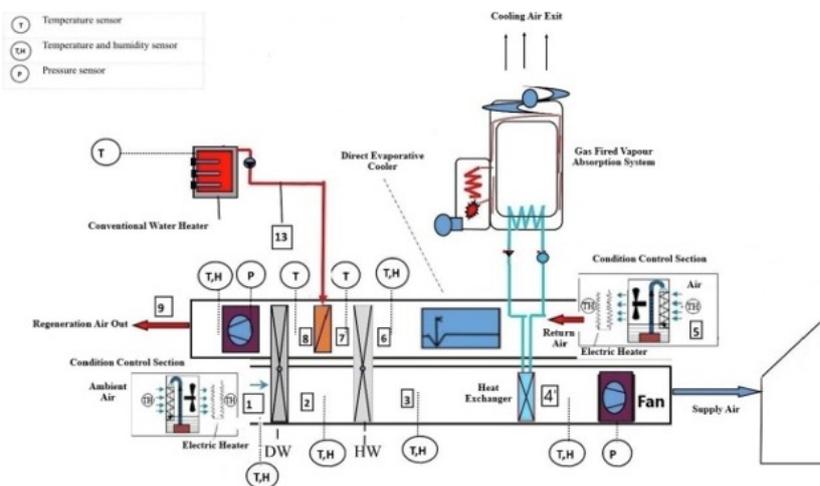


Figure 6. Schematic presentation of the integrated system. Source: (Ali et al., 2022).

2.2.3. CLOSE CYCLE COOLING SYSTEM- ABSORPTION SYSTEM

Riffat et al. (2022) presented an innovative passive-active hybrid absorption cooling system that integrates Phase change materials (PCMs) with a chilled ceiling panel and a transparent infrared membrane, powered by a solar PV driven variable speed DC compressor refrigeration system (See Figure 7). The core technology involves using hydrated salt-based PCM with a melting point of 13°C embedded in a ceiling-mounted radiant cooling panel. The panel is covered with an infrared-transparent membrane to allow radiative cooling while suppressing convective heat transfer, thus preventing surface condensation in humid environments. The system stores excess cooling energy generated during the day in the PCM, which is then used to maintain comfort conditions at night. PV-driven DC compressor system is employed to match variable solar input, eliminating the need for batteries or inverters, which often add cost and inefficiencies. The results showed that the PCM-integrated system maintained 2–2.5°C lower temperatures compared to the non-PCM case for up to 4.5 hours. The transparent membrane effectively prevented condensation but slightly reduced cooling capacity due to the limited convection. Comparisons between chilled beam and chilled ceiling configurations indicated that the chilled ceiling panel with membrane covering provides superior thermal stability in the post-cooling period, due to better PCM utilisation. However, the system's reliance on radiant cooling and lack of active humidity control may restrict its applicability in extremely humid climates without additional dehumidification strategies. Future work is needed to optimise system configurations, scale up for field testing.

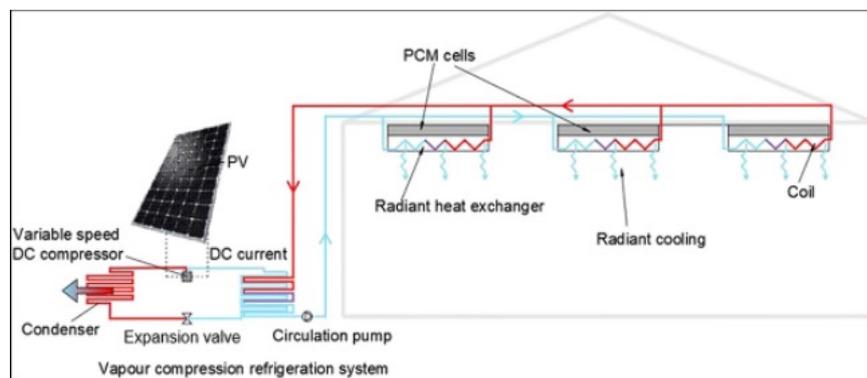


Figure 7. Schematic of a solar PV driven vapour compression cooling system with PCM-integrated chilled ceiling panel. Source: (Riffat et al., 2022).

Jarimi et al. (2024) proposed an absorption system integrates a solar PV-powered DC vapour compression cooling unit with a low-cost ice gel thermal battery as a PCM-based thermal energy storage to mitigate the intermittency of solar power and reduce reliance on expensive batteries or grid extension (See Figure 8). The study introduces four operation modes combining solar PV, grid, battery, and ice gel storage, but identifies Mode B, which is a configuration where the PV system operates the DC vapour compression unit at full power for three hours with the support of ice gel thermal storage and limited battery use as the most optimal. This configuration showed superior COP, particularly COP_{pv} of 4.04 and COP_{system} of 5.05, and the highest SFPVVC (9.10) among the four modes. Moreover, the levelised cost of cooling (LCOC) for Mode B was only 0.0979 USD/kWh, significantly lower than the grid-based or conventional PV systems without thermal storage, making it an economically viable and sustainable alternative for off-grid cooling. Besides, the system employs a DC-powered variable refrigerant flow (VRF) compressor that directly utilises solar energy during the day. Excess cooling is stored in the ice gel thermal battery, a PCM composed of water, glycerine, and alcohol with a freezing point of $\sim 1.9^{\circ}\text{C}$ and latent heat capacity of 361.86 J/g. The thermal storage enables stable indoor temperatures ($22\text{--}26^{\circ}\text{C}$) even during periods of low or no solar irradiance, enhancing thermal comfort and operational reliability in remote settings. To validate system performance, the study also combines artificial neural networks (ANN) for predicting evaporator and inlet temperatures with TRNSYS for building and system simulation. Experimental validation shows great agreement with simulations. The system was field evaluated for a rural healthcare facility in Malaysia, demonstrating it can reliably meet a monthly cooling demand of 631 kWh, with sufficient storage and cooling performance maintained during cloudy conditions. While the system demonstrates significant promise, the authors highlight limitations, including reliance on a proof-of-concept prototype, need for real-world long-term testing, and potential optimisation of control strategies for improved thermal management. Nevertheless, the approach offers a compelling low-cost,

sustainable cooling alternative for underserved rural areas.

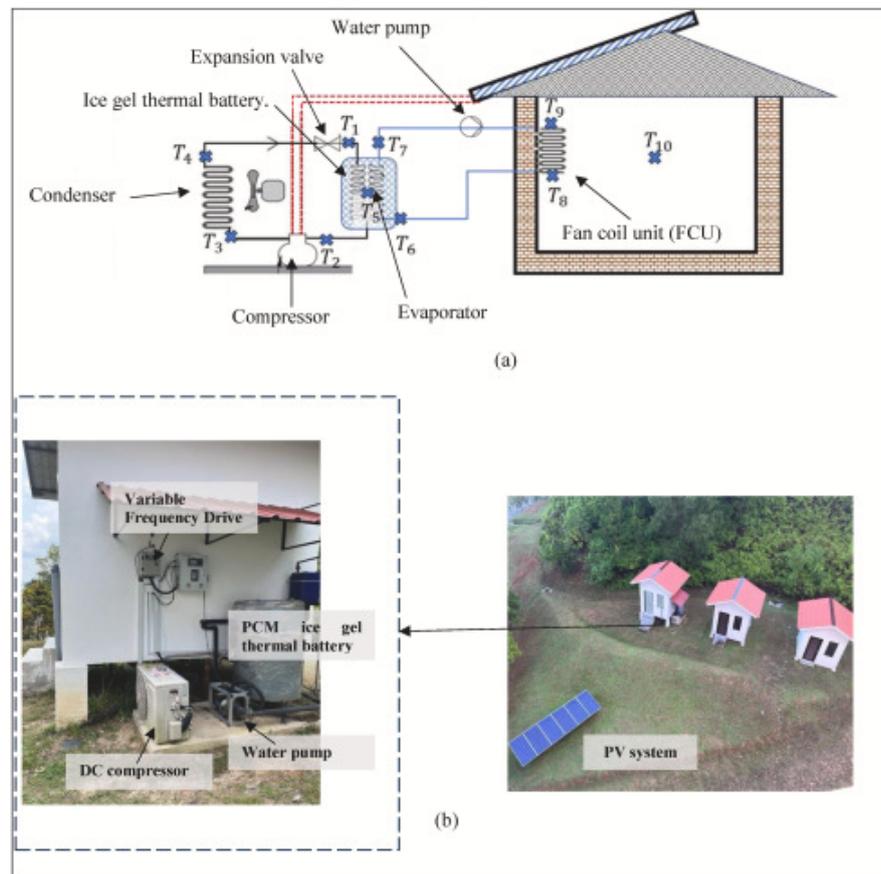


Figure 8. The schematics of the components of the solar PV cooling system (b) the experimental setup of the proof-of-concept prototype.

Source: (Jarimi et al., 2024).

Suhendri et al. (2022) presented a hybrid passive ventilation strategy integrating a solar chimney (SC) and a radiative cooling (RC) cavity (see Figure 9). This dual-system approach is proposed to address the limitations of conventional SC systems by extending ventilation effectiveness into nighttime hours, leveraging the distinct thermodynamic mechanisms of solar-induced buoyancy and nocturnal radiative cooling. The authors developed a two-dimensional transient computational fluid dynamics (CFD) model using ANSYS Fluent to investigate the dynamic performance of the SC-RC system under a range of design and environmental conditions. The simulations were validated against experimental data and applied to a prototypical building model situated in multiple global climate zones. The results indicate that the SC-RC system outperforms conventional SC ventilation in terms of both thermal and ventilation performance, particularly in arid and semi-arid climates. The system achieved a maximum indoor temperature reduction of $2\text{ }^{\circ}\text{C}$ and an average of $0.56\text{ }^{\circ}\text{C}$ below ambient, with ventilation rates reaching up to 2.1 air changes per hour (ACH), an improvement of approximately 0.4 ACH over the reference case. The inclusion of a polyethylene convection cover significantly enhanced the sub-ambient performance of the RC emitter by mitigating convective heat gains. Moreover, the presence of high thermal mass in building materials contributed to thermal stability, while narrower RC cavity gaps enhanced cooling performance at the expense of reduced airflow. The study further demonstrated that the SC-RC system maintained sub-ambient indoor temperatures under internal heat gains up to 4 W/m^2 , beyond which performance began to deteriorate. Notably, in humid climates, the cooling efficacy of the RC component was substantially diminished, rendering the SC-RC system less effective than the SC-alone configuration. However, the authors acknowledge several limitations inherent in the study. These include the exclusion of wind-driven ventilation effects, the simplified assumption of uniform internal heat gains, and the idealisation of boundary insulation on certain building facades.

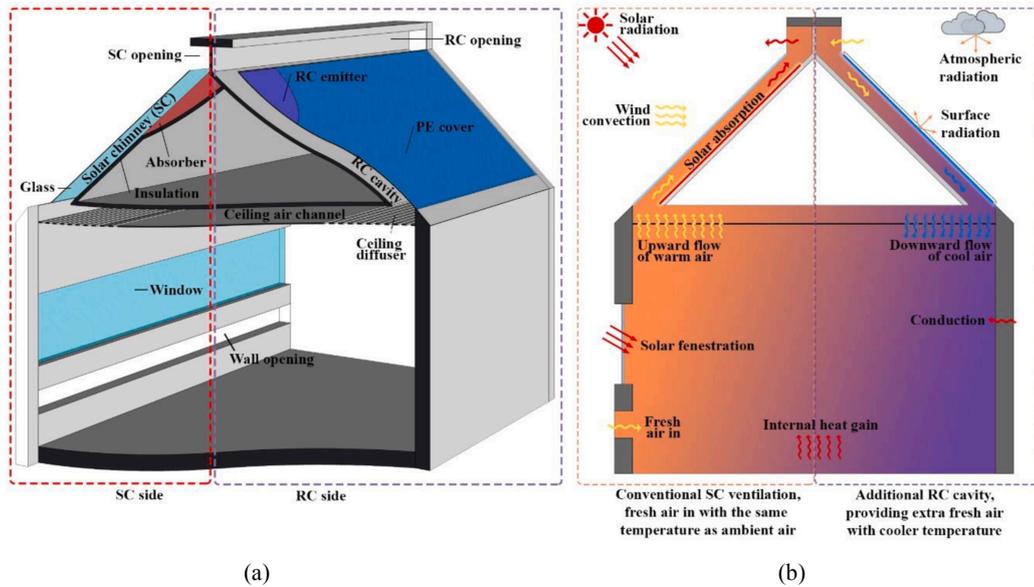


Figure 9. (a) Schematic diagram of roof solar chimney combined with radiative cooling cavity applied in a building and (b) cross-sectional diagram of the transfer phenomena in the building.

Source: (Suhendri et al., 2022).

2.2.4. CLOSE CYCLE COOLING SYSTEM - ADSORPTION SYSTEM

Gado et al. (2021) a comprehensive theoretical investigation into three distinct configurations of solar-powered hybrid cooling systems (See Figure 10) that integrate adsorption and vapour compression technologies, with the aim of enhancing both energetic performance and economic viability under the climatic conditions of Cairo, Egypt. The systems employ silica gel-water as the working pair in the adsorption cycle and R410A as the refrigerant in the compression subsystem. Configuration I integrates a solar thermal subsystem with a hybrid adsorption-compression cycle; Configuration II augments this setup with PV panels to achieve net-zero electricity consumption; and Configuration III incorporates an intermediate cold storage tank to extend operational duration. A dynamic simulation model was developed in MATLAB/Simulink and validated against experimental benchmarks, demonstrating good agreement. The findings indicate that increasing the adsorption-to-compression capacity ratio from 0.867 to 1.333 in Configuration I reduces the intermediate temperature from 15.8 °C to 5.7 °C and enhances daily electricity savings from 23% to 62.5%. Configuration II achieves complete offset of electricity demand via PV supplementation and offers the most favourable economic outcome, with an annual energy saving of 2897 kWh and a payback period of 9.65 years. Although Configuration III enables extended operation (13 vs. 12 hours), it delivers lower annual energy savings (47%) and is economically unviable due to elevated capital costs and a negative internal rate of return. The maximum overall COP of the hybrid system reaches approximately 5.59, compared to 6.9 for a standalone compression system, reflecting the intrinsic thermodynamic limitations of thermal-driven cycles. The study underscores the promise of optimally sized, solar-assisted hybrid systems, particularly those incorporating PV modules, as a viable pathway toward reducing electricity consumption in cooling applications while maintaining reasonable investment payback timelines.

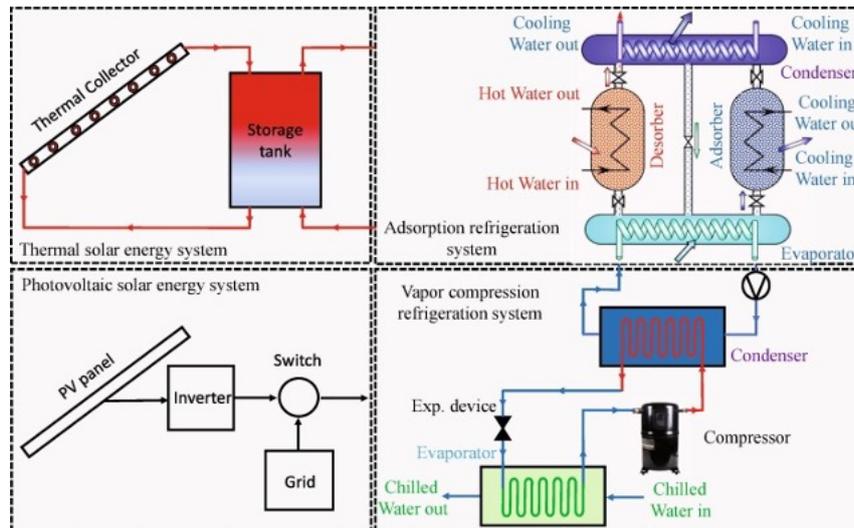


Figure 10. Hybrid adsorption-vapour compression cooling system integrated with thermal solar energy and photovoltaic solar energy system.

Source: (Gado et al., 2021).

Ghazy et al. (2022) explores a novel integration of a PV/T with an adsorption desalination system (ADS) to enhance the efficiency of solar cells and concurrently produce cooling and fresh water, which is shown in Figure 11. This hybrid approach targets the pressing issues of reduced photovoltaic efficiency under high temperatures and freshwater scarcity in hot, arid regions. The core innovation lies in using the chilled water generated from the evaporator of the ADS to actively cool the back of the PV module via a custom-designed sheet-and-tube collector. In turn, the heat extracted from the PV panel is used to enhance the desorption process of the ADS, thus creating a synergistic energy exchange loop between electricity generation and water desalination. This bidirectional thermal integration is tested under real-world hot weather conditions in Sohag, Egypt. The results demonstrate that the hybrid HPV/T-ADS system achieves an electrical efficiency of 11.5% and a thermal efficiency of 77.5% at 1000 W/m² solar radiation and 45 °C ambient temperature. Additionally, the system yields a specific daily water production (SDWP) of 6.31 m³/ton-day, a specific cooling power (SCP) of 152.3 W/kg, and a COP of 0.25. These figures reflect a 17.5% improvement in electrical power, 19.69% enhancement in water production, and a 9.9% increase in COP when compared to the performance of the PV module and ADS operated independently. Furthermore, the study compares this integrated system with other PV cooling technologies (e.g., water, air, nanofluids, PCM) and finds that the proposed system delivers the highest rate of electrical efficiency improvement among them. The authors also emphasise that this is the first experimental study to integrate PV/T cooling with an adsorption desalination unit, setting the foundation for subsequent development in off-grid solar-assisted polygeneration systems.

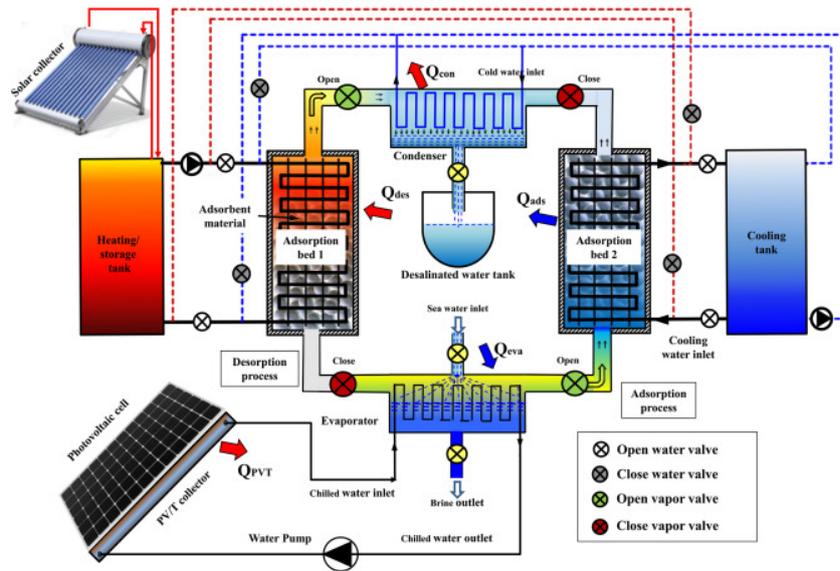


Figure 11. Schematic diagram of the PV/T integrated with adsorption desalination system. Source: (Ghazy et al., 2022).

2.2.5. CLOSE CYCLE COOLING SYSTEM - CHEMICAL REACTION SYSTEM

Ren and Ogura (2021) experimentally evaluates the performance of an off-grid solar-powered chemical heat pump (CHP) system capable of providing both space heating and cooling, with the objective of enabling autonomous operation in remote or infrastructure-limited regions (See Figure 12). The system comprises two fixed-bed thermochemical reactors operating in an alternating hydration–dehydration cycle, using a CaCl_2 –silica gel composite as the thermochemical sorbent and water as the working fluid. Thermal energy is supplied by evacuated tube solar collectors, while auxiliary electrical demands are met via photovoltaic modules, ensuring complete off-grid functionality. Under real environmental conditions, the system demonstrated thermal COPs of 0.35 for cooling and 0.64 for heating, with corresponding energy efficiencies of 0.45 and 0.69, and exergy efficiencies of 0.18 and 0.22, respectively. The authors further conducted a performance sensitivity analysis, projecting that optimisation of the heat transfer fluid, particularly by selecting a lower-viscosity medium—and improving the circulation pump efficiency could increase the total system COP (COP_{tot}) from 1.6 to as high as 4.0. Despite its demonstrated viability, the system exhibits several limitations: the thermal COP, particularly in cooling mode, remains modest compared to conventional technologies. The cyclic operation is constrained by relatively long charging and discharging times (~6 hours per phase), potentially limiting responsiveness to dynamic load demands. Nonetheless, the study affirms the potential of thermochemical energy storage as a sustainable pathway for decentralised thermal energy management, particularly in solar-rich, energy-scarce contexts.

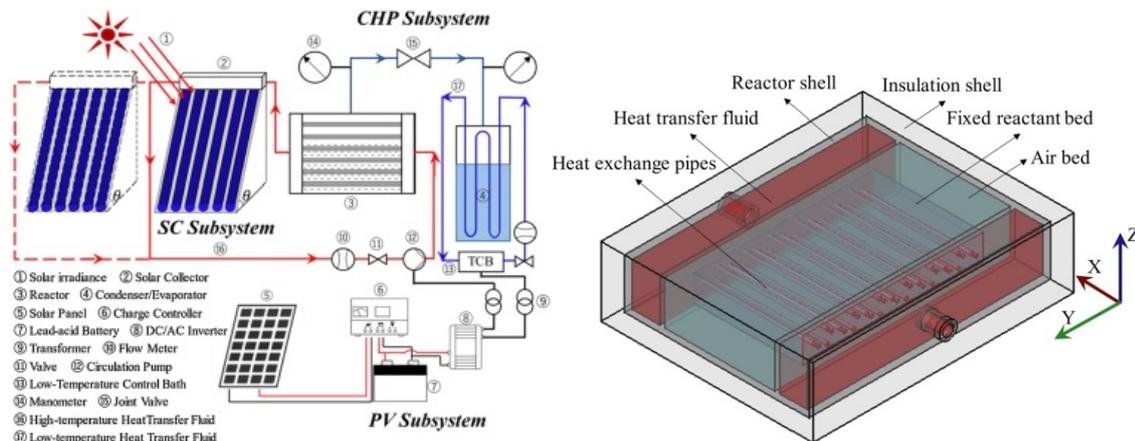


Figure 12. Schematic diagram of off-grid SCHP system and simulated reactor. Source: (Ren and Ogura, 2021).

2.2.6. OPEN CYCLE COOLING SYSTEM-SOLAR RADIATION COOLING SYSTEM

Shurafa et al. (2025) investigates hybrid photovoltaic-thermoelectric generator (PV-TEG) systems using different thermal interface materials (TIMs) under natural cooling conditions (See Figure 13). It compares pyrolytic graphite sheets (PGS) and thermal grease as TIMs, alongside a standalone PV system as a reference. PGS, known for its high thermal conductivity ($1600 \text{ W/m}\cdot\text{K}$ in-plane), is used to enhance heat dissipation and improve overall system efficiency. An Arduino-based data logger is employed to monitor temperature, voltage, and current in real time. The PV-TEG system with PGS achieved a 17.95% efficiency, outperforming the system with thermal grease (16.87%) and the PV-only system (16.42%). The PGS-based system maintained a lower surface temperature (39.01°C) compared to thermal grease (48.88°C) and the standalone PV module (55.37°C). Power output was 4.87 W for PGS, 4.67 W for thermal grease, and 4.55 W for PV-only, showing that PGS enhances energy conversion. The temperature gradient across TEG modules was 150% higher with PGS, leading to increased thermoelectric power generation. The study highlights thermal contact resistance as a key limitation in TIMs, with thermal grease trapping heat and reducing TEG efficiency. While PGS improves performance, its manufacturing cost and durability require further study. Additionally, the natural cooling method limits heat dissipation compared to forced cooling techniques like water cooling. Future research should explore alternative TIMs, integrated cooling systems, and automation to optimise hybrid PV-TEG efficiency.

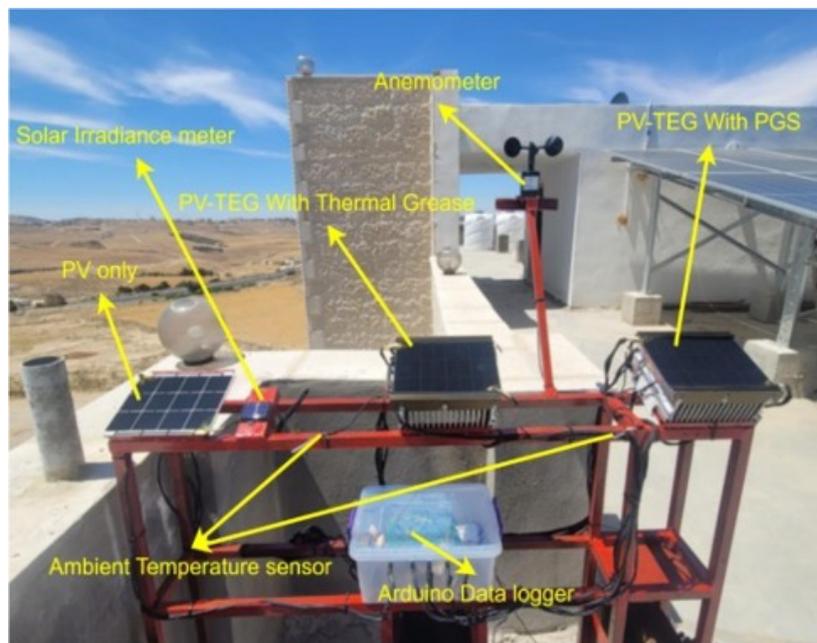


Figure 13. Experimentally PV-TEG system.

Source: (Shurafa et al., 2025).

2.2.7. THERMAL MECHANICAL COOLING SYSTEM- EJECTOR COOLING SYSTEM

Zarei et al (2022) investigates presents the thermodynamic design and performance analysis of a novel solar-assisted cooling system that integrates a vapour compression refrigeration cycle with an ejector subsystem, both powered by a hybrid PV/T collector (See Figure 14). The system simultaneously uses electrical energy from the PV panel to operate a scroll compressor and thermal energy from the collector to preheat the refrigerant vapour entering the ejector, thereby enhancing entrainment efficiency and reducing compressor workload. Three refrigerants, R134a, R1234yf, and R290, are evaluated based on their thermodynamic behaviour and environmental impact. A validated model developed in Engineering Equation Solver (EES) is used to perform parametric simulations across a range of generator temperatures ($60\text{--}90^\circ\text{C}$), ejector efficiencies, and operating conditions. The results demonstrate that R290 achieves the highest system $\text{COP} \approx 1.00$, followed by R134a (0.98) and R1234yf (0.96). The ejector subsystem contributes up to 30% of the total cooling capacity, significantly improving energy efficiency and reducing reliance on electricity. However, the system faces several limitations: its performance is highly sensitive to ejector geometry and

mixing efficiency, which are difficult to optimise due to complex two-phase flow interactions; the effectiveness of solar-driven thermal preheating is constrained by fluctuating irradiance, which may lead to unstable ejector operation; and while R290 delivers superior performance, its high flammability raises safety concerns that may hinder practical deployment. Furthermore, the integration of multiple subsystems requires precise thermal and control coordination, increasing system complexity and potential maintenance burdens. Despite these challenges, the proposed hybrid configuration offers a promising and environmentally sustainable pathway for reducing electricity consumption in cooling applications, particularly in regions with high solar availability.

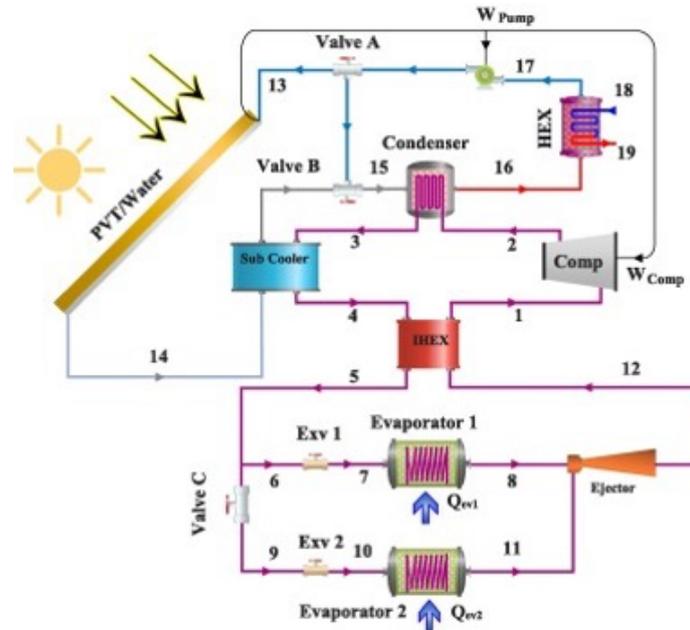


Figure 14. Schematic diagram of the novel solar cooling and heating system based on PVT water collector. Source: (Zarei et al., 2022).

2.3. SUMMARY

Following a comprehensive analysis of the various solar powered cooling technologies employed to enhance system efficiency, it is essential to synthesise the key technologies and findings in a clear and structured manner for stakeholders and researchers interested in these solutions. Table 1 presents a comparative summary, outlining the respective advantages, and limitations.

Table 1. Summary of previous studies about solar powered cooling system

Authors	Technology Classification	Key Technology	Key Findings	Key Limitations
Li et al. (2021)	PV-Driven Air Conditioning with Ice Storage.	3 HP solar direct-drive air-conditioning system with ice thermal storage, MPPT, and variable-speed compressor.	Achieved COP of 0.289; MPPT improved PPE by 81.7%; inverter compressor reached 96.24% efficiency; enhanced PV power utilization and stability.	Compressor performance highly sensitive to PV power fluctuations; system requires adaptive controller and matched compressor for stable operation.
Du et al. (2021)	PV Direct-Drive Cold Storage with PCM	Roof-mounted PV array powering DC compressor and PCM-based cold thermal energy storage unit	Max EER 2.35; daily average 1.75; PCM stabilized temperature 5–15°C; enabled cooling during non-solar hours; dynamic model matched field performance.	Sensitive to PV fluctuation; limited autonomy without battery; system stability compromised under prolonged low-irradiance conditions.

Authors	Technology Classification	Key Technology	Key Findings	Key Limitations
Bhowmik et al. (2021)	Solar-Assisted Liquid Desiccant Dehumidification	Closed-loop thermal LDAC using structured packed bed with mixed desiccant (LiBr + CaCl ₂ , 85:15) and evacuated tube collectors	Max LHR = 0.92, TCOP = 1.1; ANFIS model achieved MAPE ~2.5%; counterflow improved heat/mass transfer; high solar integration efficiency.	Performance dependent on solution-to-air ratio tuning; complex instrumentation and modelling required; efficiency varies with solar availability.
Zhang et al. (2025)	PV/T-Assisted Liquid Desiccant Evaporative Cooling	Integrated PV/T + liquid desiccant (LiCl) dehumidification and evaporative cooling system, optimized via NSGA-III and RSM	Energy savings of 58.1%, CO ₂ reduction of 61%; cooling capacity of 22.9 kW; peak energy savings 62.3%; optimized operation improves urban cooling performance.	High system complexity; performance sensitive to solar radiation variability; lacks energy storage integration; adaptation to diverse climates not addressed.
Ali et al. (2022)	Open cycle - Solid desiccant	Integrated NH ₃ -H ₂ O absorption chiller + solid desiccant wheel	COP ~0.72; thermal coupling improves energy recovery; enhances latent/sensible load management.	Thermal interdependence complicates control; requires precise desiccant regeneration and stable solar input.
Riffat et al. (2022)	Close cycle - Absorption system	Hybrid absorption cooling with PCM-integrated chilled ceiling and PV-driven DC compressor	2–2.5°C lower temperatures maintained for 4.5 hours, enhanced passive cooling.	No active humidity control; limited applicability in humid climates.
Jarimi et al. (2024)	Close cycle - Absorption system	PV-powered vapour compression with PCM-based ice gel thermal storage	COP _{pv} = 4.04, COP _{sys} = 5.05, SFPVVC = 9.10, LCOC = 0.0979 USD/kWh, stable indoor temperatures even without sun.	Prototype-level study; requires field trials and better control strategies.
Suhendri et al. (2022)	Open cycle - Solar chimney and radiative cooling	Hybrid SC-RC passive ventilation using CFD simulation and experimental validation	ACH improved by 0.4, indoor temperatures up to 2°C below ambient, effective in arid zones.	Not effective in humid climates, excludes wind-driven ventilation and assumes ideal insulation.
Gado et al. (2021)	Close cycle - Adsorption system	Silica gel-water adsorption with VCR system using R410A and solar thermal/PV energy	Max COP ~5.59; electricity savings up to 62.5%; PV hybrid system achieved net-zero energy use.	Configuration III had low economic viability; hybrid complexity increases capital cost and control demand.
Ghazy et al. (2022)	Close cycle - Adsorption desalination system	Sheet-and-tube PV/T cooled with chilled water from adsorption desalination system	11.5% elec. eff., 77.5% thermal eff., COP = 0.25, SDWP = 6.31 m ³ /ton-day	System complexity and integration challenges; no long-term outdoor performance assessment.
Ren and Ogura (2021)	Close cycle - Chemical reaction system	Off-grid solar-powered CaCl ₂ -silica gel chemical heat pump with dual reactors	COP _{cooling} = 0.35, COP _{heating} = 0.64; projected COP _{tot} up to 4.0; complete off-grid capability demonstrated.	Long cycle time (~6 hours); low cooling COP; dynamic load response limited.
Shurafa et al. (2025)	Open cycle - Solar radiation cooling	Hybrid PV-TEG system with pyrolytic graphite thermal interface material (PGS)	Efficiency 17.95%, TEG power boosted, surface temp reduced to 39°C	Natural cooling limited, high PGS cost and unclear durability.
Zarei et al. (2022)	Thermal mechanical - Ejector cooling	Solar PV/T-powered scroll compressor +	Max COP ≈ 1.00 with R290; ejector	High flammability (R290), complex flow

Authors	Technology Classification	Key Technology	Key Findings	Key Limitations
		ejector system (R290, R134a, R1234yf)	contributed ~30% cooling; hybrid reduced compressor load	control, and instability under fluctuating solar input.

3. FUTURE DIRECTIONS

3.1. CRITICAL CHALLENGES

Solar-powered cooling systems present a promising solution to reducing energy consumption and mitigating greenhouse gas emissions in both residential and commercial applications. The global transition to solar-powered cooling systems is impeded by multifaceted challenges rooted in technical, economic, and operational domains. A primary technical barrier stems from the inherent intermittency of solar energy, which introduces variability in system performance, particularly in regions prone to seasonal cloud cover or low solar irradiance. While short-term energy storage solutions, such as ice tanks and PCMs, mitigate diurnal fluctuations, they remain inadequate for addressing prolonged periods of low solar availability. For example, systems relying on cool storage often face limitations in storage capacity, requiring oversized tanks to sustain cooling demand during multi-day overcast conditions, which escalates space and cost requirements.

Efficiency limitations further constrain the viability of these systems. While PV-driven systems offer modularity and ease of integration, they are constrained by relatively low electrical COP values, typically ranging from 0.2 to 0.4 in direct-drive systems. Conversely, solar thermal cooling systems, particularly those utilising absorption or adsorption cycles, achieve higher thermal COP values, often in the range of 0.5 to 1.2, depending on the working fluid and operating conditions. While effective for large-scale applications, demand heat sources exceeding 70°C to achieve optimal COP, necessitating high-temperature collectors such as parabolic troughs or evacuated tubes (Kumar, Hasanuzzaman and Rahim, 2019). Advanced hybrid systems, such as concentrating CPV/T and desiccant-based cooling configurations, have shown promise in improving performance, with some achieving COP values exceeding 1.5 when optimised. These systems also suffer from thermodynamic losses, particularly in heat exchangers and absorption cycles, where exergy efficiencies rarely exceed 40% due to irreversibility in heat transfer and chemical processes (Lin et al., 2020).

Economic barriers compound these technical challenges. The capital costs of advanced components, such as concentrated PV/T collectors, lithium bromide absorption chillers, and thermoelectric modules, remain prohibitively high compared to conventional vapour-compression systems. For instance, PV/T systems require precision optics and tracking mechanisms, increasing installation costs by 30–50% (Zhang et al., 2025). Additionally, regulatory frameworks in many regions lack incentives for grid integration, such as net-metering policies or feed-in tariffs, which discourages investment in hybrid solar cooling systems.

Operational challenges include material degradation under thermal stress and climate-specific performance limitations. For example, Thermoelectric coolers experience gradual efficiency losses due to thermal cycling, while photovoltaic cells degrade at rates of 0.5–1% annually under prolonged exposure to high temperatures (Al Shurafa et al., 2025). Climate adaptability also poses a hurdle: desiccant-based systems underperform in temperate climates with low humidity, while radiative cooling technologies lose efficacy in humid environments due to atmospheric absorption of infrared radiation.

3.2. FUTURE RESEARCH PRIORITIES

To overcome these barriers, the field must prioritise innovations across materials science, system design, and policy frameworks. Future research must focus on enhancing system efficiency by addressing these limitations. Improvements in PV technology, Advancements in PV technology should focus on next-generation materials such as perovskite-silicon tandem cells, which combine the high efficiency of perovskites with the stability of silicon. Laboratory prototypes of these cells have demonstrated efficiencies exceeding 25.7%, promising to reduce the physical footprint and cost of solar arrays while enhancing energy yield (Duan et al., 2023). The advanced PV technology could increase electrical conversion efficiency and thereby enhance the COP of PV-driven cooling systems. Similarly, advancements in solar thermal collectors and absorption

chiller designs could push thermal COP values beyond 1.5, making them more competitive with conventional vapour-compression systems.

High performance thermal management innovations are equally critical. Integrating advanced thermal interface materials, such as graphene-enhanced composites (Fu et al., 2020) or MXene coatings (Marian et al., 2022), could minimise thermal resistance in hybrid PV/T systems, improving heat dissipation and prolonging component lifespans. Concurrently, the development of multifunctional building materials, such as aerogel-insulated windows with embedded radiative cooling layers that could enable passive thermal regulation, reducing the energy demand for heating and cooling.

Beyond hardware improvements, smart control system optimisation through artificial intelligence (AI) and machine learning represents another transformative opportunity. AI-driven predictive controllers could dynamically adjust operational parameters to maintain optimal COP level, such as compressor speeds, desiccant regeneration rates, and storage cycles in response to real-time weather forecasts and load profiles (Ntakolia et al., 2022). For example, reinforcement learning algorithms could optimise the balance between cool storage utilisation and direct solar-driven cooling (Zhou, Zheng and Zhang, 2020), maximising energy autonomy while minimising wear on mechanical components (Jamil et al., 2024).

Both short and long term intermittency should be addressed in energy storage research (Cosgrove, Roulstone and Zachary, 2023). Hybrid systems combining cool storage with electrochemical batteries, such as vanadium redox flow (Li, Xu and Wu, 2023) or zinc-bromine cells (Jiménez-Blasco, Arrebola and Caballero, 2023), could provide uninterrupted cooling while stabilising grid interactions. Seasonal storage solutions, leveraging sorption technologies with high-enthalpy materials like metal-organic frameworks, could store excess solar heat during summer months for winter space heating, enhancing annual energy utilisation (Gao et al., 2022).

Finally, climate-adaptive designs must be prioritised to ensure global applicability. In humid regions, biomimetic radiative coolers inspired by natural structures, such as the water-capturing microtextures (Hou et al., 2020) of desert beetles (Grotsky, Campbell and Hernandez, 2021), could enable sub-ambient cooling even at high humidity levels. Modular, scalable cooling systems tailored for urban environments could address the cooling demands of densely populated cities while minimising land use conflicts (Grotsky, Campbell and Hernandez, 2021).

4. CONCLUSION

The advancement of solar-powered cooling technologies represents a critical step in addressing the growing demand for global warming and energy-efficient cooling solutions. This study has systematically reviewed recent developments in solar cooling technologies, highlighting both electrical and thermal approaches. However, despite the increasing integration of hybrid approaches, such as PV-TE, desiccant-based cooling, and radiative cooling, several technical, economic, and operational challenges persist. Technical challenges related to low COP, intermittency, and system degradation limit the operational effectiveness of current systems. Economically, high capital investments and the absence of robust policy incentives restrict broader deployment. Climatic constraints further complicate implementation, especially for radiative and desiccant-based systems in humid or variable environments.

To advance the field, future research must address these limitations by advancing PV materials, optimising thermal energy management, and integrating artificial intelligence for smart system control. Next-generation materials have the potential to surpass the efficiency constraints of traditional silicon-based solar cells, thereby enhancing the viability of solar-driven cooling. Innovations in thermal interface materials, such as graphene-enhanced composites and aerogels, could further improve heat dissipation and insulation performance, reducing overall energy losses. Additionally, the integration of machine learning algorithms in solar cooling systems could enable predictive optimisation, dynamically adjusting cooling operation based on real-time weather conditions and energy demand patterns.

The future development of hybrid storage systems is also essential to ensure the reliability of solar cooling technologies. While thermal storage solutions and phase-change materials offer short-term energy buffering, combining these with electrochemical storage solutions could provide more stable, long-term energy management. Furthermore, climate-adaptive cooling strategies must be explored, particularly for humid environments where radiative cooling methods face efficiency challenges due to atmospheric infrared absorption. Biomimetic approaches, inspired by natural thermoregulatory mechanisms, could lead to

innovative passive cooling materials capable of enhancing energy efficiency.

Ultimately, a multi-disciplinary approach that combines advances in material science, engineering optimisation, and energy policy is crucial for accelerating the global adoption of solar-powered cooling systems. By addressing the existing limitations and leveraging emerging technologies, solar cooling solutions can play a pivotal role in mitigating climate change, reducing energy demand, carbon emissions and mitigating global warming.

AUTHOR CONTRIBUTIONS

Tianhong Zheng: Conceptualisation; methodology; literature search and screening; data curation; formal analysis; visualisation; writing—original draft; writing—review and editing. **Hasila Jarimi:** Supervision; validation; critical review of technical content; writing—review and editing. **Yuehong Su:** Supervision; strategic direction; resources; writing—review and editing.

COMPETING INTERESTS

The authors declare no competing interests.

DATA ACCESSIBILITY

The data used in this study will be made available upon request.

REFERENCES

- Ali, M. et al. (2022) Experimental investigation of an integrated absorption–solid desiccant air conditioning system. *Applied Thermal Engineering*, 203, p. 117912. doi:10.1016/j.applthermaleng.2021.117912.
- Allen, A. et al. (2020) Evaluation of low-exergy heating and cooling systems and topology optimization for deep energy savings at the urban district level. *Energy Conversion and Management*, 222, p. 113106. doi:10.1016/j.enconman.2020.113106.
- Al Shurafa, S.M. et al. (2025) Experimental study of photovoltaic–thermoelectric systems using thermal interface materials and natural cooling. *Applied Thermal Engineering*, 258, p. 124855. doi:10.1016/j.applthermaleng.2024.124855.
- Amponsah, N.Y. et al. (2014) Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. *Renewable and Sustainable Energy Reviews*, 39, pp. 461–475. doi:10.1016/j.rser.2014.07.087.
- Bhowmik, M., Muthukumar, P. and Anandalakshmi, R. (2021) Experimental study of coupled heat and mass transfer phenomena between air and desiccant in a solar-assisted thermal liquid desiccant system. *International Journal of Thermal Sciences*, 162, p. 106795. doi:10.1016/j.ijthermalsci.2020.106795.
- Cosgrove, P., Roulstone, T. and Zachary, S. (2023) Intermittency and periodicity in net-zero renewable energy systems with storage. *Renewable Energy*, 212, pp. 299–307. doi:10.1016/j.renene.2023.04.047.
- Dilshad, S., Kalair, A.R. and Khan, N. (2020) Review of carbon dioxide (CO₂) based heating and cooling technologies: Past, present, and future outlook. *International Journal of Energy Research*, 44(3), pp. 1408–1463. doi:10.1002/er.4930.
- Du, W. et al. (2021) Dynamic energy efficiency characteristics analysis of a distributed solar photovoltaic direct-drive solar cold storage. *Building and Environment*, 206, p. 108324. doi:10.1016/j.buildenv.2021.108324.
- Duan, L. et al. (2023) Stability challenges for the commercialization of perovskite–silicon tandem solar cells. *Nature Reviews Materials*, 8(4), pp. 261–281. doi:10.1038/s41578-022-00492-9.
- Fu, Y. et al. (2020) Graphene related materials for thermal management. *2D Materials*, 7(1), p. 012001. doi:10.1088/2053-1583/ab4f86.
- Gado, M.G. et al. (2021) Performance and economic analysis of solar-powered adsorption-based hybrid cooling systems. *Energy Conversion and Management*, 238, p. 114134. doi:10.1016/j.enconman.2021.114134.
- Gao, D. et al. (2022) Seasonal-regulatable energy systems design and optimization for solar energy year-round utilization. *Applied Energy*, 322, p. 119500. doi:10.1016/j.apenergy.2022.119500.

- Ghazy, M. et al. (2022) Experimental investigation of hybrid photovoltaic solar thermal collector (PV/T)-adsorption desalination system in hot weather conditions. *Energy*, 254, p. 124370. doi:10.1016/j.energy.2022.124370.
- Grodsky, S.M., Campbell, J.W. and Hernandez, R.R. (2021) Solar energy development impacts flower-visiting beetles and flies in the Mojave Desert. *Biological Conservation*, 263, p. 109336. doi:10.1016/j.biocon.2021.109336.
- Hou, K. et al. (2020) Tunable wetting patterns on superhydrophilic/superhydrophobic hybrid surfaces for enhanced dew-harvesting efficacy. *Advanced Materials Interfaces*, 7(2), p. 1901683. doi:10.1002/admi.201901683.
- Jamil, M.A. et al. (2024) Machine learning-based process design of a novel sustainable cooling system. *Energy Conversion and Management*, 319, p. 118941. doi:10.1016/j.enconman.2024.118941.
- Jarimi, H. et al. (2024) Solar photovoltaic-assisted DC vapour compression with a low-cost ice gel thermal battery for off-grid building cooling. *Journal of Building Engineering*, 91, p. 109350. doi:10.1016/j.jobeb.2024.109350.
- Jiménez-Blasco, U., Arrebola, J.C. and Caballero, A. (2023) Recent advances in bromine complexing agents for zinc–bromine redox flow batteries. *Materials*, 16, p. 7482. doi:10.3390/ma16237482.
- Kumar, L., Hasanuzzaman, M. and Rahim, N.A. (2019) Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy Conversion and Management*, 195, pp. 885–908. doi:10.1016/j.enconman.2019.05.057.
- Li, G. et al. (2021) Study on matching characteristics of photovoltaic disturbance and refrigeration compressor in a solar photovoltaic direct-drive air conditioning system. *Renewable Energy*, 172, pp. 1145–1153. doi:10.1016/j.renene.2021.03.081.
- Li, J., Xu, Z. and Wu, M. (2023) Halogen enabled aqueous flow cells for large-scale energy storage: Current status and perspectives. *Journal of Power Sources*, 581, p. 233477. doi:10.1016/j.jpowsour.2023.233477.
- Lin, L. et al. (2020) A novel solar system integrating concentrating photovoltaic thermal collectors and variable effect absorption chiller for flexible co-generation of electricity and cooling. *Energy Conversion and Management*, 206, p. 112506. doi:10.1016/j.enconman.2019.112506.
- Marian, M. et al. (2022) Layered 2D nanomaterials to tailor friction and wear in machine elements—A review. *Advanced Materials Interfaces*, 9(3), p. 2101622. doi:10.1002/admi.202101622.
- Ntakolia, C. et al. (2022) Machine learning applied on the district heating and cooling sector: A review. *Energy Systems*, 13(1), pp. 1–30. doi:10.1007/s12667-021-00474-5.
- Pérez-Lombard, L., Ortiz, J. and Pout, C. (2008) A review on buildings energy consumption information. *Energy and Buildings*, 40(3), pp. 394–398. doi:10.1016/j.enbuild.2007.03.007.
- Ren, Y. and Ogura, H. (2021) Performance evaluation of off-grid solar chemical heat pump for cooling/heating. *Solar Energy*, 224, pp. 1247–1259. doi:10.1016/j.solener.2021.07.031.
- Riffat, J. et al. (2022) A preliminary experimental study of a novel incorporation of chilled ceiling with phase change materials and transparent membrane cover. *International Journal of Low-Carbon Technologies*, 17, pp. 258–265. doi:10.1093/ijlct/ctac020.
- Suhendri, S. et al. (2022) Parametric study of a novel combination of solar chimney and radiative cooling cavity for natural ventilation enhancement in residential buildings. *Building and Environment*, 225, p. 109648. doi:10.1016/j.buildenv.2022.109648.
- Ürge-Vorsatz, D. et al. (2015) Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews*, 41, pp. 85–98. doi:10.1016/j.rser.2014.08.039.
- United Nations Environment Programme (2024) Emissions Gap Report 2024: No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nairobi: UNEP.
- Zarei, A., Elahi, S. and Pahangeh, H. (2022) Design and analysis of a novel solar compression-ejector cooling system with eco-friendly refrigerants using hybrid photovoltaic thermal (PVT) collector. *Thermal Science and Engineering Progress*, 32, p. 101311. doi:10.1016/j.tsep.2022.101311.
- Zhang, Y. et al. (2025) Multivariate hyperplane optimization of integrated photovoltaic/thermal-assisted desiccant evaporative cooling system. *Energy Conversion and Management*, 325, p. 119334. doi:10.1016/j.enconman.2024.119334.
- Zhou, Y., Zheng, S. and Zhang, G. (2020) Machine learning-based optimal design of a phase change material integrated renewable system with on-site PV, radiative cooling and hybrid ventilations—Study of modelling and application in five climatic regions. *Energy*, 192, p. 116608. doi:10.1016/j.energy.2019.116608.