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Review

A Review of Using Solar Energy for Cooling Systems: Applications, Challenges, and Effects

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Abstract: Energy security refers to a country's capacity to provide the energy resources essential to its wellbeing, including a reliable supply at an affordable costs. Economic growth and development cannot occur without access to reliable energy sources. Energy availability is a proxy for a country's standard of living and a key factor in its economic development and technical progress. Solar power is the most reliable and cost-effective option when it comes to meeting the world's energy needs. Solar-powered cooling systems are one example of how solar energy may be used in the real world. Solar-powered air conditioners have become more popular in recent years. The problems caused by our reliance on fossil fuels may be surmounted with the help of solar cooling systems that use solar collectors. Solar cooling systems may utilize low-grade solar energy, making them popular in the construction industry. Solar cooling systems powered by photovoltaic–thermal (PVT) collectors have been the subject of much research to improve the thermodynamic and economic performance of solar cooling systems. This research focuses on exploring the potential of solar-generated heat for use in cooling systems. This study will also examine the current challenges involved with using solar energy in cooling applications, as well as the possible benefits that may help pave the way for more research and greater employment of heat gain from the solar system in various cooling applications.

Keywords: solar energy; cooling systems; applications; challenges; effects; review

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1. Introduction

Any melting of frozen soil causes degradation in foundations, which may lead to the destruction of the embankments in places of the globe where trains and highways employ permafrost foundations. A major challenge to improving transportation in these areas is halting the melting of permafrost [1–4]. Permafrost protection may be either passive or active. Embankment heightening and thermal insulating materials are examples of the passive technique, whereas crushed-rock foundations and the distribution of air ventilation and heat pipes are examples of the active method [5–9]. Although these strategies help decrease the pace at which frozen soil is thawing, they are not always successful in halting permafrost deterioration [10]. Furthermore, many permafrost warming tendencies beneath embankments have been found using these cooling properties [11–13]. Therefore, creating better strategies to preserve the permafrost as soon as possible is crucial.

Significant reductions in energy usage in this sector are possible via the sustainable construction of energy-efficient buildings with renewable energy technology [14]. Solar power is one of the most promising renewable energy sources for reducing use. Solar collectors and photovoltaic (PV) panels are advantageous in the construction industry because they are practical and cost-effective [15]. Solar technology integration into buildings is one approach used by various EU countries nowadays to take advantage of renewable energy sources [16]. Building elements, such as the roof and façade, may generate energy and significantly lower energy usage if these systems are integrated with the building envelope. One method of producing both energy and heat on the construction site is the Building Integrated Photovoltaic Thermal Collector (BIPVT) [17]. Because buildings integrated with collectors are constructed simultaneously by a construction team rather than by separate teams (as is the case with traditional systems), the installation cost of this system is also cheaper than that of a conventional one [18]. By using short circuit current measurements of thin film photovoltaic cells and MINSUN simulations, the geometrical design of a concentrating PV/thermal hybrid collector is optimized for maximum energy production, with the goal of integration into a wall element. From 70 kWh/m^2 for a vertical reference cell to 120 kWh/m^2 for an absorber area, the findings demonstrate that the yearly energy production might improve. We show results for many geometries.

Several options exist for mitigating the negative effects of space cooling on overall energy consumption, including new energy-efficient building construction [19], renovation of older structures [20], and the incorporation and use of renewable energy sources [21]. Manufacturing and usage phases are the most researched aspects of the life cycle. Similarly, embodied energy and the possibility of global warming are the most important kind of impacts. The key obstacles that have been identified in the process of dissemination are the functional unit, LCI methodologies, the operational stage, the definition of the end-of-life stage, and the system boundaries interpretation of EN 15978:2011 [22]. As the energy required for space cooling is connected with the high availability of solar radiation, utilizing solar energy to fulfill this need is realistic from a technological standpoint, making the use of solar-based systems in buildings an intriguing possibility. Some novel methods are being researched to increase the efficiency of solar systems. Adding a nanoparticle-based volumetric absorber to the usual absorbent surface is one approach to raising the thermal parameters. There is much work to be conducted in minimizing heat losses via the transparent walls [23], but the literature demonstrates that this technology enables us to boost the efficiency of solar devices. Researchers intended to provide discourse on the future stages for development by critically comparing design considerations and the most recent experimental findings of less extensively investigated sectors, such as direct steam production and hybrid photovoltaic/thermal systems.

Because of their reduced starting and operational costs, evaporative cooling systems are the ideal alternative for air-cooling operations under climatic conditions (high temperature and moderate or medium relative humidity) [24]. Although the vapor compression method was superior, DEVap was the way to go in cities with a combination of humid and temperate climates, as well as for those with a combination of hot and semi-humid temperatures. Approximately 1930 kilowatt-hours (kWh) of primary energy usage and 3300 metric tons of carbon dioxide (CO_2) were cut per year as a result. Saving up to 4875 kWh in PEC, 5.6 tons of CO_2, and $168 in cooling costs for the dry region were achieved through the use of DEC. Evaporative cooling systems (ECs) may be further subdivided into direct evaporative coolers (DECs) and indirect evaporative coolers (IECs) based on the nature of the water and air interaction. Statistics show that people increasingly favor DECs over VCs because of their cheaper total cost and greater ease of use [25,26]. Pads may be made from various materials, such as cellulose, wood, and PVC. Evaporative pads of several varieties are most often made of cellulose [27]. The analyzed case obtained thermal comfort conditions with minimum values of 7 cm for pad thickness and 420 $m^2\ m^{-3}$ for specific contact area, which were determined to be the optimal values. As an alternative to traditional systems, research into using direct evaporative cooling with partial air recirculation in very hot and dry weather was undertaken. The cooling efficiency of CPDECs was investigated by Sheng and Nnanna [28], who looked at the effect of variables such as input air temperature and pad frontal velocity. The experimental test data displayed the empirical associations for the instances under study.

Solar cooling and air conditioning systems (SCACSs) were introduced and discussed by Al-Yasiri (2022) [29]. Popular solar thermal energy-powered SCACSs were described in depth, focusing on their functioning and development. Several technical, operational, economic, and environmental parameters were used to compare solar thermal SCACSs. Recent studies on PVT collector advancements, thermally driven cooling cycle creation, and the efficacy of solar cooling systems powered by PVT collectors were summarized by Jiao and Li (2023) [30]. When compared with traditional PV systems and PVT systems that use water cooling, researchers found that the PVT collector could achieve electrical efficiencies of 0.85–11% and thermal efficiencies of 1.9–22.02%, respectively. An additional 4–20 °C was added to the new thermally driven cooling system's minimum heat source temperature limit. Lastly, solar cooling systems powered by PVT collectors have a minimal payback time of 8.45–9.3 years, indicating promising economic viability.

PVT collectors play a pivotal role in enhancing the thermodynamic and economic performance of solar cooling systems by combining the generation of electricity and heat from sunlight. This dual functionality ensures heightened overall efficiency, addressing the intermittent nature of solar energy and providing a consistent year-round energy supply. The versatility of PVT collectors makes them adaptable to various solar cooling technologies, contributing to improved cost-effectiveness over time. With the ability to reduce greenhouse gas emissions and reliance on non-renewable sources, PVT collectors emerge as a key component in advancing sustainable and efficient solar energy utilization in cooling systems for both residential and commercial applications.

Recent developments on the potential of dish collectors and linear Fresnel reflectors for use in cooling systems were addressed by Esfanjani et al. (2022) [31]. Cryogenic systems and traditional absorption chillers driven by the sun were also examined. Additionally, solar-based combination cooling, heating, and electricity systems and hybrid cooling solar systems are being investigated. Hydrogen generation in cold thermal energy storage and cold integrated systems have been covered. Some explanations of the thermodynamic and economic characteristics of the systems were offered in each section, in addition to a basic overview of the system. Using solar dish collectors in a hybrid system created for freshwater and LNG production resulted in a 40% decrease in carbon dioxide emissions, a 95% increase in freshwater production, and a 4.7% increase in LNG production, respectively. Using a linear Fresnel reflector may reduce the biomass and acreage required by 29% in hybrid trigeneration solar–biomass power plants.

For the reasons stated above, it is reasonable to draw the conclusion that there has not been comprehensive research conducted on all of the significant problems associated with the use of solar energy for the purpose of system cooling. The purpose of this study is to provide a complete examination of solar energy systems for cooling applications, with the intention of bringing to light crucial topics that need additional investigation and deriving significant conclusions from the current body of literature. This summary provides an overview of the different methods that may be used to cool systems by using solar energy, including those that are utilized in research and development. Considering that this will assist researchers in gaining a better understanding of the many concerns that still need to be addressed in relation to the use of solar energy in cooling applications, the findings of the present review have the potential to serve as a roadmap for future research. This is because they will enhance the knowledge that scientists have of the myriad topics that are still unresolved.

2. Review Method

To provide an overview of papers that investigated solar-powered cooling systems, a systematic literature review is performed. The review is carried out by conducting a critical analysis of existing academic literature. Various databases have been used to identify peer-reviewed academic literature, including SpringerLink, ScienceDirect, Google Scholar and Scopus. The keywords for the search included solar energy, cooling systems, applications, challenges and effects. Although there were no stringent restrictions on the publication timeframe, emphasis was placed on prioritizing recent publications between 2019–2023 in order to address the recent state-of-the-art research.

3. Cooling Systems

Two types of solar thermal systems are used in buildings: passive and active. The need for supplementary energy for comfort heating is mitigated with passive systems as the building's fabric lets in, stores, and releases solar energy. DEC is one of the simplest, oldest, and least expensive cooling methods. Evaporative air conditioning systems, particularly DEC units, have a long usage history in many dry regions. However, further research on the efficacy of these devices is required in light of the global dehydration issue. Researchers have separated their work into two subfields: PV and hybrid.

3.1. Using PV for Cooling Systems

To match the ideal operating impedance of the PV array, Han et al. (2019) [32] presented an integrated control technique for a solar cooling system that is directly powered by distributed photovoltaics (PVs) without a battery. Two experimental processes are analyzed at varying degrees of sun irradiation, and the theoretical working principle of the control technique is described. The experiment findings show that the average photoelectric conversion efficiency increased to around 0.129 under the impedance matching control approach, which is an increase of 83.7% over the control system without a controller. Using a model that incorporates ice thermal storage, the coefficient of performance (COP) solar was increased by 60.4%, reaching 0.263. The compressor operated continuously when the instantaneous irradiance was higher than 143 W/m^2. The control system's average efficiency was 0.96, with a three-phase power factor of around 0.71.

The whole DC air conditioning system powered by solar energy was constructed by Pang et al. (2019) [33] using R134a as the refrigerant. The results demonstrate that the DC air-conditioning system effectively maintained a comfortable temperature within the vehicle, satisfying the needs of its occupants. In addition, the minimum refrigerating capacity in the experiment should be 1500 W, maintaining the temperature balance within the vehicle while it is parked in direct sunlight with no one inside. The success of the solar-powered DC air-conditioning system in experiments suggests that a solar-powered vehicle air conditioning system is technically possible. In addition, the developed DC air conditioning system is more environmentally friendly than the standard car air conditioning system, which is great news for the planet. Moreover, unlike conduction and convection heat, radiation heat primarily raises the temperature within the vehicle.

A prototype concentrated photovoltaic cooling system was developed by Zuhur et al. (2019) [34]. The cooling and power needs of the building where this system was installed were met by this system. The manufactured prototype was put through its paces with and without a concentrator. While conducting studies, using a concentrator had no discernible impact on the system's thermal energy gain, which was estimated to be about 30 W. Concentrator use raised the temperature of the panels' rear sides, resulting in less electrical output compared with systems without concentrators. Measures taken by the system to reduce the quantity of the carbon dioxide (CO_2) gas emitted from burning coal are shown in Figure 1a. Figure 1b depicts the environmental cost, a measure of savings achieved by avoiding the production of CO_2 concentration. The findings indicated that CO_2 emissions were reduced by 0.07 kg per hour, equating to a savings of around 0.1 per hour.

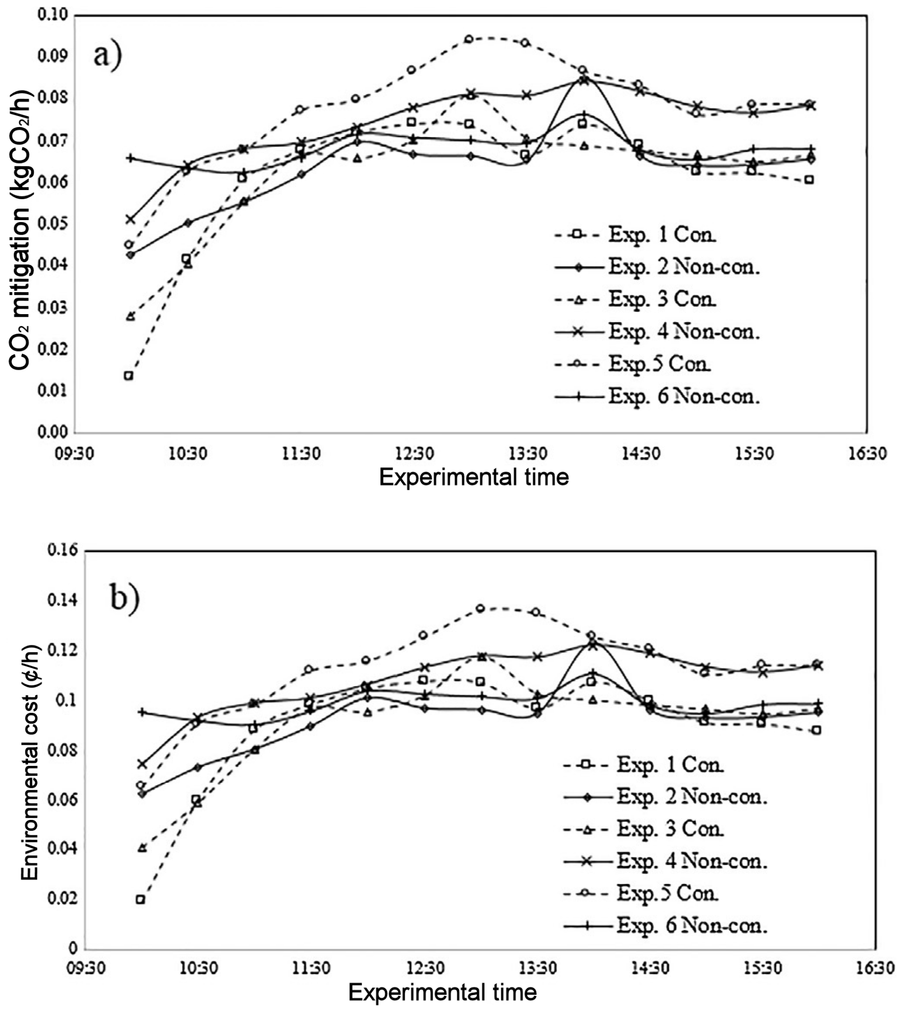


Figure 1. (**a**) the amount of CO_2 mitigation and (**b**) the environmental cost is a measure of savings achieved by avoiding the production of CO_2 concentration [34].

The direct evaporative air-cooling system powered by solar photovoltaics was the subject of an exergoeconomic study conducted by Kiyaninia et al. (2019) [35]. Various cellulose and straw pad thicknesses were used for experimental research on the system. Maximum variations in output air humidity and temperature were attained with a pad of 30 cm thickness for input air flows up to 1000 m^3/h. The exert economic study of the system was performed after a detailed mathematical model was constructed for it. The highest exergy efficiency of the system was about 20% for input air at 30 °C and 30% relative humidity. There may be a 60% shift in the systems exert economic factor if the water temperature is changed from 15 to 27 °C, the intake air flow is changed from 300 to 1500 m^3/h, and the inlet air temperature is changed from 26 to 34 °C. Figure 2 compares the current system to a conventional system over its lifetime, showing that in the first four years, the conventional system had a higher exergoeconomic factor than the solar system due to its lower initial investment, and in the later years, the solar system had a lower exergoeconomic factor due to its higher operating cost.

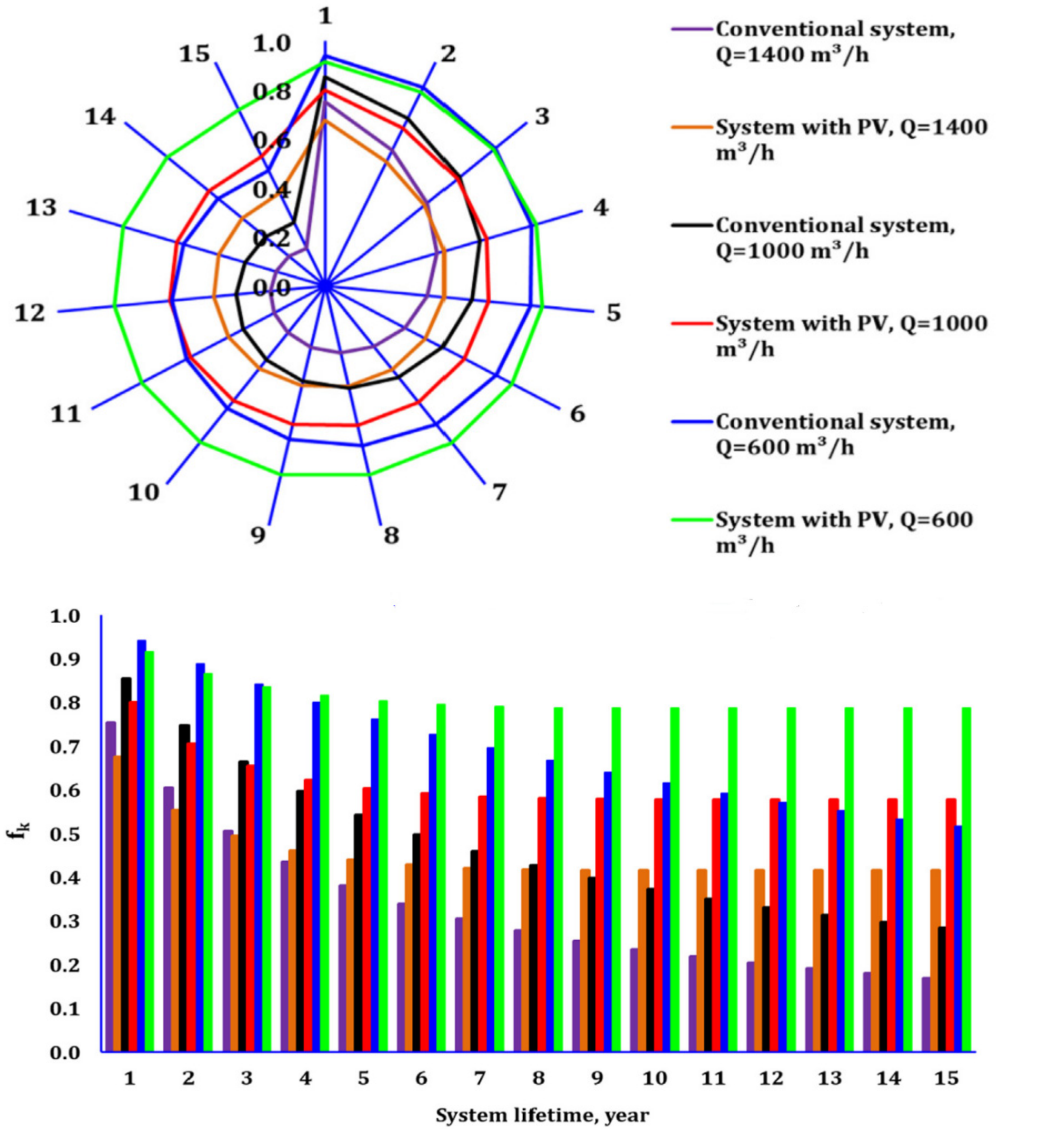


Figure 2. Exergoeconomic factor variation across system lifespan for traditional and current systems [35].

Lin et al. (2020) [36] suggested a revolutionary solar system that integrates concentrating photovoltaic and thermal collectors and a variable effect absorption chiller for more adaptable and effective co-generation of power and cooling. Researchers improved the variable effect chiller, demonstrating that its three operating modes and refined control made it a better option than the single-effect and double-effect varieties. According to the findings, setting the chiller's cutoff temperature high usually meant more cooling power, decreased operating hours, and, in certain circumstances, frequent on/off cycling. The cooling exergy efficiency improved as the working temperature increased, while the overall exergy efficiency fell because of the solar cell's diminished performance. Overall, it was between 32% and 33% efficient regarding exergy. The unique solar co-generation system may provide a cooling-electricity ratio of 1.4 to 2.0, which was sufficient for satisfying the needs in many instances, depending on the temperature management approach used.

The transient performance of a novel solar desiccant air-cooling system improved by the phase change material (PCM) and Maisotsenko cooler was evaluated by Song and Sobhani (2020) [37]. PCMs experience a physical transition, commonly transitioning between solid and liquid states within a defined temperature range. This phase transition process enables them to assimilate, retain, and discharge substantial energy. PCMs offer significant benefits, such as a high energy storage capacity per unit mass or volume, the ability to maintain a consistent temperature during the phase shift, and the ability to enhance thermal comfort and energy efficiency in various applications. Their capacity to store and discharge energy at precise temperatures renders them highly beneficial in thermal regulation systems, including building insulation, temperature control in electronics, and solar energy storage applications. The (PVT) solar collector is used to heat the regeneration section, and the solar system's power conversion module (PCM) supplies the air conditioning system's electricity needs after the sun goes down. The seasonal study took place over five hot months (June through October), and August was selected to investigate the proposed system's performance as it has the highest cooling demand. The system's highest values were COPth = 0.415, COPel = 16.27, and COPtot = 0.404. The PV module's highest power output was about 0.77 kW at noon in October, while its lowest electrical efficiency was around 13.6% at 14:00 in September.

The energy needs of a Mediterranean multifamily structure during the summer were investigated by Bilardo et al. (2020) [38]. To optimize the system design, maximize its energy advantages, and connect the energy performance to investment and operating costs, a TRNSYS energy model was built, and a simulation-based optimization methodology was deployed. As a consequence of this ideal design, the proportion of renewable energy to total energy consumption increased to 83% from the original 48%. The findings show that the suggested method may help designers make better decisions in this area, and they highlight how solar cooling can help us reach the nZEB goal in light of climate change and the increasing energy demands on buildings in the future.

To optimize and compare façade integrated solar cooling systems in terms of technical and economic performance, Wu et al. (2020) [39] developed a consistent strategy. There were four systems evaluated and compared with a standard electric vapor compression chiller: a VCC chiller powered by semi-transparent photovoltaics (STPVs), an absorption chiller, an adsorption chiller, and a VCC chiller coupled with an ORC powered by evacuated tube solar collectors. Each solar cooling system in seven Australian cities was characterized by two parameters: solar fraction (SF) and unit cooling cost (UCC). When comparing ORC-VCC with the adsorption and absorption chillers in subtropical and temperate climatic zones, the grid acted as a virtual store, increasing SF by 40% and 50% while decreasing UCC by 10%. The adsorption chiller systems in nine different orientation combinations throughout seven different cities are shown in Figure 3. Except Darwin, the optimal city orientation was a mix of northwest and northeast.

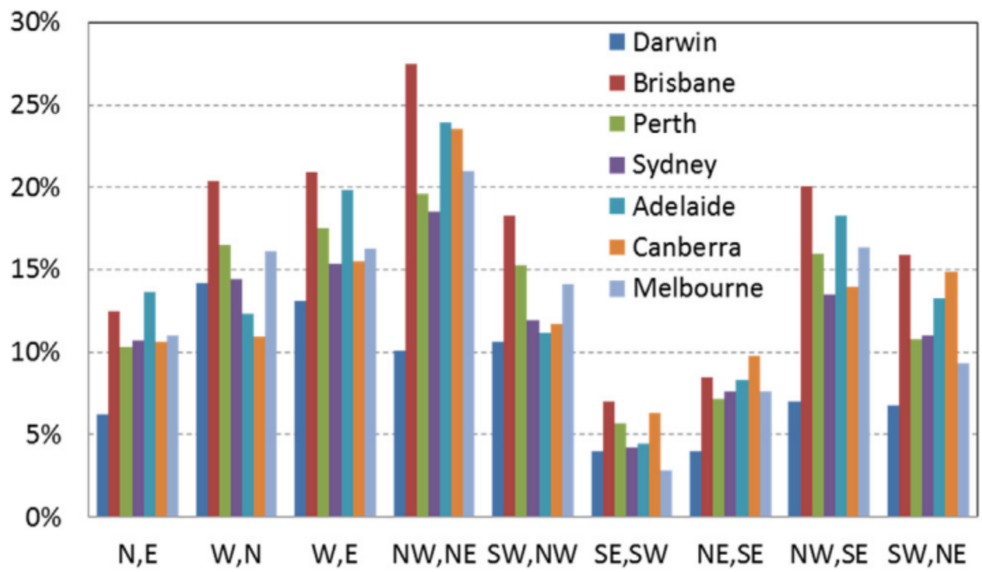


Figure 3. Orientation combinations affect the adsorption chiller solar fraction [39].

The technical validation of two control algorithms designed for the compressor of the HP unit, the Maximum Power Point Tracking control (MPPT) and the inverter control, was provided by Lorenzo et al. (2020) [40]. This system operates autonomously, without batteries. The values of the three primary key performance indicators (KPIs) often used to characterize PV and HP systems were determined: the performance ratio (PR), the energy efficiency ratio (EER), and the seasonal performance factor (SPF). The findings revealed that the PR, EER, and SPF all fell from 2.51 to 3.06. Instead of poor quality in the PV-HP system, the low PR value was explained by the utilization ratios of the system (UREF varied from 0.27 to 0.77).

Sky radiative cooling may be improved by using a solar photovoltaic–thermoelectric cooler, as suggested by Lv et al. (2021) [41]. They proposed this improvement with their innovative PVRC-TE (incorporating radiative cooling with solar photovoltaic–thermoelectric cooler) system. Reducing solar incidence and heat absorption while increasing diurnal radiative cooling was made possible by photovoltaic cells. Meanwhile, the heat from the PV cells powered the TEC module, providing cooling power. The impact of varying climatic conditions on the system's operation was addressed using Hefei as an illustrative case study. The simulation findings revealed high-performance systems worked best in regions with drought and extended sunlight at middle latitudes. The geometric ratio of the photovoltaic and radiant cooling area was maximized in a PVRC-TE system. Figure 4 shows the system's highest daily cooling energy gain at 285.57 MJ/m^2 when the ratio of the photovoltaic and radiation cooling area was 1.

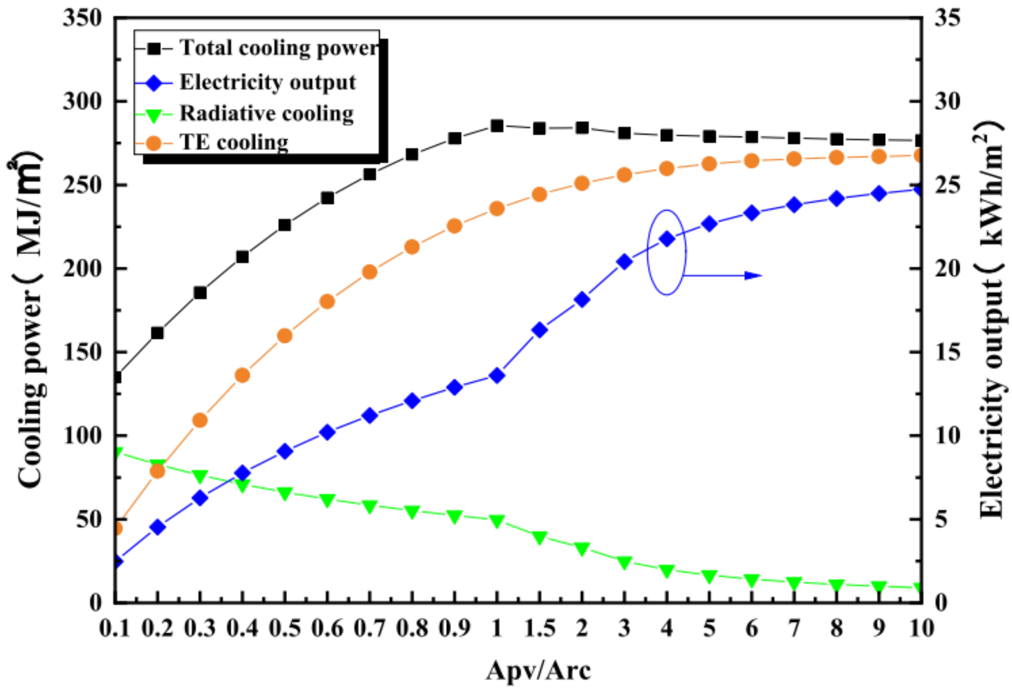


Figure 4. Effect of Apv/Arc on PVRC-TE [41].

Omar et al. (2021) [42] investigated the impact of a solar-assisted evaporative cooling system in a greenhouse on the environmental parameters that contribute to the increased production of cucumbers. The research included two separate trials (a pilot study and a field investigation). The first research used a MATLAB-created mathematical model to estimate the worth of environmental parameters in the chilled greenhouse. The goal of the field test was to verify the effects of the solar photovoltaic (PV) system, the cooling systems, and the model findings on cucumber production and water use. The greenhouse cover was painted, and evaporative cooling took around 8.32 MJ/day of solar power (PV) to bring the temperature down by roughly 10 °C. The efficiency of evaporation was 74%.

Using water from the ship's power plant cooling system, Zapaowicz and Zenczak (2021) [43] offered mathematical techniques to evaluate the energy profits attainable due to the implementation of the PV module cooling system. Photovoltaic systems (PV systems) are one of the most often-used setups, and this holds, regardless of the size of the ship. Adding water cooling to PV panels increases their efficiency and contribution to the ship's power output. The PV system provides for the ship's demands, as shown in Figure 5, with extra advantages from their cooling (DPVC). The PV system produces 1177 kWh of electric energy during the 6 h stay in port in May, and an extra 148 kWh of electric energy is possible after the cooling is applied, or by about 13% more. The diesel generators produced an additional 3475 kWh of electrical energy.

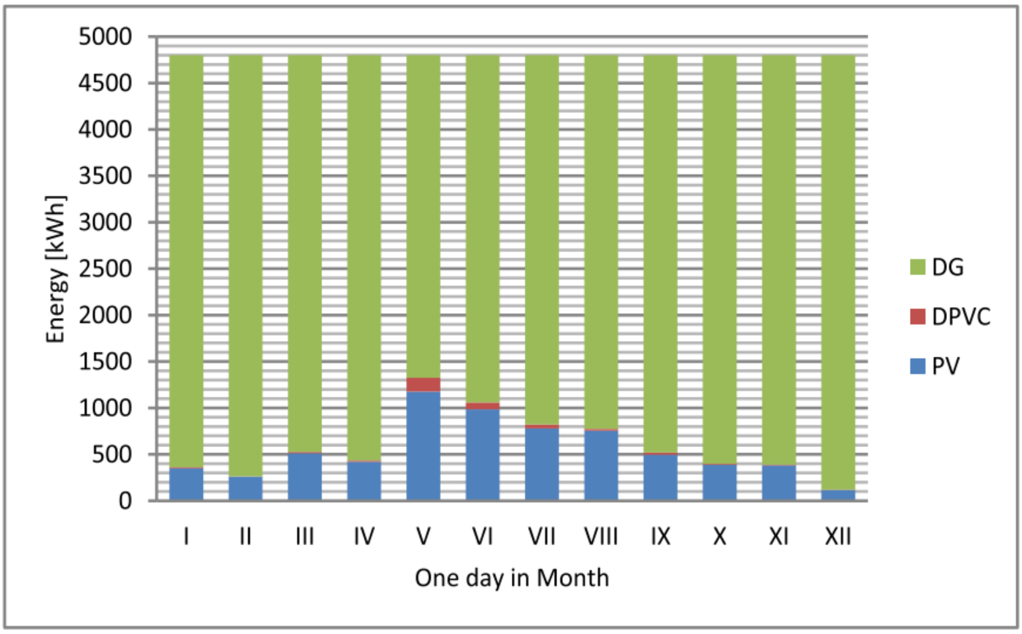


Figure 5. Energy is produced via cooled PV panels throughout the ferry's 6 h port stay. Diesel generator-generated energy, PV-generated electricity without cooling. The PV panel cooling contributed to DPVC-generated electricity [43].

To show how successful and profitable it is to employ renewable energy and smart-control systems in a closed farm setting, Al-Naemi and Al-Otoom (2023) [44] developed a smart, sustainable greenhouse concept model (SSGHCM). Solar photovoltaic energy was used to power SSGHCM, which also used water recycling. The greenhouse's watering, temperature, and humidity were all managed by microcontrollers and a complex network of sensors. Microcontrollers with LabVIEW integration and a wireless control system based on the Internet of Things were employed. It was determined that the necessary energy could be met by the installed PV capacity with storage. With the Internet of Things (IoT), microcontrollers, and renewable energy sources, growing vegetables in greenhouses in GCC nations may be economically viable. The water need for hydroponic greenhouses was reduced by around 40% thanks to water recycling and management systems. About 65% of the water required for irrigation may be met by collecting condensate from air conditioning systems.

To compare the monetary worth of various HVAC systems in private American homes, Kim and Junghans (2022) [45] developed an integrative framework. TRNSYS was used to analyze a single-family, two-story house in Detroit, Michigan. The building's systems were divided into passive (insulation) and active (heating, ventilation, and air conditioning). Using the U-values, the insulation was ranked into three categories: low, medium, and high. However, the research also demonstrated that despite their excellent system efficiencies, both renewable energy systems had significant payback times (ranging from 8.08 to 20.50 years). This exemplified how 'building energy optimization' might be misunderstood if the total efficiency of energy systems in a building was evaluated without further economic analysis. The scientific community offered additional evidence supporting ETS's broad use in U.S. homes. Many home HVAC systems would have shorter payback times due to the rising demand for ETS, particularly if renewable energy sources became more widespread.

Without the need for batteries, Li et al. (2021) [46] demonstrated a 3 HP solar direct-drive photovoltaic air-conditioning system that utilized ice thermal storage to store excess solar energy. If the PV power output unexpectedly varied, the refrigeration compressor would lose power and be unable to launch or shut down. An adaptive controller and a suited compressor needed to be matched to the solar air conditioning system's power requirements to keep the system operating continuously and steadily. For this outdoor experiment, various solar air conditioners were constructed and tested, each with a unique combination of PV panel capacity, MPPT controller presence/absence, and compressor type. Good ice-making performance, dependable operation, and a significant increase in available solar energy were seen in the trial results of the system using a variable speed compressor and a maximum power point tracking (MPPT) controller.

Through numerical and experimental research, Ozcan et al. (2021) [47] addressed the impact of weather conditions and operational factors on the energy and economic performances of a solar PV-powered air-conditioning unit (ACU) with a battery system (PBAS). The tests were performed to validate the TRNSYS model that had been built. The simulated studies showed that annual energy performance measures (self-consumption, self-sufficiency, grid independence, and energy conversion ratios) were highly influenced by environmental and operational factors. In addition, for the warmest climate (Seville), the economic analysis showed a clear correlation between the net present value and the energy consumption profiles or diverging values for the condition of charges.

Haffaf et al. (2021) [48] offered a comprehensive study of the technological and economic viability of a solar photovoltaic (PV) air-conditioning system for an office building, as well as its environmental benefits. HOMER was used for the system's design, simulation, and optimization. As objective functions, we analyzed the system's performance based on total net present cost, energy cost, renewable fraction, and carbon dioxide emissions. Not only were the net energy purchases, energy sales, and grid interactions studied, but also the energy purchases. Based on the modeling findings, we determined that TNPC, CoE, and RF were USD 2276.61, USD 0.0655/kWh, and 79.2%, respectively. The system was projected to generate a total of 2875 kWh per day, with PV accounting for 80.5% (2315 kWh) and the grid contributing the remaining 19.5%. The system reported 559 kWh of grid energy buy, 1094 kWh of energy sales, and a net purchase of 534.11 kWh. The energy requirements of the air conditioner were satisfied in full, with no load or capacity shortages and a surplus of 73.5 kWh.

Li et al. (2023) [49] studied the compatibility features of a PVAC in an office space that was 207.34 m^2 in size. A single, comprehensive simulation model included a building model, a PV calculation model, an air conditioning model, and a control method. Two heat exchangers, a compressor and a throttle, were modeled as parts of the air conditioner's cooling system. EnergyPlus was used to model both the structure and the PV system. When the inside temperature was within the acceptable range, the AC compressor speed was adjusted such that the AC power consumption equaled the PV generation. The PV capacity significantly affected the daily matching features of PVAC. The findings indicated that a PV factor (PVF) of 1 maximized the AC efficiency by matching the AC and PV power. The grid's adaptability could be guaranteed with a battery factor of at least 0.7.

For passive heating, ventilation, and air conditioning (HVAC) throughout the day in electric vehicle charging station control rooms, Ra et al. (2023) [50] developed a solar-battery storage integrated switchable glazing architecture. A solar PV source was placed on top of the EV charging station to further the goals of promoting renewable energy and environmentally friendly mobility. Incorporating a vanadium redox flow battery (VRFB) as a long-term energy storage option increased the system's reliability and safety regarding power supply. IoT-based smart scheduling of solar PV, VRFB storage, and the regional distribution grid was proven to meet the glazing load requirement of a building in response to real-time, dynamic climatic circumstances. The suggested system's efficacy has been verified in four distinct transient conditions: clear skies, brief cloud cover, persistent cloud cover, and low solar irradiance with frequent grid disruptions.

Omar et al. (2022) [51] proposed a technique for converting a traditional school building into a net-zero energy building (nZEB) as a viable option for addressing the pressing issue of rising energy costs. An Egyptian school was chosen as a case study for this retrofitting strategy technique. To lower energy use, many methods were used. The first method was lighting retrofitting, which entailed switching inefficient incandescent bulbs with newer, more energy-efficient LED ones. The second method was to retrofit cooling by installing solar air conditioners instead of conventional split-system ACs. The third option was integrating a photovoltaic (PV) system into the existing power grid. Following an increase in the building's energy efficiency, the ideal PV system and inverter sizes were attained at a capital cost of $98,000 and $30,399 for 140 kW and 120 kW, respectively. In addition, the system generated around 82% of its energy from renewable sources. It would take the PV/grid system 24 years to recoup all of its initial investment after the increased load (after using the retrofitting method).

To achieve a virtually zero energy building (nZEB) within the framework of the Energy Performance of Buildings Directive 2010/31/EU, Delač et al. (2022) [52] provided an approach for optimizing a building with its HVAC system. The technique relied on using the non-dominated sorting genetic algorithm (NSGA-II) as the engine to optimize for low global cost (GC) and low primary energy consumption (PEC) in dynamic simulation models developed in the TRNSYS program. Energy efficiency measures (EEM) on a building envelope and a parameterized HVAC system model constituted the optimization. The technique executed building simulations under designed weather conditions for heating and cooling to determine the correlation between building design and HVAC system size. The study used manufacturer-reported data on the sizes and specifications of individual pieces of equipment, guaranteeing the use of genuine items and their associated expenses.

With an eye on energy, economic, and environmental (E3) performance, Luo et al. (2022) [53] analyzed five different building envelope systems: photovoltaic (PV) + thermal energy (S1), grid (S2), hybrid (PV + Grid + TE) (PV + S3), battery (PV + S4), and hybrid (PV + Grid + BTE) (PV + S5). nZEBs can make more progress due to the new envelope systems' ability to reduce thermal loads, while offering extra cooling/heating supplies. It was determined that each of them had a thermal energy load setting that resulted in the lowest yearly power usage. Except for the S1 system, the remainder of the systems could achieve negative cumulative power consumption in a year-round operation, which might result in a zero-thermal load on the building envelope. Under a 4% interest rate, the consistent yearly cost per square meter for S1 through S5 was 19.78, 14.77, 23.83, 60.53, and 64.94 ($\$/m^2$). The S5 system reduced CO_2 by 3.04 t/m^2 over 30 years of operation, making it the most environmentally friendly option.

The radiative characteristics of infrared transparent mesoporous materials were studied by Huang et al. (2022) [54]. To mimic the mesoporous materials' microscopic structures, the diffusion limited cluster aggregation method was used. By combining the discrete dipole approximation with the Monte Carlo approach, we forecasted the structure-dependent normal hemispherical transmittance. The findings demonstrated that the aerogel made of polyethylene (PE) had the highest performance in terms of thermal insulation and spectrum selectivity. The radiative cooling surface could use it as both a thermal insulator and an infrared clear window. Passive cooling to temperatures up to 13 K below ambient during the day and 15 K below ambient during the night at a wind speed of 2.8 m/s was made possible by combining the radiative cooling surface with PE aerogel.

Vakilinezhad and Ziaee (2023) [55] analyzed the energy-saving potential of solar PV panels installed on the roofs of typical Iranian homes in four cities with substantially diverse climates. The energy demands of the building and the power output of the PV panels were calculated using a simulation program called Ladybug Tools. The findings showed that PV panels considerably impacted the building's cooling burden, particularly during peak hours. Bandar-Abbas, the warmest city, benefited the most, with a maximum SER of 3.4%; Ardabil, the coldest city, benefited the least, with a SER of 0.5%. Furthermore, in cold and mild climates, the roof with the lowest R-value and solar absorption had the greatest SER, whereas in hot climates, the roof with the highest R-value and the lowest solar absorption had the highest SER. When the R-value of a roof was low and solar absorption was high, the shadowing impact of PV panels became more noticeable. Although PV panels reduced the need for cooling energy, they could raise the need for heating.

By replacing R134a with a low global warming potential (GWP) refrigerant (R290), Zarei et al. (2023) [56] improved the efficiency of a solar compression refrigeration system utilizing a single PV-thermal (PVT) collector linked with a refrigeration system. The electrical efficiency of the PVT collector was also increased by using a zinc oxide (ZnO) nanofluid, which absorbed the thermal energy from the collector. At the condenser output, subcooling of the refrigerant was accomplished by using the fluid discharged from the PVT collector. Theoretical analysis using the first and second laws of thermodynamics revealed that increasing the concentration of ZnO nanoparticles from 0% to 6% improved the system's solar cooling efficiency (SCE) and coefficient of performance by more than 30%, from 21% to 28% and from 9% to 12%, respectively. Compared with using just water in the solar-collector circuit, the nanofluid reduced the overall heat exchanger area by 1–6%. Last, but not least, it was stated that switching to R290 improved SCE by 3% in comparison with an R134a-based system.

Xiao et al. (2023) [57] showed that spectrum beam splitters (SBSs) made of carbon quantum dot (CQD) nanofluids worked superbly in photovoltaic (PV) and thermoelectric (T) systems. A simple microwave heating approach may be used to produce CQD-nanofluid filters, which exhibit ultra-stability over an extended length of time. At the same time, by adjusting the heating duration and PEG concentration, the optical property of CQD nanofluids was sharpened. As the heating duration increased, the absorption of nanofluids throughout the spectrum improved, and the absorption to particular wavelengths could be controlled by varying the concentration of PEG. With a merit function (MF) value of 1.904 and a worth factor (w) of 3, the nanofluid filter with a 50% PEG content and a 20 min heating period exceeded the previously reported nanofluid filters in the literature.

An innovative colored transparent aerogel (CTA) window design that combined thermal insulation, color modification, and strong light transmission was introduced by Maoquan et al. (2023) [58]. Using a mix of Mie theory and Monte Carlo approaches, the radiative characteristics of the core–shell plasmonic particle-doped aerogel were predicted theoretically. In addition to exhibiting a variety of vibrant hues, the findings demonstrated that the CTA window had a low thermal conductivity of around 0.018 W/m K and a high visible light transmittance of circa 45%. In very cold areas, a simulation of CTA windows' energy usage in several Chinese climates revealed possible savings of up to 90% compared with the single tinted window.

As an energy-saving window, Pu et al. (2023) [59] suggested a VO_2/SiO_2 core–shell nanosphere-based dynamic aerogel. By integrating the Mie theory with the Monte Carlo approach, the radiative characteristics of aerogel windows were theoretically investigated with respect to the particle size, outer-to-inner diameter ratio, volume percentage, and thickness. Specifically, the dynamic aerogel's solar control ability and haze were calculated. The findings demonstrated that a solar control ability of 124.2 W/m^2 was achieved by a 0.25 cm thick aerogel doped with core–shell nanospheres of D/d = 2 (fv = 0.01%). For the insulating (metallic) phase, the solar transmittance was 70% (55%) and the haze was 0.067 (0.097).

Table 1 summarizes research conducted using PV for cooling systems.

Table 1. A summary of research conducted using PV for cooling systems.

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Han et al. (2019) [32]	Integrated control method for a solar cooling system that does not need a battery and is instead directly powered by distributed photovoltaics (PVs).	Solar air conditioning relies only on a network of PV panels.	Impedance matching control scheme experiments show an increase in efficiency of 83.7% compared to a system without a controller, with an average photoelectric conversion efficiency of around 0.129. Using a model that incorporates ice thermal storage, the COP solar was increased by 60.4%, reaching 0.263.
Pang et al. (2019) [33]	The DC air-conditioning system uses R134a as the refrigerant, with solar energy as the replacement power source.	Air cooling system for vehicles.	The developed DC air conditioning system is preferable to the standard car air conditioning system from an environmental perspective, saving energy and reducing pollutants.
Zuhur et al. (2019) [34]	System of photovoltaic concentration for cooling.	Cooling and electricity of the building.	Concentrator use raises the temperature of the panels' rear sides, resulting in less electrical output compared to systems without concentrators. Because less carbon dioxide is produced, the technology saves around 0.1 per hour.
Kiyaninia et al. (2019) [35]	System for the direct evaporative cooling of the air powered by solar photovoltaics.	Air-cooling system.	The conventional system has a higher exergoeconomic factor than the solar system because of its cheaper initial investment and a lower exergoeconomic factor in subsequent years because of its higher running cost.
Lin et al. (2020) [36]	Concentrating photovoltaic and thermal collectors are part of this solar system's integration.	Cooling-electricity ratio from 1.4 to 2.0.	The unique solar co-generation system may provide a cooling-electricity ratio of 1.4 to 2.0, which is sufficient for satisfying the needs in many instances, depending on the temperature management approach used.
Song and Sobhani (2020) [37]	Solar desiccant air-cooling system with PCM and a Maisotsenko cooler for an added cooling capacity.	Desiccant cooling system.	The PV module's highest power output is about 0.77 kW at noon in October, while its lowest electrical efficiency is around 13.6% at 14:00 p.m. in September.
Bilardo at al. (2020) [38]	Solar cooling system.	The cooling of the Mediterranean-style apartment complex.	It is generally not feasible to attain a significant renewable energy ratio only via renewable energy for winter heating and DHW generation, but a solar cooling system makes it possible to use the sun's energy.

Table 1. *Cont.*

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Wu et al. (2020) [39]	Façade integrated solar cooling systems.	Solar cooling system.	When comparing ORC-VCC to adsorption and absorption chillers in subtropical and temperate climatic zones, the grid acts as a virtual store, increasing SF by 40% and 50% while decreasing UCC by 10%.
Lorenzo et al. (2020) [40]	Independent PV-HP system that functions without batteries, with two distinct control algorithms designed and implemented for the compressor of the HP unit.	General cooling applications.	Instead of poor quality in the PV-HP system, the low PR value is explained by the utilization ratios of the system (UREF varied from 0.27 to 0.77).
Lv et al. (2021) [41]	Incorporating a solar PV–thermoelectric cooler system, which uses radiation to chill the air.	Enhancing sky radiative cooling.	The system's maximum cooling energy gain per day is 285.57 MJ/m^2 when the ratio of photovoltaic cooling area to radiation cooling area is 1.
Omar et al. (2021) [42]	Greenhouse cover painting and solar-assisted evaporative cooling for cucumbers.	Cooling greenhouse.	You can calculate the daily specific energy consumption for the evaporative cooling system or any other energy consumption on the farm from the overall value of electrical energy production from PV.
Zapałowicz and Zenczak (2021) [43]	Implementing a cooling system for PV modules utilizing water from the ship's power plant.	Ship's power plant cooling system.	On a typical day in May with no wind, the PV module with a cooling system gained the most power, equivalent to around 25 W/m^2, 17% more than the parameter for the PV module without a cooling system.
Al-Naemi and Al-Otoom (2023) [44]	Closed-loop agriculture using renewable energy and intelligent control technologies.	Smart, sustainable greenhouses.	The water need for hydroponic greenhouses is reduced by around 40% thanks to water recycling and management systems. About 65% of the water required for irrigation may be met by collecting condensate from air conditioning systems.
Kim and Junghans (2022) [45]	A comprehensive method for determining the monetary worth of various HVAC units.	Residential energy systems.	The term "building energy optimization" may be misleading if it is used to assess the effectiveness of energy systems in buildings without further economic research.
Li et al. (2021) [46]	Solar air conditioner with a direct-drive photovoltaic motor and 3 horsepower output.	Air conditioning system.	In addition to a significant increase in usable solar power, the system's variable-speed compressor and maximum power point tracking (MPPT) controller have proven effective in making ice.

Table 1. *Cont.*

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Ozcan et al. (2021) [47]	Battery-operated ACU driven by photovoltaics (PVs).	Air conditioner system.	Climate and operational factors significantly impact annual energy performance measures, including self-consumption, self-sufficiency, grid independence, and energy conversion ratios.
Haffaf et al. (2021) [48]	AC for an office building on solar photovoltaic panels.	Air conditioning of an office building.	The system has reported 559 kWh of grid energy buy, 1094 kWh of energy sales, and a net purchase of 534.11 kWh. The energy requirements of the air conditioner are satisfied in full, with no load or capacity shortages and a surplus of 73.5 kWh.
Li et al. (2023) [49]	Air conditioning powered by solar panels.	Air conditioning system.	It is recommended that the PV factor be set to 1 to improve AC efficiency. This will ensure that the AC power is matched with the PV power. The grid's adaptability may be guaranteed with a battery factor of at least 0.7.
Ra et al. (2023) [50]	The integration of solar panels and batteries into a switchable glazing topology.	Passive heating, ventilation, and air conditioning (HVAC) for EV charging station control rooms during daylight hours.	The sensitive electronic panels and controllers in EV charging stations need secure and reliable functioning.
Omar et al. (2022) [51]	Traditional school structure to a net-zero energy structure.	Net-zero energy building.	After using the retrofitting method, the PV/grid system for the additional load will have a payback period of 24 years.
Delač et al. (2022) [52]	The structure has an HVAC system for climate control.	Achieving nearly zero energy building.	When the size of the HVAC system is proportional to the design load, the best results are attained.
Luo et al. (2022) [53]	There are five distinct kinds of exterior wall systems.	Net zero energy building	NZEBs can progress more due to the new envelope systems' ability to reduce thermal loads while offering extra cooling/heating supplies.
Huang et al. (2022) [54]	Radiative characteristics of infrared transparent mesoporous materials.	Radiative cooling.	Passive cooling to temperatures up to 13 K below ambient during the day and 15 K below ambient during the night at a wind speed of 2.8 m/s is made possible by combining the radiative cooling surface with PE aerogel.
Vakilinezhad and Ziaee (2023) [55]	Solar photovoltaic panels on roofs are made of various materials.	A typical residential building.	The cooling demand of a building is significantly impacted by PV panels, particularly during peak hours.
Zarei et al. (2023) [56]	An all-in-one PV–thermal (PVT) collector and refrigeration system for solar refrigeration.	Solar compression cooling system.	Compared with using just water in the solar-collector circuit, the nanofluid reduces the overall heat exchanger area by 1–6%.

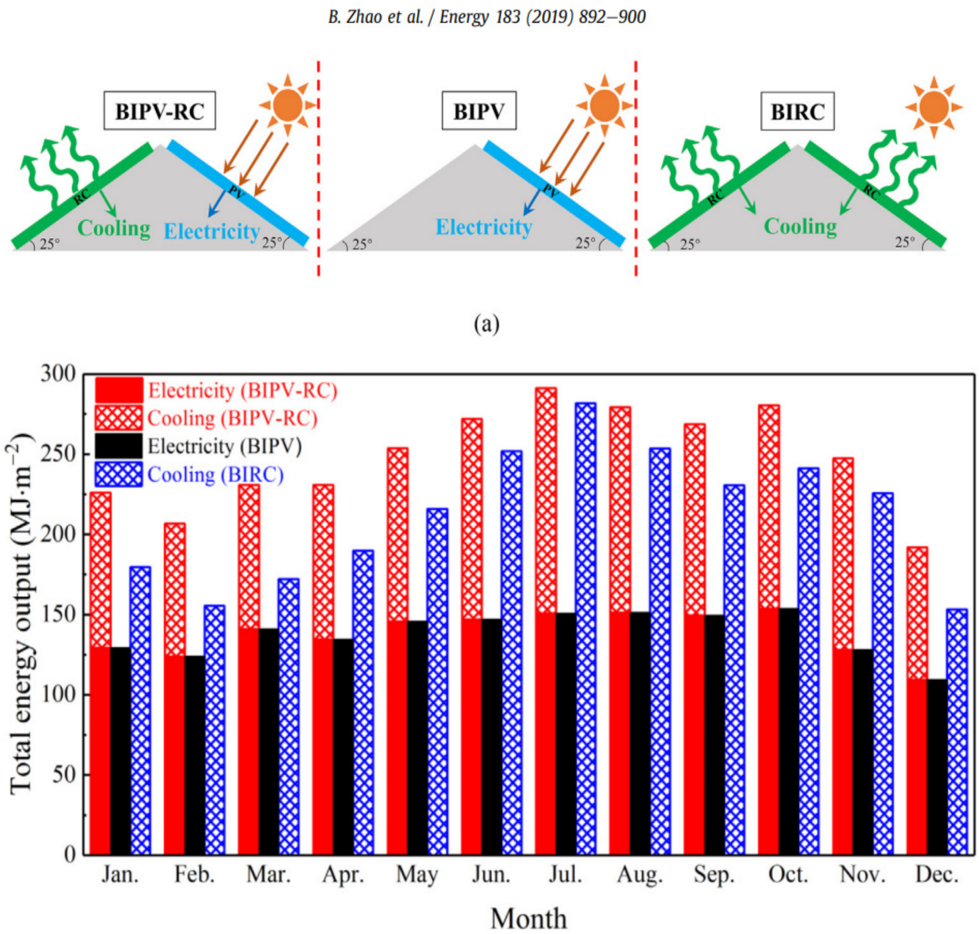
Table 1. *Cont.*

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Xiao et al. (2023) [57]	Spectral beam splitters.	PV/T applications.	With a merit function (MF) value of 1.904 and a worth factor (w) of 3, the nanofluid filter with a 50% PEG content and a 20 min heating period exceeds the previously reported nanofluid filters in the literature.
Maoquan et al. (2023) [58]	Plasmonic aerogel window with structural coloration.	Energy-efficient and sustainable building envelopes.	The CTA window had a low thermal conductivity of around 0.018 W/m K and a high visible light transmittance of circa 45%. In very cold areas, a simulation of CTA windows' energy usage in several Chinese climates revealed possible savings of up to 90% compared to the single tinted window.
Pu et al. (2023) [59]	Transparent aerogel window based on silica aerogel.	Energy-saving window.	A solar control ability of 124.2 W/m^2 is achieved by a 0.25 cm thick aerogel doped with core-shell nanospheres of D/d= 2 (fv = 0.01%). For the insulating (metallic) phase, the solar transmittance is 70% (55%) and the haze is 0.067 (0.097).

3.2. Using Hybrid Techniques for Cooling Systems

By covering the sunny side of a rooftop with PV modules and its free side with all-day RC modules, the BIPV-RC system proposed by Zhao et al. (2019) [60] integrated solar energy collection and RC utilization into a single building unit. Case studies were conducted in two tropical cities (Karachi, Pakistan, and Riyadh, Saudi Arabia), and a mathematical model was built for the proposed BIPV-RC system. Based on the data, the BIPV-RC system in Riyad produced around 20.7% and 94.0% more power and cooling than Karachi, at 462.1 kWh·m^2 and 1315.3 MJ·m^2, respectively. Figure 6 displays the results of a comparison study between the BIPV-RC system and the more common BIPV and building-integrated RC (BIRC) system, which shows that the BIPV-RC system had an annual total energy output that was nearly 79.1% and 16.8% higher, respectively.

Using compound parabolic concentrator photovoltaic thermal (CPC-PVT) collectors, Wang et al. (2019) [61] proposed and evaluated a new hybrid combined cooling heating and power (CCHP) system. Electricity and waste heat transported by exhaust gas and jacket water from an internal combustion engine were combined with electricity and hot water from CPC-PVT to boost energy performance. The simulation results were compared with previous research to build and verify the thermodynamic models. To measure the value of solar energy's contribution, researchers used the levelized primary energy saving ratio (PESR) and the carbon dioxide emission reduction ratio (CDERR) of the hybrid CCHP system against the CCHP system without solar energy. Based on the findings, the summertime energy efficiency was 63.3%, the exergy efficiency was 21.8%, and the wintertime efficiency was 61.8%. As can be seen in Figure 7, the hybrid system was capable of a higher levelized PESR (28.6%) and CDERR (36.7%) than the CCHP system without solar energy due to its greater flexibility in adjusting the heating-to-electricity ratio.



(a)

(b)

Figure 6. (**a**) BIPV-RC, BIPV, and BIRC schematic; (**b**) Riyadh's BIPV-RC, BIPV, and BIRC yearly energy output [60].

For performance assessment and optimization, Fan et al. (2019) [62] created a model of a desiccant cooling system that included a hybrid photovoltaic thermal collector-solar air heater (PVT-SAH) that was paired with a building model. The desiccant in a desiccant wheel was regenerated by increasing the air temperature at the PVT-SAH output using a double-pass PVT-SAH system with heat pipes. When the PVT-SAH was designed optimally for a case study commercial building in a hot and humid region, the annual solar fraction and the electrical COP of the cooling system achieved up to 96.6% and up to 19.8 respectively. For the hybrid desiccant cooling system to achieve a COP greater than the normal COP for commercial buildings (2.6–3.0), it was determined that a PVT-SAH with a surface area of 0.35 m^2 per m^2 of conditioned floor area was necessary. With larger PVT-SAH systems, both the electrical COP and solar fraction of the cooling system rose, albeit at different rates, as shown in Figure 8.

The energy and economic performances of hybrid solar photovoltaic and combined cooling, heating, and power (CCHP + PV) systems with varying degrees of PV penetration were studied by Ahn et al. (2019) [63]. The researchers looked at both a deterministic and a stochastic model. Hourly energy use at a DOE reference big office building in San Francisco, California, and solar irradiance profiles from TMY data were used as independent variables in a deterministic model. Uncertainties in these exogenous variables were modeled using the Monte-Carlo technique in the stochastic model. The findings revealed that the energy performance of CCHP + PV systems was mostly unaffected by the degree of PV penetration, but that uncertainties in building energy needs and solar irradiance could significantly raise yearly running costs by up to $75,000 (13%). Rising demand fees (as much as $79,000 per year) were the primary driver of the cost rise. When peak demand uncertainty grew, so did the associated demand costs. The findings implied that a deterministic model was more likely than a stochastic model to underestimate the operational costs of CCHP + PV systems or similar distributed energy systems when the demand charge was responsible for a major share of power bills (i.e., demand tariffs).

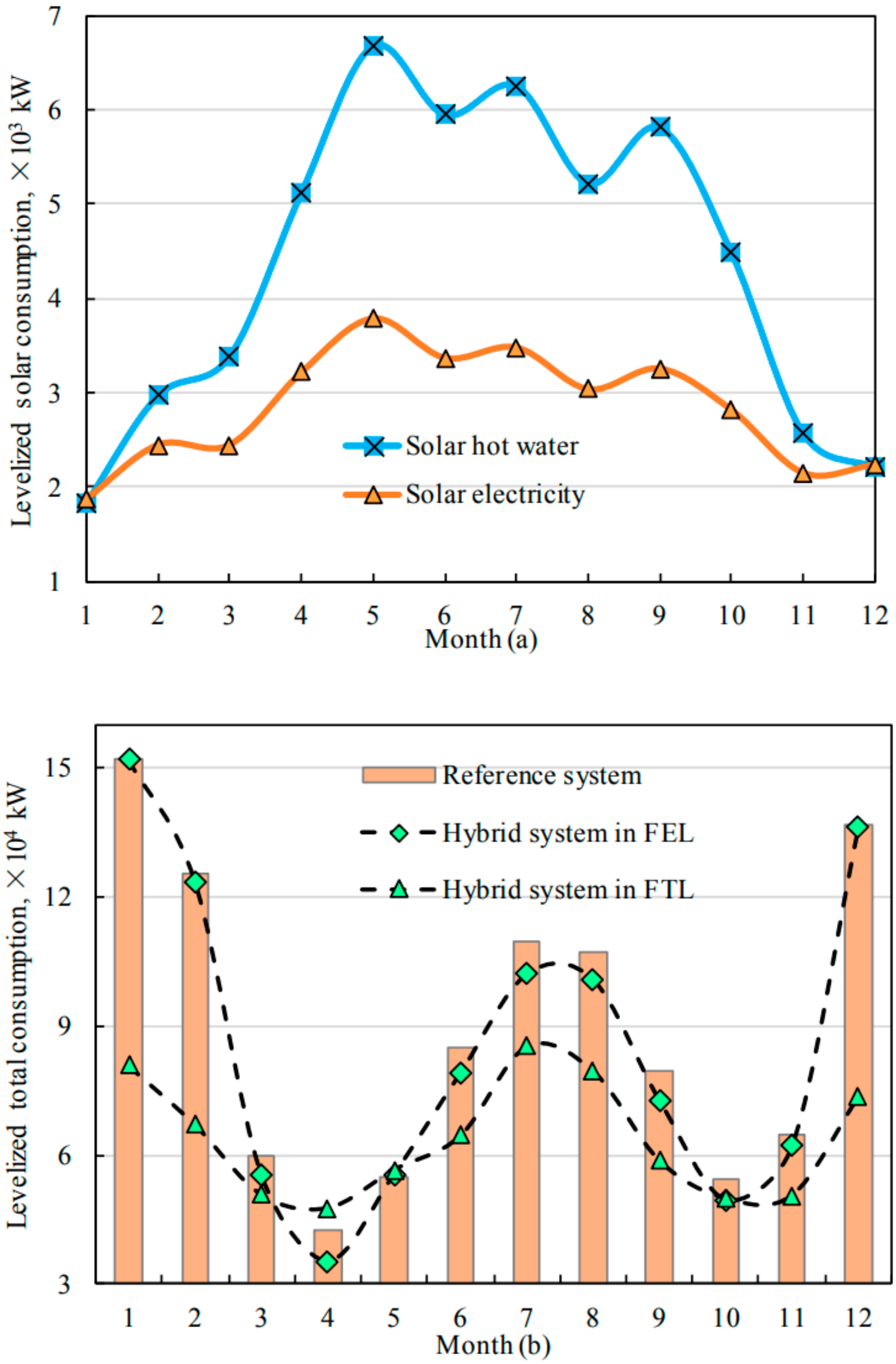


Figure 7. (**a**) monthly levelized solar consumption caused by solar hot water and solar electricity and (**b**) levelized total energy consumption of two hybrid systems and the reference system [61].

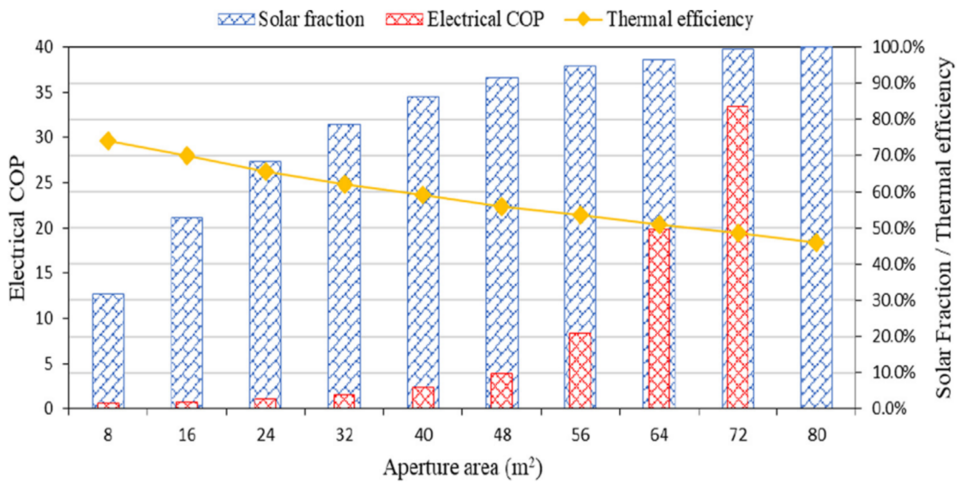


Figure 8. PVT-SAH aperture area affects electrical COP, solar fraction, and desiccant cooling system thermal efficiency [62].

Elghamry and Hassan (2020) [64] conducted an experimental examination into the effectiveness of a novel combination of solar chimney and geothermal air tube heat exchanger system in cooling and ventilating a building room in novel Borge Alarb City, Alexandria, Egypt. The efficiency of a photovoltaic (PV) panel placed at the chimney back using a novel method was measured against that of an identical PV panel placed outside the building. According to the findings, the suggested systems successfully reduced the room temperature by 3.5 °C and increased the air turnover rate by 4.2% daily. At 30 degrees and 45 degrees, respectively, roughly 56.3% and 65% of the total daily ventilation air was provided by the natural geothermal tube-chimney, and for heat emitted, the corresponding figures were about 55.6% and 64%. Although the quantity of ventilated airflow was greater in the case of 45°, as indicated earlier, Figure 9a shows that PV output power at an inclination angle of 30° was greater than 45°. This is because 30° was nearly the same latitude angle as the measured site. According to Figure 9b, the maximum power output from the PV array within the chimney was about 83.4 W or about 70% of the maximum power output from the PV array outside the chimney.

Zarei et al. (2020) [65] studied the efficiency of a combined solar cooling/heating system based on a PVT in a home setting. The primary benefit of PVT is its ability to convert as much solar energy as possible into usable energy, like electricity and heat. It was hoped that using water to cool the panel would improve performance in this application. The cooling process was a two-temperature evaporator ejector-compression refrigeration cycle. To mitigate the consequences of climate change, R134a was replaced by two alternative refrigerants, R600a and R290, both of which had a reduced GWP. The input and collector output water were heated in a condenser and heater after gaining heat from the PVT. The findings show that the total efficiency of the PVT system could be increased from 66.7% to 75.8% by raising the water mass flow rate from 0.011 kg/s to 0.03 kg/s (39–108 Lit/h) at a solar intensity (G) of 945 W/m^2. Compared with the other refrigerants, R290 had the best performance regarding both COP and exergy destruction. When R290 was used instead of R134a, the cycle's COP could improve by as much as 7.5%. As shown in Figure 10, the water's optimal mass flow rate was w = 0.013 kg/s, which yielded the maximum COP and the lowest exergy degradation. The water temperature at the system's exit ranged from 31.72 degrees Celsius in the morning to 46.73 degrees Celsius in the afternoon. When comparing a system with and without panel cooling using R134a refrigerant, it was found that using R290 for the refrigeration cycle and cooling the panel resulted in enhancing the COP of the cycle by 11.1%, increasing the temperature of the outlet water from the system by 9.17 °C and decreasing the refrigerant flow rate by 60.17%.

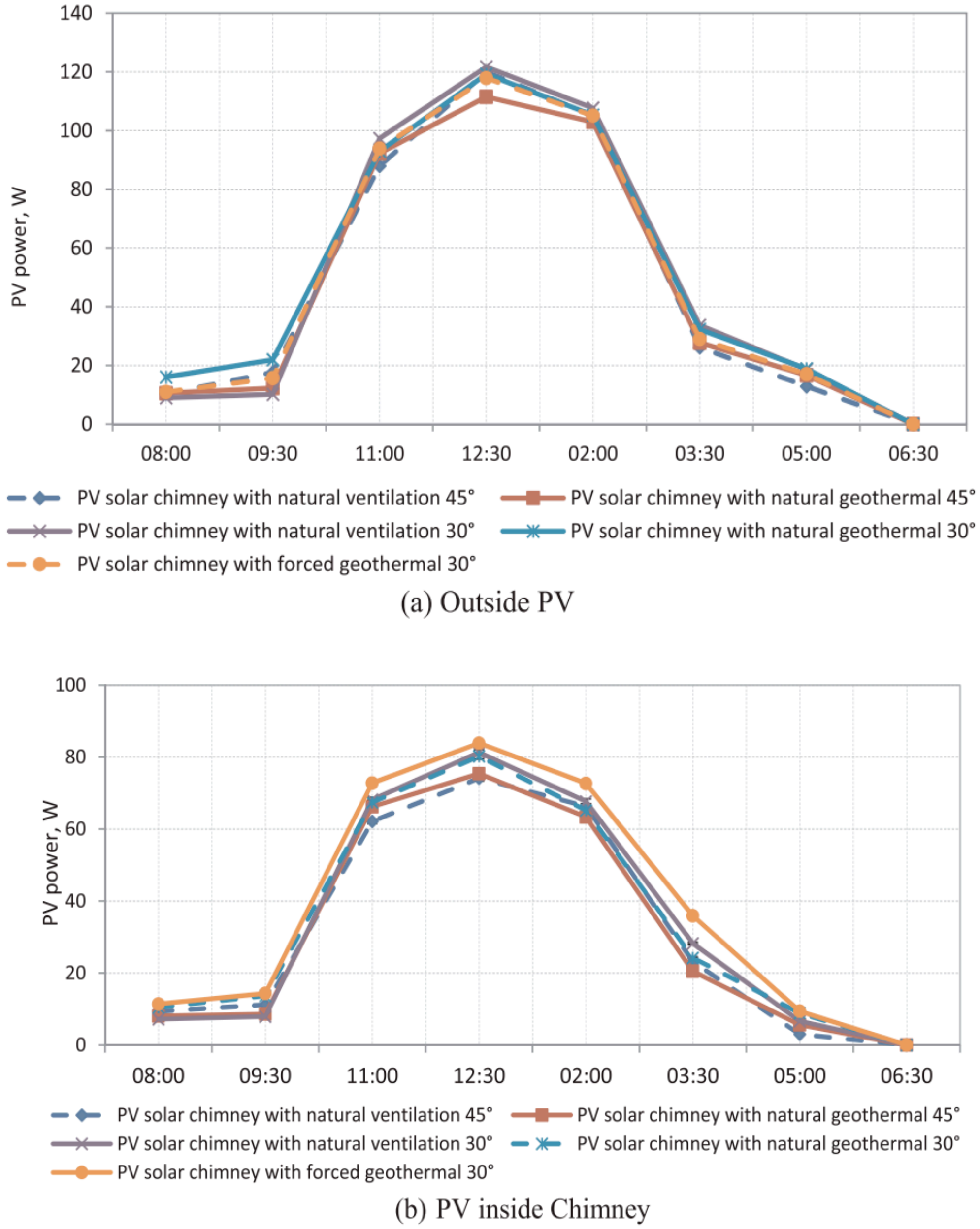


Figure 9. PV power evolution for (**a**) PV outside the chimney and (**b**) PV inside the chimney [64].

Using energy storage technologies, Pinamonti and Baggio (2020) [66] analyzed several solar-assisted heat pump (SAHP) system designs. Three buildings of varying energy efficiency levels were included in the research, which considered both heating and cooling needs. Using the TRNSYS simulation program, we suggested and tested out several different system topologies. To evaluate the success of the SAHP strategies, a conventional air-source heat pump was used as a benchmark system. Maximum energy savings (−30%) were shown when a photovoltaic (PV) system with battery storage was considered for a well-insulated structure. On the other hand, the installation of solar thermal (ST) panels were proven to be financially preferable (−24%) over the course of 20 years. When considering energy efficiency and cost, PV installation was the most cost-effective option (−25%) for a medium-insulated structure. For a poorly insulated structure (−26%), incorporating ST panels was also the most cost-effective option.

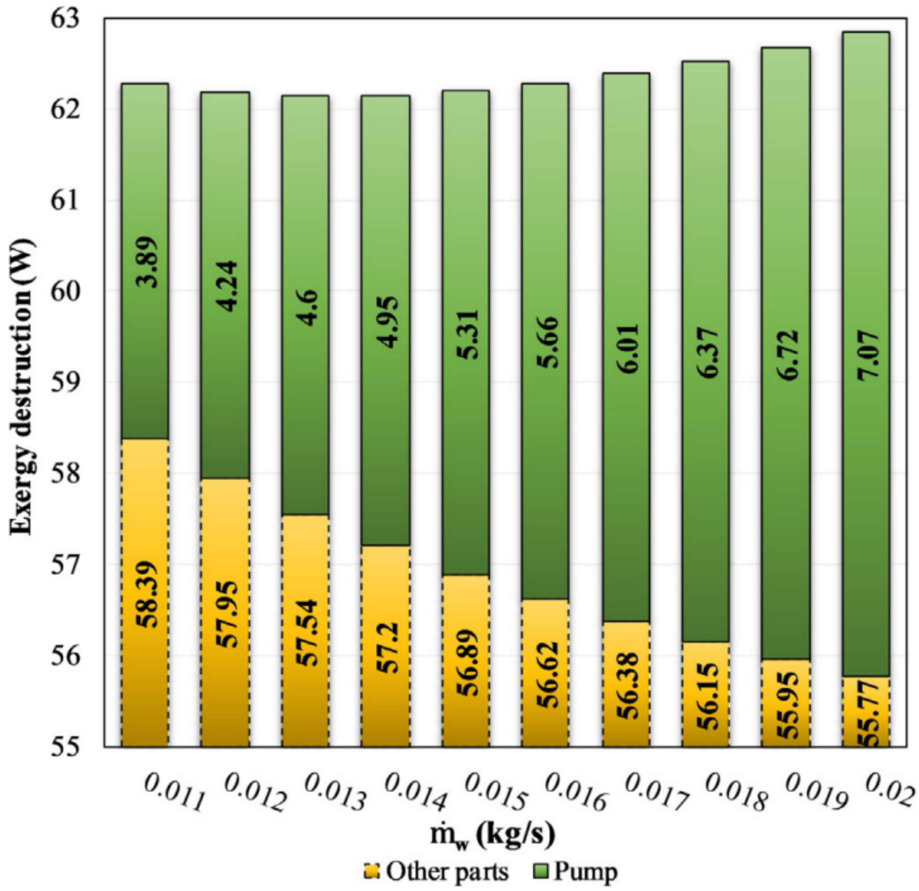


Figure 10. Effect of $\dot{m}_w$ on R290's total exergy destruction at G = 945 W/m^2 [65].

Using ground source heat exchange and flat plate photovoltaic thermal (PV/T) collectors, Guo et al. (2020) [67] studied the efficiency of a new desiccant air dehumidification and cooling cycle that supplied conditioned air. With a focus on three climates—(i) an oceanic climate (Cfb), (ii) a humid sub-tropical climate (Cfa), and (iii) a hot semi-arid climate (BSh)—the system was modeled in TRNSYS utilizing confirmed components. The collectors were calculated based on the GPVTDC system's thermal and electrical energy demands. The system was run through a year of simulations to ensure it could effectively dehumidify, cool, and ventilate an office area in each region. Figure 11 shows that the GPVTDC system may save up to 83.9%, 70%, and 55% in electrical energy compared with a compression cooling system with a cooling COP of 3.2, 6, or 9, respectively.

A unique hybrid solar cooling system powered by a concentrated photovoltaic/thermal unit (CPV/T) was described by Al-Nimr and Mugdadi (2020) [68]. The PV module's electricity powered the thermoelectric cooler, whereas the module's heat energy operated an absorption cooler. When PV modules were effectively cooled, they generated more power, yet at a lower temperature. This means that the thermoelectric cooler was more effective than the absorption cooler. Scientists sought to maximize the cooling impact of the PV panels by optimizing their operation. Based on the findings, it was determined that a higher figure of merit (COP > 6.4) for the thermoelectric cooler was necessary for the optimization process to be carried out. At 1000 W/m^2, the system's COP increased from 0.151 to 0.233 when the PV/T outlet temperature rose from 65 to 90 °C.

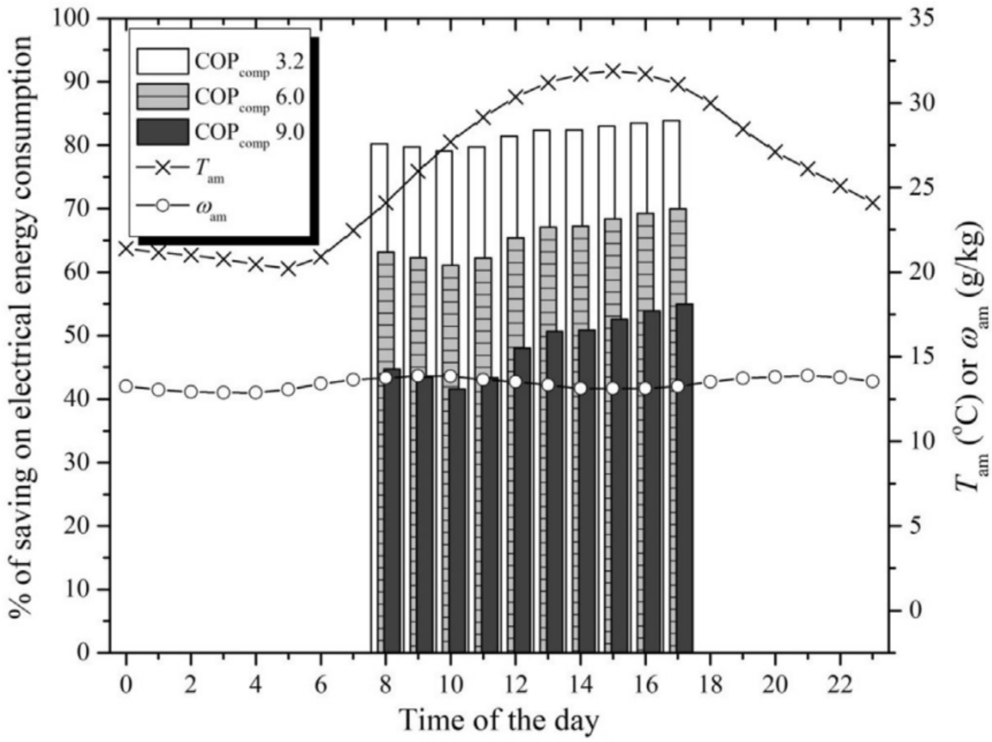


Figure 11. On 18 December GPVTDC saved % of electrical energy compared with compression cooling [67].

To prevent damage to railway and highway infrastructure projects caused by permafrost, Hu and Yue (2021) [69] compared two solar-assisted refrigeration systems. Traditional permafrost cooling procedures and refrigeration technologies, including vapor compression and heat-driven adsorption, were compared technically. They performed better in real-time when comparing the examined refrigeration systems to more conventional passive heat regulation strategies. Furthermore, solar energy showed great promise in China's permafrost areas, solving the problem of distributed electricity for refrigeration. Two novel approaches to permafrost cooling—the solar photovoltaic vapor compression refrigeration system (SPV-VCRS) and the solar photothermal adsorption refrigeration system (SPT-ARS)—were developed, produced, and tested. In the warm season, the SPV-VCRS prototype had a COP of 0.41 and maintained an average temperature of 23.55 °C continuously. As shown in Figure 12, the SPT-ARS prototype had a substantially lower COP of 0.054 per day and a refrigeration temperature of 1.83 °C during its intermittent operation.

Five scenarios were constructed and used in an energy system model for 2025 and 2030 by Noorollahi et al. (2021) [70]. In all cases, photovoltaics (PVs) and concentrated solar power (CSP) were expected to contribute maximally to meeting the estimated heating, cooling, and electrical demands. The energy system and scenario simulations were modeled using the bottom-up EnergyPLAN approach. The yearly CO_2 emissions, prices, total primary energy supply, and crucial surplus power generation were compared across the scenarios. All scenarios showed decreased CO_2 emissions, but the cheapest was the PV-based scenario, which used 1954 MW of the PV power plant to meet the demand of 599 M€ per year. The system relied mostly on natural gas as its major energy source, and a 17% drop in primary energy supply relative to business as usual (BAU) and the best-case scenario (S5) for 2030 freed up around 20 TWh/year of natural gas for export. In 2030, this province may emit as much as 9.76 Mt of carbon dioxide, or 5.59 Mt in Best Scenario (S5), according to the Paris Agreement.

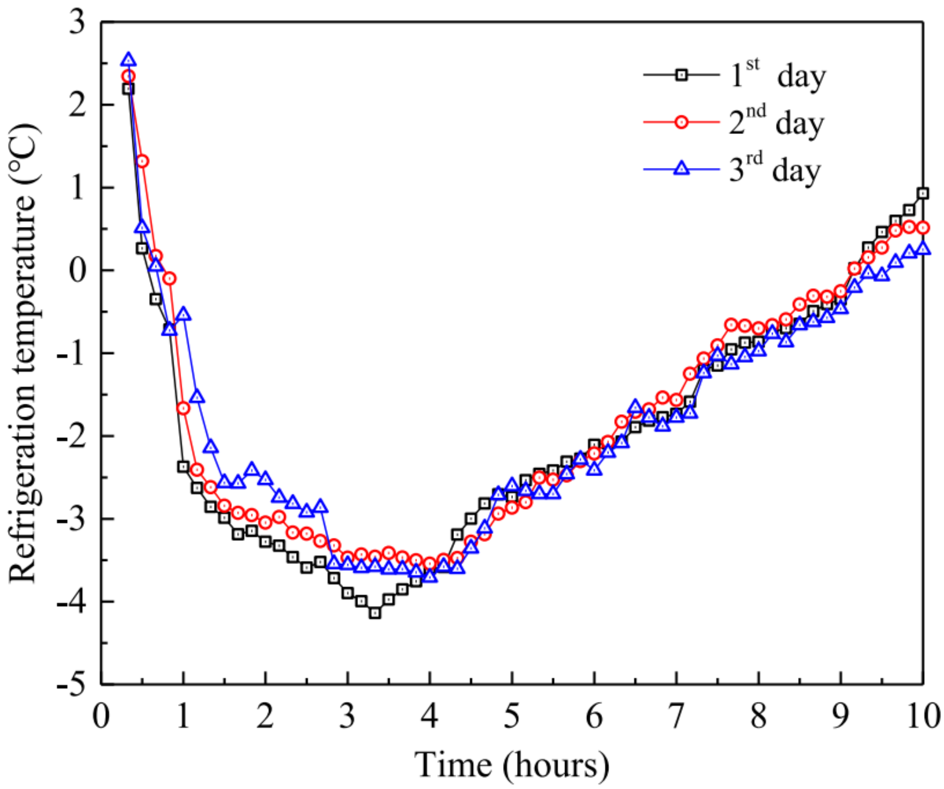


Figure 12. SPT−ARS refrigeration temperatures in all three cycles [69].

Using a solid oxide fuel cell (SOFC) as the power generation unit, a heat recovery system, a photovoltaic (PV) system, solar evacuated tube collectors (ETCs), an absorption chiller, an electric chiller, and a heat storage tank, Hou et al. (2021) [71] examined the solar-assisted combined cooling, heating, and power (SCCHP) system. The SCCHP system was operated using a suggested and implemented better operation strategy, the best operation condition point (BOCP) approach. The suggested operating method used a particle swarm optimization (PSO) technique to optimize the primary equipment's capacity. To further ensure the viability of the proposed SCCHP system structure and optimum operating approach, a case study of a Guangzhou apartment complex was carried out. The SCCHP system's performance indices for the three operational modes are shown in Figure 13. The PESR and CDER were both higher for the BOCP approach.

To meet the thermal and electrical energy needs of a case study residential building, Jalalizadeh et al. (2021) [72] presented a novel combination of glazed BIPVT solar collectors and an absorption cooling system called a trigeneration system. The cooling energy demand of the building decreased by 36% when the passive and active impacts of the BIPVT system were considered, as well as when the BIPVT system prioritized thermal energy production for the absorption chiller. As shown by the calculations, the suggested system met 29% (55.81 MWh/year) of the total annual energy demand of the building, including 34% of its electrical energy demand and 22% of its thermal energy need. The findings demonstrated that the solar percentage and overall efficiency fluctuated similarly. In October, the ratio of total energy generation (EGtot) to total energy consumption (ECtot) was highest, resulting in the highest solar percentage and overall efficiency, as illustrated in Figure 14.

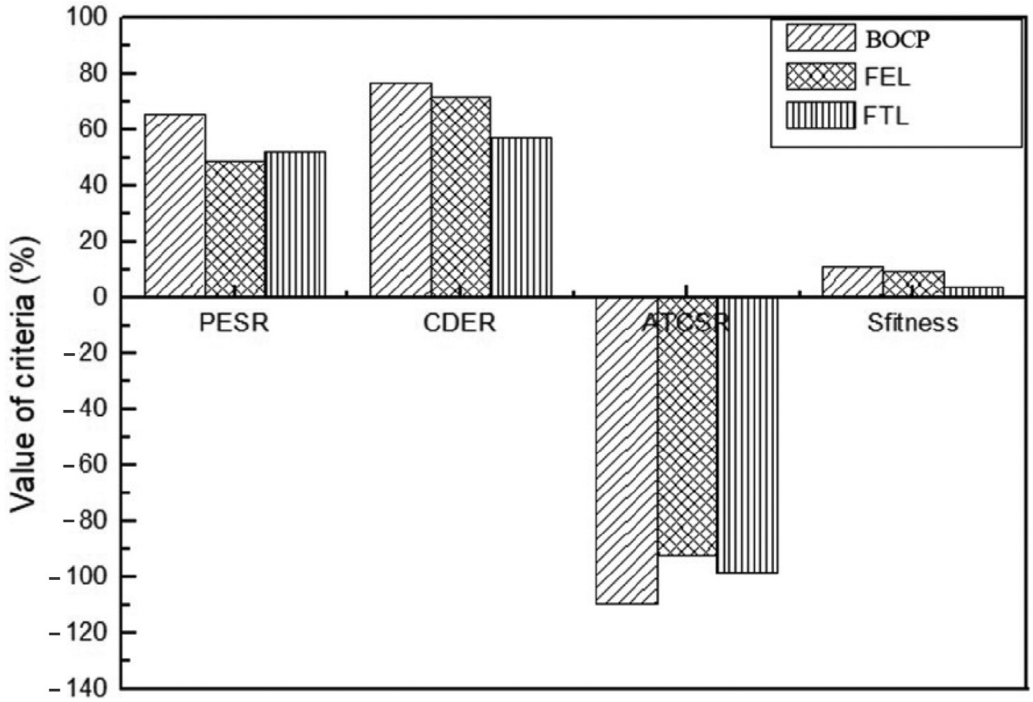


Figure 13. SCCHP system performance indices for three operating techniques [71].

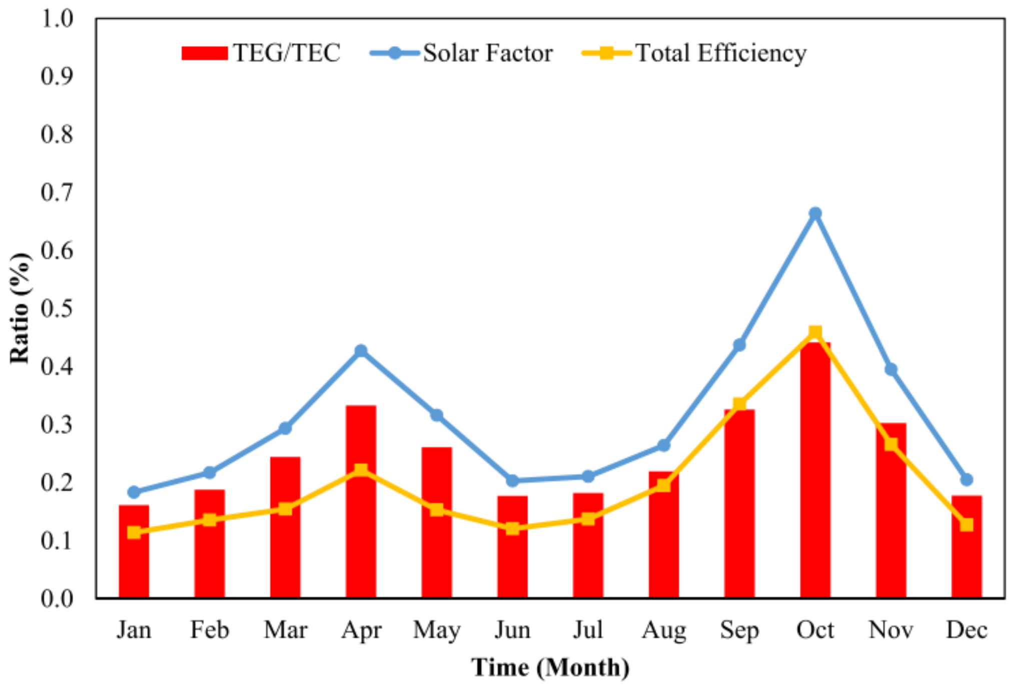


Figure 14. Total efficiency and BIPVT solar percentage monthly fluctuation [72].

Basso et al. (2021) [73] looked at the feasibility of including a new component into that cycle, such as the trans-critical CO_2 heat pump, to lessen the impact of external thermal sources. By doing so, the heat pump's hot sink's high-temperature waste heat could be used well. The conventional structure predicated on solar collectors was supplemented with a PV array to guarantee the heat pump's electrical drive. To conduct the energy analysis, a dynamic model was created in the MATLAB SIMULINK environment and used to simulate the operation of the whole cooling system. In this case, a 1200 m^3 reference conference hall's cooling load was calculated, considering fluctuations in boundary conditions (such as solar radiation, daily temperature, and relative humidity). To obtain the highest possible COP value, say 2.4, the trans-critical CO_2 heat pump needed to operate at a maximum pressure of about 140 bar. This allowed for efficient heat transmission from the heated carbon dioxide to the exhaust air.

Figaj and Zoa dek (2021) [74] offered a numerical analysis of a solar cooling installation based on such a system via dynamic modeling and experimental research of a solar dish concentrating system with thermal collectors. The suggested solar heating and cooling system was modeled in TRNSYS version 17 software to simulate its dynamic functioning. Absorption and adsorption chillers, as well as flat-plate and evacuated-tube solar thermal collectors, were also considered. Less than 5% of the energy generated was overestimated in the solar dish and collection configuration model compared with the experimental investigation. According to the findings, solar energy could provide between 23.6% and 46.2% of Warsaw and between 38.2% and 46.1% of Lisbon's cooling needs. Figure 15 depicts how the size of the solar array impacts the system's capacity to save primary energy. For relatively large values of solar collectors (15.0–20.0 m^2), the findings showed that an increase in area did not produce a substantial variance in PESr. The study's findings could significantly contribute to advancing research and increasing solar energy utilization in cooling systems. The research provided valuable insights by addressing challenges and exploring the benefits of solar-generated heat for cooling applications. The focus on enhancing solar cooling systems' thermodynamic and economic performance, particularly through photovoltaic–thermal (PVT) collectors, offered practical knowledge for improving efficiency. This information is crucial for guiding future research endeavors, driving innovation in solar cooling technologies, and ultimately promoting the broader adoption of sustainable and cost-effective solar energy solutions in cooling systems.

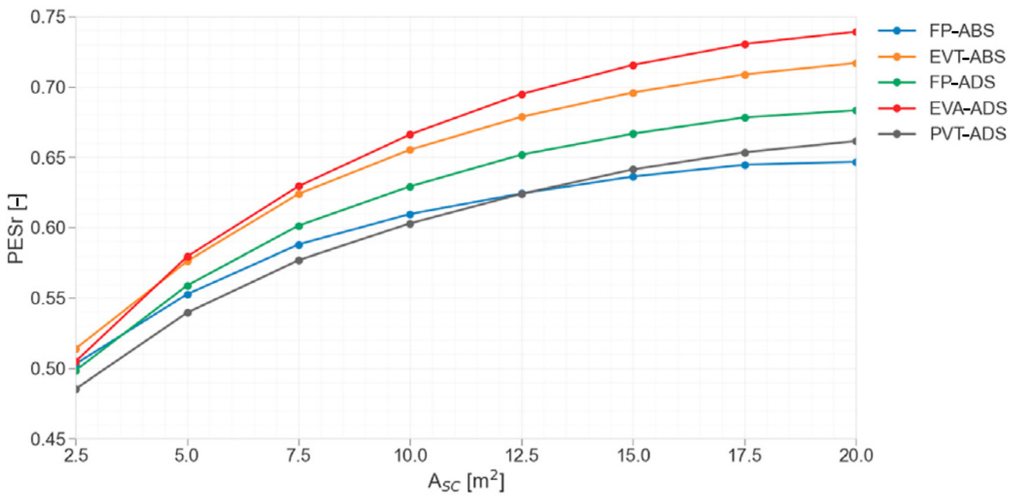


Figure 15. Primary energy daving ratio versus solar field collector area, parametric analysis [74].

Using cutting-edge optimized AI models, Almodfer et al. (2022) [75] forecasted the efficiency of a solar thermoelectric air-cooling system (STEACS). Experiments were conducted with cooling loads ranging from 65.0 W to 260 W on a solar PV-powered STEACS. The model was trained and evaluated using the acquired experimental data. The jellyfish search algorithm (JFSA), artificial ecosystem-based optimization (AEO), manta ray foraging optimization (MRFO), and the sine cosine algorithm (SCA) are some examples of metaheuristic optimizers that were used in the model. The model's inputs were time, solar irradiance, ambient temperature, wind speed, and humidity. It is suggested that RVFL-JFSA be used to model the STEACS system as it beat the other models in predicting all responses with a correlation coefficient of 0.948 to 0.999.

Three parameters impacting inverter efficiency were analyzed by Ketjoy et al. (2021) [76]. The first was connected to how long an inverter ran. The inverter efficiency of a PV system running for four years was 0.90 per year on average, very close to the 0.91 specified by the manufacturer. The research found that keeping the inverter storage room at a low temperature (about 25 °C) using air conditioning prevented a substantial loss in inverter efficiency. The second study examined how various PV module technologies affected the power input. This research showed that the inverter with p-Si PV modules achieved the best efficiency at 0.91. However, in-depth examinations revealed that the technology behind PV modules had a negligible effect on inverter efficiency.

A conceptual analysis of a solar photovoltaic (PV) integrated refrigeration system for a cold storage facility using the standard vapor compression technique for banana fruit was reported by Ikram et al. (2021) [77]. The first step was an in-depth examination of the current status quo. It was determined via mathematical modeling that the evaporator was undersized while the condenser was large. After calculating the air conditioner's power consumption under both light and heavy loads, it was determined that the compressor was around 12 kW too powerful. Second, a solar photovoltaic (PV) array included the refined, low-consumption technology. The suggested PV hybrid refrigeration system's solar field size and performance optimization were both achieved using the PV*SOL program. Under the assumed climatic circumstances, the simulations showed that a PV hybrid refrigeration system with an optimum solar field of 170 m^2 could reach a solar percentage of 58.1% at a performance ratio of 59.2%. The payback time for the hybrid system with net metering was just 5.2 years, demonstrating its great economic viability.

Table 2 summarizes research conducted using hybrid solar techniques for cooling systems.

Table 2. A summary of conducted research using hybrid solar techniques for cooling systems.

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Zhao et al. (2019) [60]	Radiant cooling (RC) and photovoltaic (PV) systems are built into the structure.	Radiative cooling system.	Riyad's BIPV-RC system generates 462.1 kWh·m^{-2} of electricity and 1315.3 MJ m^{-2} of cooling, around 20.7% and 94.0% greater than Karachi's, respectively.
Wang et al. (2019) [61]	An innovative hybrid CCHP system uses compound parabolic CPC-PVT collectors to generate cooling and heating.	Hybrid combined cooling heating and power system.	The hybrid system can reach the maximum levelized PESR of 28.6% and the CDERR of 36.7%, respectively, with more heating-to-electricity ratio flexibility than the CCHP system without solar energy.
Fan et al. (2019) [62]	Incorporated a photovoltaic PVT-SAH hybrid with a desiccant cooling system in a building mode.	Solar air heater.	Improving the system's utilization in a desiccant cooling process may depend heavily on selecting the PVT-SAH design parameters.
Ahn et al. (2019) [63]	Solar photovoltaic (PV) and combined heat and power (CHP) hybrids with varying degrees of PV penetration.	Combined cooling, heating, and power systems.	The energy performance of CCHP + PV systems is little impacted by uncertainty in building energy consumption and solar irradiation.
Elghamry and Hassan (2020) [64]	A novel method of installing PV panels at the chimney's rear has been implemented to generate electricity.	Cool the room temperature.	At 30 and 45 degrees, the percentage of daily ventilation achieved by natural geothermal tube chimneys is around 56.3% and 65%, respectively, whereas the percentage achieved via chimney–window ventilation is approximately 55.6% and 64%, respectively.

Table 2. *Cont.*

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Zarei et al. (2020) [65]	PVT solar air conditioner/heater.	Residential applications.	When comparing a system with and without panel cooling using R134a refrigerant, using R290 for the refrigeration cycle and cooling the panel results in increasing the COP of the cycle by 11.1%, increasing the outlet water temperature from the system by 9.17 °C, and decreasing the refrigerant flow rate by 60.17%.
Pinamonti and Baggio (2020) [66]	Combining solar energy with energy storage creates a solar-assisted heat pump (SAHP) system.	Heating and cooling in residential buildings.	Taking photovoltaic (PV) panels and battery storage into account, and you may cut your energy use by as much as 30%.
Guo et al. (2020) [67]	Ground source heat exchange using flat plate photovoltaic thermal collectors for desiccant air dehumidification and cooling cycle.	Providing conditioned air.	With an average system cooling COP between 9.6 and 16.3 for the three analyzed climates, it can keep a workplace inside the thermal comfort zone for up to 93% of the time.
Al-Nimr and Mugdadi (2020) [68]	Concentrated photovoltaic/thermal (CPV/T) solar hybrid cooling system.	Hybrid solar cooling system.	To achieve maximum overall cooling capacity with minimum PV panel cooling, the COP of the thermoelectric cooler must be more than 6.4, implying a figure of merit of 70.
Hu and Yue (2021) [69]	Two solar-powered air conditioners.	Engineering solutions for permafrost protection in the construction of roads and railroads.	The SPT-ARS prototype has a daily COP of 0.054, and its refrigeration temperature intermittently dips to 1.83 °C.
Noorollahi et al. (2021) [70]	Increase the use of photovoltaics (PV) and concentrated solar power (CSP) to meet your home's heating, cooling, and electrical needs.	Cooling energy system.	In 2030, the province of British Columbia had a 5.59 Mt Best Scenario (S5) limit on CO_2 emissions.
Hou et al. (2021) [71]	SCCHP refers to solar thermal combined heat and power systems.	Cooling, heating, and power.	The energy-saving performance of the improved CCHP system is remarkable. It can reduce electric energy use by 15,141.63 KWh annually and boost heat production by 170,183.57 MJ.
Jalalizadeh et al. (2021) [72]	Use of photovoltaic thermal sun collectors integrated into glazing and an absorption cooling system.	An absorption cooling system.	Here, 29% (55.81 MWh/year) of the building's yearly energy demand is met by the proposed system; specifically, 34% of the electrical energy demand and 22% of the thermal energy needs are met.

Table 2. *Cont.*

Authors (Year) [Reference]	Configuration	Application	Results/Findings
Basso et al. (2021) [73]	The carbon dioxide (CO_2) heat pump operates at a critical temperature.	Cutting down on the impact of extraneous heat sources.	To obtain the highest possible COP value, say 2.4, the trans-critical CO_2 HP must operate at a maximum pressure of about 140 bar. This allows for an efficient heat exchange between the heated carbon dioxide and the exhaust air.
Figaj and Żołądek (2021) [74]	Concentrating solar array with a heat sink.	Home HVAC (heating, ventilation, and air conditioning) system.	Solar energy meets 23.6 and 46.2% of the cooling requirement in Warsaw, whereas in Lisbon, it meets between 38.2 and 46.1% respectively.
Almodfer et al. (2022) [75]	System for cooling using solar thermal electric air convection (STEACS).	Air conditioning is powered by thermal electricity.	RVFL-JFSA had the highest correlation (0.948–0.999) in predicting all responses, making it the preferred choice to model the STEACS system.
Ketjoy et al. (2021) [76]	Inverter efficiency.	Invertors.	By keeping the inverter storage chamber at a low temperature (about 25 °C), the inverters' efficiency was not significantly reduced. When used with p-Si PV modules, the inverter achieved an efficiency of 0.91.
Ikram et al. (2021) [77]	A cooling system that uses solar photovoltaics.	Banana fruit cold storage using the standard vapor compression technique.	Under the assumed weather circumstances, a 170 square meter solar field equipped with an optimal PV hybrid refrigeration system may generate a solar portion of 58.1% with a performance ratio of 59.2%.

4. Conclusions

Both photovoltaic and hybrid cooling, which use solar energy, were examined in this article. Each type's fundamental mode of functioning is explained, and some noteworthy recent advances are emphasized. This study contributes novel insights by elucidating specific general rules and mechanisms, moving beyond general statements. Solar collectors play a pivotal role in solar cooling systems, efficiently harnessing solar energy for electricity and heat to enhance system efficiency. The rising popularity of solar collectors in the construction industry stems from their effectiveness in utilizing low-grade solar energy, aligning with the industry's shift towards sustainable and energy-efficient practices. This concise summary highlights the unique contributions of our research and its practical implications. Additionally, a quick setup and application are carried out while considering several inherent signs. Several inferences may be drawn from the literature reviews above:

- Under the assumed weather circumstances, an optimized PV hybrid refrigeration system with a 170 m^2 solar field may reach a solar percentage of 58.1% at a performance ratio of 59.2%.
- In systems with a peak load in summer, increased solar output may reduce the inter-annual fluctuation in peak residual demand.
- The system is very sensitive to generator temperatures, with 200 °C being the only figure with an excellent performance.
- The absorber accounts for 35.87% of the total exergy destruction in the system.

- For optimization purposes, the thermoelectric cooler's COP should be more than 6.4, implying a figure of merit of 70 as less cooling of PV panels results in a greater overall cooling capacity.
- At 30 degrees and 45 degrees, roughly 56.3% and 65%, respectively, of the total daily ventilation air is provided by the natural geothermal tube chimney, and for heat emitted, the corresponding figures are about 55.6% and 64%, respectively.
- Improvements in PVT-SAH use in a desiccant cooling process may depend on careful parameter selection.
- The hybrid system achieves the maximum levelized PESR of 28.6% and the CDERR of 36.7%, respectively, and has more heating-to-electricity ratio flexibility than the CCHP system without solar energy.
- Concentrator use raises the temperature of the panels' rear sides, resulting in less electrical output compared with systems without concentrators. Because less carbon dioxide is produced, the technology saves around 0.1 per hour.
- The conventional system has a higher exergoeconomic factor than the solar system because of its cheaper initial investment, and a lower exergoeconomic factor in subsequent years because of its higher running cost.
- A solar cooling system offers significant renewable energy ratio improvements over conventional solutions by harnessing the sun's energy.
- Maximum cooling power (50 kW) and generator consumption (62.5 kW) were attained using a solar flat-plate receiver area of 160 square meters.
- When the size of the HVAC system is proportional to the design load, the best results are attained.
- Compared with using just water in the solar-collector circuit, the nanofluid reduces the overall heat exchanger area by 1–6%.

The study provides significant progress in solar energy utilization in cooling systems by addressing challenges and exploring benefits. It specifically focuses on photovoltaic–thermal (PVT) collectors, and improves our understanding of these systems' thermodynamic and economic performance. This research aligns with the worldwide demand for sustainable energy solutions and provides valuable insights to reduce dependence on fossil fuels. By highlighting practical applications like solar-powered air conditioners, the findings inform future research and promote wider use of solar energy in cooling systems.

5. Challenges and Recommendations for Future Works

Current challenges in using solar energy for cooling include intermittency, storage limitations, and high initial costs. Addressing these issues requires advancements in energy storage, efficiency improvements, and cost reduction in solar collectors and cooling systems. Research and development efforts and supportive policies can play a key role in overcoming these challenges and making solar cooling more reliable and cost-effective. This research significantly contributes to exploring the potential of solar-generated heat for use in cooling systems by focusing on optimizing photovoltaic–thermal (PVT) collectors. The study delves into improving solar cooling systems' thermodynamic and economic performance, providing valuable insights into the feasibility and effectiveness of utilizing solar-generated heat. The research informs the development of more efficient and cost-effective solar cooling technologies by addressing current challenges and assessing potential benefits. The emphasis on real-world applications, such as solar-powered air conditioners, further underscores the practical relevance of the study, making it a valuable resource for advancing the utilization of solar energy in cooling systems. This review's primary results may shed light on future directions, upcoming trends, and innovative uses for solar energy in the system cooling industry. The findings of this study suggest that more investigation is needed to solve the many obstacles now hindering the widespread adoption of solar energy for use in cooling systems. Here are some of them:

1. Solar cooling has been used in various industrial contexts, although it is frequently not cost-effective for residential use. The anticipated high cost and poor efficiency of household systems have been a key barrier to their widespread domestic adoption.
2. As a result of the limited availability and high pricing of system components like solar collectors and storage tanks, the initial investment cost is much greater than that of traditional cooling systems.
3. Over the next several years, predictions indicate a steep rise in worldwide demand for cooling systems. Because of the increase in demand, environmentally friendly options like solar cooling need to be investigated.

The following is an example of a set of recommendations that may enhance the use of solar energy in system cooling contexts:

1. To make use of radiative cooling's (RC) unique passive property, further research may be conducted on the problem of time and energy match between a building's cooling demand and the cooling supply of RC. To address this problem, a comprehensive installation and operation plan should be developed to integrate the RC process in buildings with cold storage techniques. The hybrid system may, for instance, benefit from incorporating a phase transition material.
2. Depending on the nature of the energy demand in the area and its seasonal variation, several combinations of solar energy collecting and RC usage may be possible. Substituting a photovoltaic (PV) module for a photothermic (PV/T) module would be a workable option as it would provide a fresh technique for power, heating, and cooling for buildings.
3. The ideal operating approach that reduces the negative effects of uncertainties on the energy and economic performances of CCHP + PV systems may be investigated in future research. Utility companies, distributed energy customers, and customers who rely only on conventional systems (i.e., separate heat and power systems) are all potential targets for the socioeconomic impact of increasing distributed energy systems (e.g., CCHP + PV systems) and redesigning tariff structures.
4. To create a design that can withstand the effects of future climate change in mind, it is important to think about how the cooling load profile will vary depending on the climatic situation in which it will be used.
5. Wind turbines, geothermal power plants, and electric cars are just a few examples of the energy system components that might benefit from closer scrutiny in future research, with the ultimate goal of deriving more optimal models.
6. To better compete with alternative air conditioning technologies in the energy market, it may be necessary to link numerous solar thermoelectric air-conditioning systems (STEACSs) in series in future projects. Techno-economic optimization studies are also necessary to determine the STEACS's potential for reducing energy use and operational costs.
7. Future studies may use a more thorough comparison with comparable TES systems to further quantify the system's advantages.
8. Explore low-energy cooling technologies by integrating advanced materials and nanotechnology, leveraging unique thermal properties for enhanced efficiency in heat transfer.
9. Develop energy-efficient cooling technologies with smart and adaptive control systems, utilizing AI and machine learning to optimize performance based on real-time data and user preferences.

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Abbreviations

Symbol	Definition
ACU	Air conditioning unit
BIPVT	Building integrated photovoltaic thermal collector
CCHP	Combined cooling, heating, and power
CoE	Cost of energy
COP	Coefficient of performance
CPV/T	Concentrated photovoltaic/thermal unit
DEC	Direct evaporative coolers
DOE	Department of energy
EC	Evaporative cooling
EEM	Energy efficiency measures
EER	Energy efficiency ratio
ETC	Evacuated tube collectors
GHG	Greenhouse gas emissions
GWP	Global warming potential
HVAC	Heating, ventilation, and air-conditioning
IEC	Indirect evaporative coolers
IoT	Internet of Things
KPIs	Key performance indicators
MPPT	Maximum power point tracking control
nZEB	Nearly zero energy building
ORC	Organic rankine cycle
PCM	Phase change material
PEC	Primary energy consumption
PR	Performance ratio
PV	Photovoltaic
PVC	Polyvinyl chloride
PVT	Photovoltaic–thermal
RC	Radiative cooling
RF	Renewable fraction
SAH	Solar air heater
SAHP	Solar-assisted heat pump
SCACSs	Solar cooling and air-conditioning systems
SER	Saved energy ratio
SF	Solar fraction
SPF	Seasonal Performance factor
SPV-VCRS	Solar photovoltaic vapor compression refrigeration system
SSGHCM	Smart, sustainable greenhouse concept model
STEACS	Solar thermoelectric air-conditioning system
STPV	Semi-transparent photovoltaics
TNPC	Total net present cost
UCC	Unit cooling cost
VCC	Vapor compression cycle
VRFB	Vanadium redox flow battery

References

1. Andersland, O.B.; Ladanyi, B. *An Introduction to Frozen Ground Engineering*; Springer: Berlin/Heidelberg, Germany, 1994; pp. 1–10.
2. Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Bernardo, L.F.A.; Abdul Redha, Z.A.; Hoshi, H.A.; Mahood, H.B.; Hashim, A. Recent Advances on The Applications of Phase Change Materials in Cold Thermal Energy Storage: A Critical Review. *J. Compos. Sci.* **2023**, *7*, 338. [CrossRef]

3. Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Mahmood, D.M.N.; Sopian, K. A Review of Recent Improvements, Developments, and Effects of Using Phase-Change Materials in Buildings to Store Thermal Energy. *Designs* **2023**, *7*, 90. [CrossRef]
4. Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Bahlol, H.Y.; Hasan, A. Recent Advances, Development, and Impact of Using Phase Change Materials as Thermal Energy Storage in Different Solar Energy Systems: A Review. *Designs* **2023**, *7*, 66. [CrossRef]
5. Goering, D.J. Passively cooled railway embankments for use in permafrost areas. *J. Cold Reg. Eng.* **2003**, *17*, 119–133. [CrossRef]
6. Liu, J.; Tian, Y. Numerical studies for the thermal regime of a roadbed with insulation on permafrost. *Cold Reg. Sci. Technol.* **2002**, *35*, 1–13. [CrossRef]
7. Wang, S.; Chen, J.; Zhang, J.; Li, Z. Development of highway constructing technology in the permafrost region on the Qinghai-Tibet plateau. *Sci. China Ser. E Tech. Sci.* **2009**, *52*, 497–506. [CrossRef]
8. Mu, Y.; Ma, W.; Liu, Y.; Sun, Z. Monitoring investigation on thermal stability of air-convection crushed-rock embankment. *Cold Reg. Sci. Technol.* **2010**, *62*, 160–172. [CrossRef]
9. Sarafraz, M.M.; Hormozi, F.; Peyghambarzadeh, S.M. Thermal performance and efficiency of a thermosyphon heat pipe working with a biologically ecofriendly nanofluid. *Int. Comm. Heat Mass Trans.* **2014**, *57*, 297–303. [CrossRef]
10. Niu, F.; Liu, M.; Cheng, G.; Lin, Z.; Luo, L.; Yin, G. Long-term thermal regimes of the Qinghai-Tibet Railway embankments in plateau permafrost regions. *Sci. China Earth Sci.* **2015**, *58*, 1669–1676. [CrossRef]
11. Tai, B.; Liu, L.; Wang, T.; Tian, Y.; Fang, J. Thermal characteristics and declining permafrost table beneath three cooling embankments in warm permafrost regions. *Appl. Therm. Eng.* **2017**, *123*, 435–447. [CrossRef]
12. Wu, Q.; Zhang, Z.; Liu, Y. Long-term thermal effect of asphalt pavement on permafrost under an embankment. *Cold Reg. Sci. Technol.* **2010**, *60*, 221–229. [CrossRef]
13. Li, S.; Lai, Y.; Zhang, M.; Dong, Y. Study on long-term stability of Qinghai–Tibet Railway embankment. *Cold Reg. Sci. Technol.* **2009**, *57*, 139–147. [CrossRef]
14. Karami, M.; Javanmardi, F. Performance assessment of a solar thermal combisystem in different climate zones. *Asian J. Civil Eng.* **2020**, *21*, 751–762. [CrossRef]
15. Chel, A.; Kaushik, G. Renewable energy technologies for sustainable development of energy efficient building. *Alex. Eng. J.* **2018**, *57*, 655–669. [CrossRef]
16. Patil, R.A.; Shabunko, V.; Ramakrishna, S. *Renewable Energy and Circular Economy: Application of Life Cycle Costing to Building Integrated Solar Energy Systems in Singapore, An Introduction to Circular Economy*; Springer: Singapore, 2021; pp. 201–218. [CrossRef]
17. Athienitis, A.K.; Barone, G.; Buonomano, A.; Palombo, A. Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: Dynamic modelling and simulation. *Appl. Energy* **2018**, *209*, 355–382. [CrossRef]
18. Gajbert, H. *Solar Thermal Energy Systems for Building Integration*; Lund University: Lund, Sweden, 2008; pp. 1–310.
19. Belussi, L.; Barozzi, B.; Bellazzi, A.; Danza, A.; Devitofrancesco, A.; Fanciulli, C.; Ghellere, M.; Guazzi, G.; Meroni, I.; Salamone, F.; et al. A review of performance of zero energy buildings and energy efficiency solutions. *J. Build. Eng.* **2019**, *25*, 100772. [CrossRef]
20. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montañes, B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build.* **2017**, *135*, 286–301. [CrossRef]
21. Jo, J.H.; Aldeman, M.; Lee, H.S.; Ahn, Y.H. Parametric analysis for cost-optimal renewable energy integration into residential buildings: Techno-economic model. *Renew. Energy* **2018**, *125*, 907–914. [CrossRef]
22. *EN 15978:2011*; Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. European Committee for Standardisation: Brussels, Belgium, 2011.
23. Goel, N.; Taylor, R.A.; Otanicar, T. A review of nanofluid-based direct absorption solar collectors: Design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors. *Renew Energy* **2020**, *145*, 903–913. [CrossRef]
24. Balyani, H.; Sohani, A.; Sayyaadi, H.; Karami, R. Acquiring the best cooling strategy based on thermal comfort and 3E analyses for small scale residential buildings at diverse climatic conditions. *Int. J. Ref.* **2015**, *57*, 112–137. [CrossRef]
25. Barzegar, M.; Layeghi, M.; Ebrahimi, G.; Hamzeh, Y.; Khorasani, M. Experimental evaluation of the performances of cellulosic pads made out of Kraft and NSSC corrugated papers as evaporative media. *Energy Convers. Manag.* **2012**, *54*, 24–29. [CrossRef]
26. Wu, J.M.; Huang, X.; Zhang, H. Numerical investigation on the heat and mass transfer in a direct evaporative cooler. *Appl. Therm. Eng.* **2009**, *29*, 195–201. [CrossRef]
27. Sohani, A.; Zabihigivi, M.; Moradi, M.H.; Sayyaadi, H.; Balyani, H. A comprehensive performance investigation of cellulose evaporative cooling pad systems using predictive approaches. *Appl. Therm. Eng.* **2017**, *110*, 1589–1608. [CrossRef]
28. Sheng, C.; Nnanna, A.G.A. Empirical correlation of cooling efficiency and transport phenomena of direct evaporative cooler. *Appl. Therm. Eng.* **2012**, *40*, 48–55. [CrossRef]
29. Al-Yasiri, Q.; Szabó, M.; Arıcı, M. A review on solar-powered cooling and air-conditioning systems for building applications. *Ener. Rep.* **2022**, *8*, 2888–2907. [CrossRef]
30. Jiao, C.; Li, Z. An Updated Review of Solar Cooling Systems Driven by Photovoltaic–Thermal Collectors. *Energies* **2023**, *16*, 5331. [CrossRef]
31. Esfanjani, P.; Jahangiri, S.; Heidarian, A.; Valipour, M.S.; Rashidi, S. A review on solar-powered cooling systems coupled with parabolic dish collector and linear Fresnel reflector. *Environ. Sci. Poll. Res.* **2022**, *29*, 42616–42646. [CrossRef]
32. Han, Y.; Li, M.; Wang, Y.; Li, G.; Ma, X.; Wang, R.; Wang, L. Impedance matching control strategy for a solar cooling system directly driven by distributed photovoltaics. *Energy* **2019**, *168*, 953–965. [CrossRef]

33. Pang, W.; Yu, H.; Zhang, Y.; Yan, H. Solar photovoltaic based air cooling system for vehicles. *Renew. Energy* **2019**, *130*, 25–31. [CrossRef]
34. Zuhur, S.; Ceylan, I.; Ergün, A. Energy, exergy and environmental impact analysis of concentrated PV/cooling system in Turkey. *Sol. Energy* **2019**, *180*, 567–574. [CrossRef]
35. Kiyaninia, A.; Karimi, H.; Avargani, V.M. Exergoeconomic analysis of a solar photovoltaic-based direct evaporative air-cooling system. *Sol. Energy* **2019**, *193*, 253–266. [CrossRef]
36. Lin, L.; Tian, Y.; Luo, Y.; Chen, C.; Jiang, L. A novel solar system integrating concentrating photovoltaic thermal collectors and variable effect absorption chiller for flexible co-generation of electricity and cooling. *Energy Con. Manag.* **2020**, *206*, 112506. [CrossRef]
37. Song, J.; Sobhani, B. Energy and exergy performance of an integrated desiccant cooling system with photovoltaic/thermal using phase change material and maisotsenko cooler. *J. Energy Storage* **2020**, *32*, 101698. [CrossRef]
38. Bilardo, M.; Ferrara, M.; Fabrizio, E. Performance assessment and optimization of a solar cooling system to satisfy renewable energy ratio (RER) requirements in multi-family buildings. *Renew. Energy* **2020**, *155*, 990–1008. [CrossRef]
39. Wu, D.; Aye, L.; Yuan, Y.; Mendis, P.; Ngo, T. Comparison of optimal oriented façade integrated solar cooling systems in Australian climate zones. *Sol. Energy* **2020**, *198*, 385–398. [CrossRef]
40. Lorenzo, C.; Narvarte, L.; Almeida, R.H.; Cristóbal, A.B. Technical evaluation of a stand-alone photovoltaic heat pump system without batteries for cooling applications. *Sol. Energy* **2020**, *206*, 92–105. [CrossRef]
41. Lv, S.; Ji, Y.; Qian, Z.; He, W.; Hu, Z.; Liu, M. A novel strategy of enhancing sky radiative cooling by solar photovoltaic-thermoelectric cooler. *Energy* **2021**, *219*, 119625. [CrossRef]
42. Omar, M.N.; Taha, A.T.; Samak, A.A.; Keshek, M.H.; Gomaa, E.M.; Elsisi, S.F. Simulation and validation model of cooling greenhouse by solar energy (P V) integrated with painting its cover and its effect on the cucumber production. *Renew. Energy* **2021**, *172*, 1154–1173. [CrossRef]
43. Zapałowicz, Z.; Zeńczak, W. The possibilities to improve ship's energy efficiency through the application of PV installation including cooled modules. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110964. [CrossRef]
44. Al-Naemi, S.; Al-Otoom, A. Smart sustainable greenhouses utilizing microcontroller and IOT in the GCC countries; energy requirements & economical analyses study for a concept model in the state of Qatar. *Results Eng.* **2023**, *17*, 100889. [CrossRef]
45. Kim, H.; Junghans, L. Integrative economic framework incorporating the Emission Trading Scheme (ETS) for U.S. Residential energy systems. *Energy Convers. Manag.* **2022**, *14*, 100197. [CrossRef]
46. Li, G.; Han, Y.; Li, M.; Luo, X.; Xu, Y.; Wang, Y.; Zhang, Y. Study on matching characteristics of photovoltaic disturbance and refrigeration compressor in solar photovoltaic direct-drive air conditioning system. *Renew. Energy* **2021**, *172*, 1145–1153. [CrossRef]
47. Ozcan, H.G.; Varga, S.; Gunerhan, H.; Hepbasli, A. Numerical simulation and parametric study of various operational factors affecting a PV-battery-air conditioner system under prevailing European weather conditions. *Sustain. Cities Soc.* **2021**, *67*, 102754. [CrossRef]
48. Haffaf, A.; Lakdja, F.; Abdeslam, D.O.; Meziane, R. Sol. Energy for air conditioning of an office building in a case study: Techno-economic feasibility assessment. *Renew. Energy Focus* **2021**, *39*, 148–162. [CrossRef]
49. Li, H.; Li, J.; Li, S.; Peng, J.; Ji, J.; Yan, J. Matching characteristics and AC performance of the photovoltaic-driven air conditioning system. *Energy* **2023**, *264*, 126509. [CrossRef]
50. Ra, N.; Ghosh, A.; Bhattacharjee, A. IoT-based smart energy management for solar vanadium redox flow battery powered switchable building glazing satisfying the HVAC system of EV charging stations. *Energy Convers. Manag.* **2023**, *281*, 116851. [CrossRef]
51. Omar, A.I.; Khattab, N.M.; Abdel Aleem, S.H.E. Optimal strategy for transition into net-zero energy in educational buildings: A case study in El-Shorouk City, Egypt. *Sustain. Energy Technol. Assess.* **2022**, *49*, 101701. [CrossRef]
52. Delač, B.; Pavković, B.; Lenić, K.; Mađerić, D. Integrated optimization of the building envelope and the HVAC system in nZEB refurbishment. *Appl. Therm. Eng.* **2022**, *211*, 118442. [CrossRef]
53. Luo, Y.; Cheng, N.; Zhang, S.; Tian, Z.; Xu, G.; Yang, X.; Fan, J. Comprehensive energy, economic, environmental assessment of a building integrated photovoltaic-thermoelectric system with battery storage for net zero energy building. *Build Simul.* **2022**, *15*, 1923–1941. [CrossRef]
54. Huang, M.; Yu, X.; Wan, J.; Du, M.; Wang, X.; Sun, Q.; Tang, G.H. All-day effective radiative cooling by optically selective and thermally insulating mesoporous materials. *Sol. Energy* **2022**, *235*, 170–179. [CrossRef]
55. Vakilinezhad, R.; Ziaee, N. Assessing the combined effect of PV panels' shading and cool materials on building energy loads in different climates. *Environ. Dev. Sustain.* **2023**. [CrossRef]
56. Zarei, A.; Izadpanah, E.; Rabiee, M.B. Using a nanofluid-based photovoltaic thermal (PVT) collector and eco-friendly refrigerant for solar compression cooling system. *J. Therm. Anal. Calorim.* **2023**, *148*, 2041–2055. [CrossRef]
57. Xiao, Y.; Bao, Y.; Yu, L.; Zheng, X.; Qin, G.; Chen, M.; He, M. Ultra-stable carbon quantum dot nanofluids as excellent spectral beam splitters in PV/T applications. *Energy* **2023**, *273*, 127159. [CrossRef]
58. Huang, M.; Tang, G.H.; Si, Q.; Pu, J.H.; Sun, Q.; Du, M. Plasmonic aerogel window with structural coloration for energy-efficient and sustainable building envelopes. *Renew. Energy* **2023**, *216*, 119006. [CrossRef]

59. Pu, J.H.; Yu, X.; Zhao, Y.; Tang, G.H.; Ren, X.; Du, M. Dynamic aerogel window with switchable solar transmittance and low haze. *Energy* **2023**, *285*, 129437. [CrossRef]
60. Zhao, B.; Hu, M.; Ao, X.; Chen, N.; Xuan, Q.; Su, Y.; Pei, G. A novel strategy for a building-integrated diurnal photovoltaic and all-day radiative cooling system. *Energy* **2019**, *183*, 892–900. [CrossRef]
61. Wang, J.; Chen, Y.; Lior, N.; Li, W. Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system integrated with compound parabolic concentrated-photovoltaic thermal solar collectors. *Energy* **2019**, *185*, 463–476. [CrossRef]
62. Fan, W.; Kokogiannakis, G.; Ma, Z. Integrative modelling and optimisation of a desiccant cooling system coupled with a photovoltaic thermal-solar air heater. *Sol. Energy* **2019**, *193*, 929–947. [CrossRef]
63. Ahn, H.; Rim, D.; Pavlak, G.S.; Freihaut, J.D. Uncertainty analysis of energy and economic performances of hybrid solar photovoltaic and combined cooling, heating, and power (CCHP + PV) systems using a Monte-Carlo method. *Appl. Energy* **2019**, *255*, 113753. [CrossRef]
64. Elghamry, R.; Hassan, H. An experimental work on the impact of new combinations of solar chimney, photovoltaic and geothermal air tube on building cooling and ventilation. *Sol. Energy* **2020**, *205*, 142–153. [CrossRef]
65. Zarei, A.; Liravi, M.; Rabiee, M.B.; Ghodrat, M. A Novel, eco-friendly combined solar cooling and heating system, powered by hybrid Photovoltaic thermal (PVT) collector for domestic application. *Energy Convers. Manag.* **2020**, *222*, 113198. [CrossRef]
66. Pinamonti, M.; Baggio, P. Energy and economic optimization of solar-assisted heat pump systems with storage technologies for heating and cooling in residential buildings. *Renew. Energy* **2020**, *157*, 90–99. [CrossRef]
67. Guo, J.; Bilbao, J.I.; Sproul, A.B. A novel solar cooling cycle—A ground coupled PV/T desiccant cooling (GPVTDC) system with low heat source temperatures. *Renew. Energy* **2020**, *162*, 1273–1284. [CrossRef]
68. Al-Nimr, M.A.; Mugdadi, B. A hybrid absorption/thermo-electric cooling system driven by a concentrated photovoltaic/thermal unit. *Sustain. Energy. Technol. Assess.* **2020**, *40*, 100769. [CrossRef]
69. Hu, T.F.; Yue, Z.R. Potential applications of solar refrigeration systems for permafrost cooling in embankment engineering. *Case Stud. Ther. Eng.* **2021**, *26*, 101086. [CrossRef]
70. Noorollahi, Y.; Golshanfard, A.; Ansaripour, S.; Khaledi, A.; Shadi, M. Solar energy for sustainable heating and cooling energy system planning in arid climates. *Energy* **2021**, *218*, 119421. [CrossRef]
71. Hou, H.; Wu, J.; Ding, Z.; Yang, B.; Hu, E. Performance analysis of a solar-assisted combined cooling, heating and power system with an improved operation strategy. *Energy* **2021**, *227*, 120516. [CrossRef]
72. Jalalizadeh, M.; Fayaz, R.; Delfani, S.; Mosleh, H.J.; Karami, M. Dynamic simulation of a trigeneration system using an absorption cooling system and building integrated photovoltaic thermal solar collectors. *J. Build. Eng.* **2021**, *43*, 102482. [CrossRef]
73. Basso, G.L.; Santoli, L.; Paiolo, R.; Losi, C. The potential role of trans-critical CO2 heat pumps within a solar cooling system for building services: The hybridised system energy analysis by a dynamic simulation model. *Renew. Energy* **2021**, *164*, 472–490. [CrossRef]
74. Figaj, R.; Żołądek, M. Experimental and numerical analysis of hybrid solar heating and cooling system for a residential user. *Renew. Energy* **2021**, *172*, 955–967. [CrossRef]
75. Almodfer, R.; Zayed, M.E.; Elaziz, M.A.; Aboelmaaref, M.M.; Mudhsh, M.; Elsheikh, A.H. Modeling of a solar-powered thermoelectric air-conditioning system using a random vector functional link network integrated with jellyfish search algorithm. *Case Stud. Ther. Eng.* **2022**, *31*, 101797. [CrossRef]
76. Ketjoy, N.; Chamsa-ard, W.; Mensin, P. Analysis of factors affecting efficiency of inverters: Case study grid-connected PV systems in lower northern region of Thailand. *Energy. Rep.* **2021**, *7*, 3857–3868. [CrossRef]
77. Ikram, H.; Javed, A.; Mehmood, M.; Shah, M.; Ali, M.; Waqas, W. Techno-economic evaluation of a solar PV integrated refrigeration system for a cold storage facility. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101063. [CrossRef]

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