

Review

Contribution of Solar Energy to Buildings' Energy Demands: A Review

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Abstract

Buildings account for a significant portion of global energy consumption, estimated at 30-40%, and also contribute to greenhouse gas emissions. Energy consumption in a building is mainly thermal (natural gas) and electrical. This energy is usually used for heating water, cooking, illumination, ventilation and air conditioning, powering appliances, floor heating, and other activities. These activities were examined, and their substitution by solar-based energy sources was reviewed. To achieve this objective, an extensive literature review across Scopus, Direct Science, and Web of Science in relevant areas, including building



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energy needs, thermal and visual comfort, and construction materials and components, was conducted. Innovative construction materials, including mortars, bricks, concrete, and components such as Trombe walls, can enhance thermal efficiency and thermal comfort. Solar energy can replace fossil-based energy for the provision of hot water, and hot fluid for air conditioning absorption chillers systems. Building components such as thermally efficient windows (double-glazed, evacuated, etc.), bright windows, and facades can help maintain a thermally and visually comfortable indoor environment. Electric energy for buildings' services, such as illumination, ventilation, and other services, can be provided by solar PV panels. The review shows that solar energy can significantly contribute to decarbonizing buildings' energy needs, maintaining passive thermal and visual comfort, and reducing emissions. The review indicates that a solar air conditioner with a 12,000 BTU cooling capacity can save 8-28% of energy and reduce emissions by 7.74-28.27%. It also showed that selecting windows and facades is a critical issue. A comparison of the energy-saving of thermo-chromatic, double-glazed, and clear glass windows indicated a reduction of 8.91% to 10.96% in energy consumption due to double-glazed windows and a reduction of 20.22% to 24.19% due to thermo-chromatic windows. Smart windows with photovoltaic electrochromic (PV-EC) enabled a useful daylighting illumination of about 75.26% and energy saving of about 15.79% compared to ordinary windows. It is recommended that applications such as hot water, water distillation, illumination, electricity, and air conditioning be powered by solar energy. In the construction of buildings, thermally efficient materials and components should be prioritized. To promote building decarbonization, it is necessary to reduce the cost of materials, create financial incentives and low-interest grants for retrofitting, and create public policies to promote solar-based energy applications in buildings.

Keywords

Decarbonization of buildings; PV panels; smart windows and façades; solar-powered air conditioning; building's heating and cooling systems

1. Introduction

Currently, more than half of the world's population lives in cities, and it is expected that by 2030 it will reach 60% and by 2050 it will exceed two-thirds. A very important part of this consumption occurs in buildings in the residential and tertiary sectors. Buildings account for a significant portion of global energy consumption, estimated at around 30-40%, and contribute to greenhouse gas emissions both directly and indirectly [1]. It is possible to understand the importance of buildings to all government authorities; that is, any action to reduce energy consumption or to change the type of energy consumed is welcome. Globally, this is reflected in the Sustainable Development Goals 7, 11, 12, and 13, which address the use of clean energy, making cities sustainable, achieving responsible consumption and production, and combating climate change, respectively. Energy in buildings is primarily used for space heating, cooling, water heating, and powering appliances and lighting, and the type of energy is mainly thermal (natural

gas) and electrical. Most of the solar energy used for low and moderate-temperature applications is technically dominated and commercially available and can be implemented in buildings. It is possible to understand the importance that buildings have for all governmental authorities, that is, any action to reduce energy consumption or on the type of energy consumed is usually most welcome [1].

The insertion of solar energy technologies in buildings can improve the building's performance and turning them comfortable all the year around with minimum expenditure of energy. This can be achieved by using innovative construction designs that can use better the position and orientation of the sun to improve the internal living conditions of the buildings especially in cold and hot regions. Innovative construction materials with proven qualities and specifications can also be used for construction of buildings with natural illumination and ventilation, and steady internal temperature. Bricks, concrete blocks, and mortars, are among the construction materials which received intense research and development, however, durability, degradation and cost reduction need to be addressed to enhance the insertion of these materials and popularize their use in modest homes [1].

Windows and façades are usually responsible for a big part of energy losses or gains in buildings. This led to extensive research and development in this area resulting in double and triple glass windows with and without vacuum and windows with different layers of aerogel were proposed for very cold climates. Developments in window technology included windows with internal fillings such as flowing or stagnant gases and water. Windows with inserted PCM were proposed and experimented with, showing good results. Smart windows can adjust themselves according to the external ambient conditions to prevent (or permit) solar radiation from entering the building to provide natural heating and natural illumination. Their performance proved to be exceptional, although their cost is extremely high. With this large number of efficient alternatives, there is a space for improvement and cost reduction to make this technology for moderate homes [1].

Solar energy for low temperature applications in buildings such as water heating, cooking, heating and cooling of walls and floors, special walls (Trombe wall) and roofs and water distillation, among others, can be adequately attended. Absorption chillers for centralized air conditioning and refrigeration applications, window-type air conditioning units and other small refrigeration and air conditioning systems, electric energy for illumination, ventilation and other uses can be supplied by solar energy using solar concentrators for providing hot fluid for the chillers, and PV panels for generating electricity for electrical applications in buildings.

The novelty of this review is to demonstrate that the implementation of the solar energy technology in buildings and components can effectively attend the buildings necessities, decarbonize its energy demands and maintain its passive thermal and visual comfort. Different from other reviews, widely covers innovative and applicable energy solutions from various engineering areas for use in buildings according to the intended task. With this in mind, literature revision in Scopus, Direct Science, and Web of Science in relevant areas such as building energy needs, thermal comfort, and visual comfort, as well as construction materials and components, was conducted. Low and medium temperature tasks, such as hot water, hot air for ambient comfort, water distillation, hot fluid for air conditioning absorption systems, etc., can be attended by solar flat and low concentration collectors. To supply electric energy for building activities, solar PV panels can be the solution. This review recommends some actions to promote building

decarbonization such as the reduction of cost of materials and components, financial incentives and grants for retrofitting besides public policies.

The review is composed as follows: 1 Introduction; 2 Low temperature demands; 3 Moderate temperature demands; 4 Electricity demands; 5 Conclusions and future research opportunities; References.

2. Low Temperature Demands

Low temperature demands in a building include water heating, cooking, building applications, and saline water distillation. Normally most of these demands are accomplished by using electric energy. Solar energy applications for this temperature level are available commercially at a reasonable cost. Perhaps, financial incentives, public policies, and retrofitting grants can help extend these benefits to moderate urban homes, rural areas, and isolated communities.

2.1 Water Heating

Hot water is of essential use in cold countries and is usually produced by using electric energy and waste heat from other applications. This application can consume a fair amount of electric energy and contribute to building emissions. Abdelsalam et al. [2] created and validated a numerical simulation model for a sensible heat storage water tank. Numerical results indicate that thermal stratification in the direct system increases the solar fraction by 18-23% compared to the indirect system. Additionally, incorporating PCMs in the water tank has the potential to reduce the storage volume by approximately 40%.

Simonetti et al. [3] conducted a numerical investigation on direct absorption solar collectors (DASC) and compared its performance to that of indirect vacuum tube solar collector. Although the DASC tube showed marginal advantages compared to existing configurations, it could provide substantial benefits in case of poor insulation design.

Gunasekaran et al. [4] investigated the use of twisted tape inserts in evacuated tube collector (ETC) solar water heaters to enhance system performance. The experiment compares three modes with and without twisted tapes. Results showed significant improvement in solar energy recovery, with tank water temperature increases of 4.5°C and 3°C, and daily energy efficiency improvements of 6.8% and 4.6%, respectively.

Mallouh et al. [5] compared four different solar water heating (SWH) system configurations in a MATLAB/Simulink environment to evaluate the systems' ability to keep the exit water temperature at the preset value while minimizing pump energy consumption. The configurations are illustrated in Figure 1. SWH System 2 showed the best performance regulating the outlet temperature for a longer duration, which makes it ideal for environments with variable solar radiation.

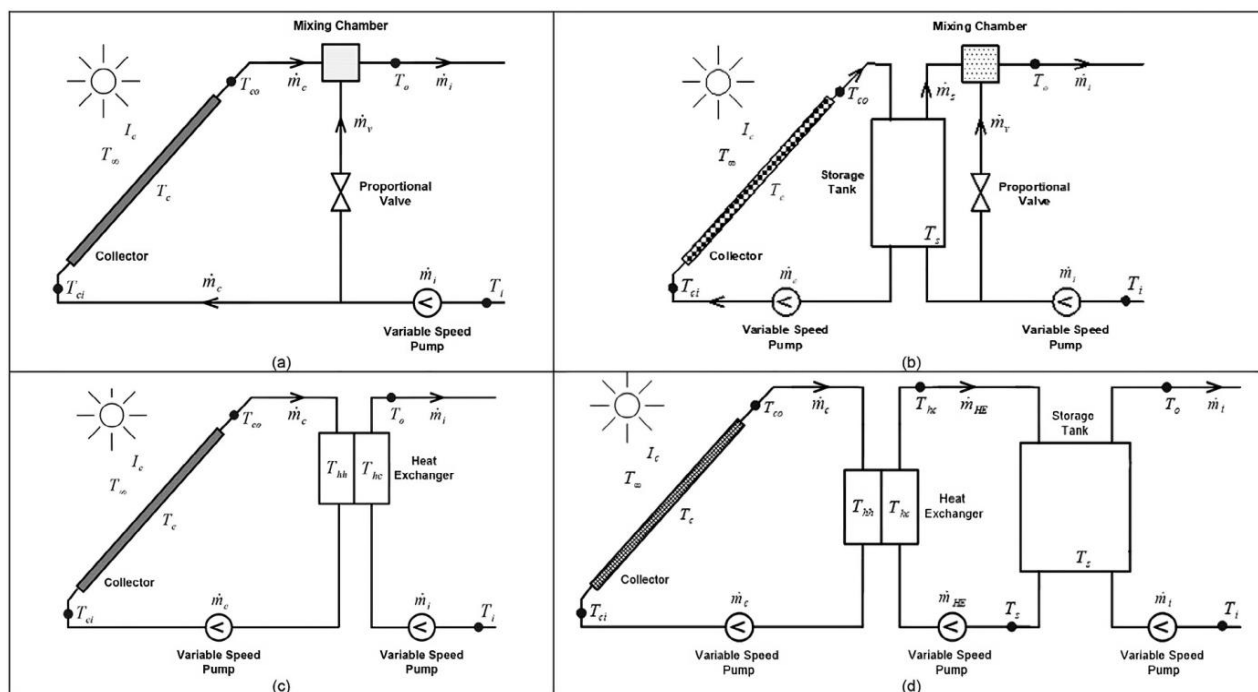


Figure 1 The four SWH systems under investigation [5].

Hachchadi et al. [6] optimized the heating element of a solar PV water heater for different climatic conditions (Montreal and Bagotville in Canada, and Fez in Morocco) over a one-year period through simulations using MATLAB/Simulink and TRNSYS software. The main findings indicate that the optimal resistance values are inversely related to solar irradiance levels as well as the I-V characteristics of the PV array.

Jalaluddin et al. [7] investigated a solar water heating (SWH) system to enhance its performance by including an Al + Al₂O₃ composite as thermal storage. The results indicated that incorporating the composite increases solar irradiation absorption and the collector performance. Pambudi et al. [8] investigated a V-corrugated zinc collector for solar water heater applications in Solo, Central Java, Indonesia. Results indicated the highest energy efficiency of 50% at 240 L/h and a heat absorption efficiency of 97%. The device demonstrated feasibility and cost-effectiveness by achieving 50% energy efficiency with low-cost zinc material. Terashima [9] developed a portable and size-adjustable solar water heater (SWH) using a commercial black container as the heat absorber and greenhouse materials for insulation. Exposed to sunlight during the day, the system can heat 150 L of water by over 20°C year-round, with 25%-50% energy conversion efficiency and reducing annual gas consumption for home bathing by approximately 25%. Al-Dujaili et al. [10] investigated an evacuated tube-based electric/solar water heater (ESWH). The system used an aluminum sheet reflector positioned beneath the tubes to enhance solar energy capture. When solar energy is insufficient, a 3 kW electric heater acts as a backup. This multi-source heating system achieved a 15.4% improvement in annual energy consumption compared to a hybrid electric/solar water heater and a 46.2% improvement over a traditional electrical water heater.

Other studies explore advancements in solar water heating systems, including the use of PCMs to store thermal energy, improving the efficiency of solar domestic hot water systems [11]. Solar collectors used in solar greenhouses can provide additional heating to enhance plant growth [12]. The use of solar absorber coatings applied to solar absorbers can increase their efficiency [13].

Further studies and detailed information regarding these and other solar water heating advancements can be found in [14-17].

2.1.1 Remarks

Water heating technologies are focused on improving energy storage efficiency and system designs. Portable and off-grid solutions offer versatility, especially in regions with limited access to infrastructure. Future research could explore optimizing PCM mixtures and further improvements to solar collector designs, including the use of advanced materials and cost-effective production methods. There is also potential to expand off-grid applications, particularly in remote and developing areas. Table 1 summarizes some research on solar water heating and applications.

Table 1 Solar water heating.

Reference number	Subject	Main Remarks
[2]	Hybrid energy storage systems with PCM	Incorporating PCM in water tanks can reduce storage volume by 40%, increasing solar fraction by up to 23%.
[3]	Numerical investigation on solar collectors (DASC)	DASC using nanofluids showed limited efficiency improvements compared to commercial vacuum tube collectors.
[4]	Tape inserts in ETC solar heaters	Twisted tape inserts improved energy recovery and daily energy efficiency by up to 6.8%.
[5]	Comparison of different solar water heating configurations	Closed-loop systems performed better under variable solar radiation, optimizing pump energy consumption.
[6]	Solar photovoltaic water heater	Direct-coupled PV water heaters achieved significant solar fraction; MPPT controllers improved energy by up to 36%.
[7]	Al + Al ₂ O ₃ composite in solar water heating system	Thermal storage increased efficiency, with the C1 composite achieving the highest solar thermal efficiency.
[8]	V-corrugated collector	Modified zinc collector achieved up to 50% energy efficiency, demonstrating cost-effectiveness for low-cost materials.
[9]	Portable solar water heater	A portable, size-adjustable solar water heater system achieved 25%-50% energy conversion efficiency.
[10]	Reflectors to maximize solar absorption	Aluminum reflectors improved energy consumption by 15.4% over hybrid systems.

2.2 Cooking

Cooking is an essential activity usually accomplished in developing countries by using natural gas, wood blocks, and biomass, which contributes to building emissions and fossil fuel

consumption. Over recent years, many efforts have been made to improve these practices by incorporating solar energy and new innovations using PCM for energy storage.

A published study on solar cookers compared storage pots with and without PCM. The main findings indicated that during off-sunshine periods, the erythritol PCM pot showed smaller temperature drops (0.1-9.7°C versus 8.3-9.7°C). Using sunflower oil as the cooking fluid, instead of water, shortened the solar cooking period and achieved higher temperatures. Additionally, the effectiveness of storage cooking was improved with sunflower oil [18, 19].

Singh [20] investigated an indoor solar cooking system composed of a solar parabolic dish collector, a PV module, a battery, a solar pump, a solar heater plate, pipes, and a receiver. The PV module charges a 12 V battery that powers a solar tracker connected to the parabolic collector. This setup allows the heater plate to be placed indoors to provide cooking heat. The results showed a thermal efficiency of 21% and an exergy efficiency of 1.96%.

Saini et al. [21] conducted a study on a hybrid solar electric oven. The oven operates in three modes: solar, electric, and hybrid. It includes a microcontroller-based smart control system with a thermocouple for temperature detection and relays to control the heating elements and convection fan. The findings revealed that the oven achieved 51% energy savings and reduced cooking time compared to electric ovens and solar cookers.

An indirect solar cooking system was designed, built, tested, and compared to a solar cooker without reflectors, with the PCM serving as a thermal storage unit. The daily average increase in solar radiation falling on the collector with four reflectors was 42.3% higher than on the collector without reflectors. The results showed that with reflectors, the maximum absorber plate temperature was about 130°C, the maximum output water temperature was about 103.65°C, while the maximum energy efficiency was about 79% [22].

An experimental characterization was conducted on a foldable solar cooker composed of a trapezoidal cooking chamber of a volume of 0.0218 m³. Two equal-sized aluminum reflector panels were used to direct solar radiation into the cooking chamber. Several advantages of the cooker include ease of mass production, compactness, and portability [23]. Other studies in the literature explore various aspects of solar cooking systems and further information can be found in [24-29].

2.2.1 Remarks

Solar cooking technologies are evolving through a combination of heat storage materials, such as and innovative designs (indoor cooking systems, hybrid thermal-electric ovens). While significant efficiency gains have been achieved, there is room for further exploration into more durable, cost-effective heat storage materials and systems that can operate in varying climatic conditions. Opportunities for future research lie in improving thermal storage, developing systems that work in off-sunshine periods, and creating portable solar cooking solutions. Table 2 summarizes the studies presented on solar cooking.

Table 2 Solar cooking.

Reference number	Subject	Main Remarks
[18]	Solar cookers	Sunflower oil shortened cooking times; erythritol PCM improved off-sunshine storage.
[20]	Indoor solar cooker	Achieved 21% energy efficiency with a system combining a solar collector and an indoor cooking setup.
[21]	hybrid solar-electric cooking oven	Hybrid mode achieved higher energy savings (63%) and reduced cooking times compared to electric and solar-only modes.
[22]	Solar cooker with reflectors	Reflectors increased efficiency by 42.3%, achieving higher absorber plate temperatures.
[24]	PCMs for solar cookers	Blackened pebbles and aluminum balls showed the highest heat storage and cooking efficiency.

2.3 Building's Materials

The integration of solar energy technology into buildings and components can reduce buildings' GHG emissions and energy demand. The choice of innovative construction materials with adequate thermal properties can also promote passive thermal and visual comfort. These materials include cement mortars, bricks, concrete, and finishing mortars. Innovative components include Trombe walls, multi-layered thermally efficient windows, fluid-filled double-glazed windows, and bright windows and facades that can adjust their characteristics to the external ambient, maintaining the internal ambient thermally and visually comfortable.

Zhang et al. [30] investigated a wall system where a dynamic PCM was placed between two wall layers. This proposed system was simulated by CFD and compared to a conventional wall with static PCM. The findings indicated that the dynamic PCM wall can reduce the heating duration by 89%.

The performance of a PCM dynamic Trombe wall was compared with that of a traditional static Trombe wall. The dynamic Trombe wall functions as a multi-panel solar collector-storage system. During sunlight hours, the panels are oriented to face the sun to absorb solar energy, and then rotated towards the ambient for temperature conditioning. It was shown that the dynamic Trombe wall configuration was at least 20% more thermally efficient [31].

A low-temperature solar thermal power system was analyzed to meet residential electrical needs and contribute to overall electricity demand while operating alongside the electric grid. The system utilizes flat plate solar collectors to absorb radiation, Figure 2. Average efficiencies ranged from 2.7% to 5.2%, varying with climate zone and season. The highest efficiency of 9.5% was achieved in Denver and Knoxville [32, 33].

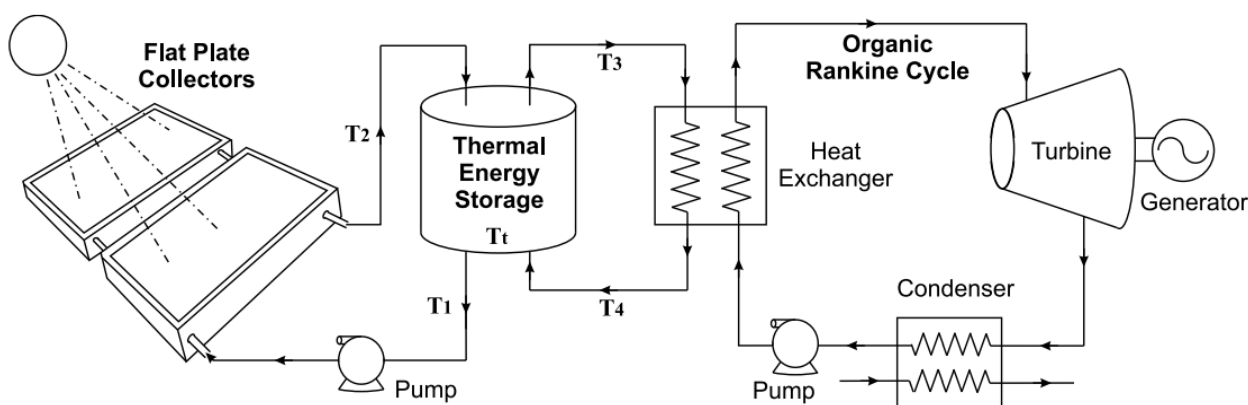


Figure 2 Solar thermal power system [32].

An experimental study on an underfloor heating system was conducted in Al-Jouf Province, Saudi Arabia, in January 2022. The setup included a small-scale chamber representing a residential building, a water storage tank, a flat plate solar collector, and two circulation pumps. The results showed that the overall efficiency ranged from 35% to 62%, with an average efficiency of 51% [33, 34].

Sathish et al. [35] developed a house heating system using a parabolic trough collector (PTC). The system uses water as the heating fluid, which is circulated through a PTC equipped with a PCM-filled absorber. Findings showed that the increase in the number of fins enhanced the system performance, achieving an energy efficiency of 72.3% and exergy efficiency of 7.1%.

Liu and Lu [36] conducted a study on a building heating system using a packed-bed PCM storage integrated with flat-plate collectors. The study employed a 1D transient mathematical model developed in MATLAB. Increasing the storage tank volume improved the effective heat storage utilization rate, and the optimal heat transfer fluid flow rate was 0.05 kg/s.

Other studies in the literature, including passive solar buildings, thermo-chemical solar energy storage for building heating and cooling, solar chimney, etc. besides further information on solar low-temperature applications in buildings can be found in [37-42]. Table 3 summarizes the presented studies on building's materials.

Table 3 Building materials.

Reference number	Subject	Main Remarks
[30]	Dynamic PCM wall for passive solar energy utilization	Dynamic PCM walls reduced heating time by 89% compared to conventional walls without PCM.
[31]	Dynamic Trombe wall for efficient heating	A dynamic Trombe wall improved thermal efficiency by 20% compared to static walls.
[32]	Residential low-temperature solar power system	The system achieved up to 9.5% efficiency, depending on climate and seasonal variations.
[36]	Packed-bed latent heat storage for building heating	Optimized storage tank volume and flow rates improved the performance of heating systems in residential buildings.
[35]	Solar parabolic trough collector for building heating	Finned PCM absorbers increased heat transfer and room temperature, achieving a thermal efficiency of 72.3%.

2.3.1 Remarks

Building materials are increasingly incorporating PCMs into walls to improve passive heating and cooling. These technologies are promising for reducing energy consumption in residential settings, especially when combined with PCMs. Future work should explore integrating these systems with smart grids and enhancing PCM materials to store more heat efficiently. Moreover, new designs, including passive ventilation techniques, could further improve heat distribution in buildings.

2.4 Thermally Efficient Windows and Façades

The deficient thermal and optical properties of ordinary glass used in windows and facades led to intensive research and development efforts to enhance their thermal performance by using solar reflective films, low-E films, aerogel panels, solar shades, PCM in multiple glass windows, and, recently, bright windows and façades, which are by far the most efficient. Still, their cost is high, limiting their broad utilization in buildings. The performance of these windows and façades is essential to reduce solar heat gain and thermal losses, and to maintain thermal and visual comfort without adding or removing heat or artificial lighting. In this manner, they can contribute significantly to decarbonizing buildings.

Feng et al. [43] reviewed the gas-chromic bright windows, calculated their energy consumption, and compared them with various glazing systems. The decrease in air conditioning loads in summer and winter in Shanghai was 28.4% and 11.5%. Baldassarri et al. [44] evaluated the manufacturing phase of Near-infrared switching electrochromic (NEC) windows and compared the performance with that of electrochromic (EC) smart ones. The results for the conventional EC device were 85 kg CO₂-eq/m² and 1680 MJ-eq/m², while those for the NEC device were 50 kg CO₂-eq/m² and 1050 MJ-eq/m². Fathi and Kavoosi [45] assessed the impact of EC windows on energy consumption. Results showed a 35.57% energy reduction with EC windows. Pereira et al. [46]

reviewed the solar control films (SCFs) for building glazing systems and showed that SCFs attenuated indoor solar radiation, excessive luminance, and glare. Moghaddam et al. [47] presented the results of a proposed methodology for evaluating glazings in terms of performance, thermal comfort, and costs. Hendinata et al. [48] presented a comparison of the energy-saving benefits of thermochromic, double-glazing, and clear glass windows. They found reductions of 8.91% to 10.96% in energy consumption due to double-glazed windows and of 20.22% to 24.19% due to thermochromic windows. Mustafa et al. [49] reviewed the technology of bright windows, limitations, challenges, and future applications. Krarti [50] investigated the optical properties and performance of bright windows to maximize their efficiency benefits and concluded that significant energy savings can be achieved. Zhang et al. [51] investigated innovative smart windows with photovoltaic electrochromic (PV-EC). The combination showed the largest useful daylighting illumination of about 75.26% and energy saving of about 15.79% compared to ordinary windows. Ghosh et al. [52] studied four active smart switchable glazings. The authors discussed the integration of this type of window in buildings and their impact on smart buildings and cities.

2.4.1 Remarks

Common glass windows are weak barriers against solar radiation transmission and heat losses and gains of the building. This led to intensive research and development to enhance the windows' thermal and optical performance by using solar reflective films, low-E films, aerogel panels, solar shades, PCM in multiple glass windows, and fluid-filled double glass windows. Bright windows and façades, by far, are the most efficient, but their cost is high, limiting their broad utilization in buildings. Future research should address technical problems such as leakage of PCM, vacuum deterioration, and aging of materials, and full-scale field tests, besides reducing the production costs.

2.5 Water Distillation

Water is an essential resource for sustaining life on Earth, but only a fraction of it is directly usable due to salinity and contamination issues. The ever-increasing demand for potable water urged for more research and development on low-cost, efficient, and eco-friendly desalination techniques. Solar distillation has emerged as a sustainable technique to provide potable water that is safe for human consumption, free from harmful chemical pollutants and waterborne diseases. Some countries are facing high water stress, like Bahrain, Cyprus, Kuwait, Lebanon, Oman and Qatar. Countries with water stress problems use saline water distillation systems driven by fossil fuels to provide potable water. Solar-based distillation units are usually small units, with modest structure, low efficiency and low productivity. Continuous research efforts and developments led to improvements in the design of the distillation units and their performance, but they are still not sufficient for home use.

Hassan et al. [53] assessed a hybrid solar distiller integrated with a parabolic trough solar collector. The system demonstrated good performance and its energy efficiency increased from 23.04% to 33.04%. Çolak et al. [54] developed a water distillation system (Figure 3) to investigate the factors that can impact the distillation efficiency. The parameters examined included insulation, painting the reservoir black, using an internal fan, adding external fans, incorporating a water-spraying mechanism to cool the external heat exchanger of the Peltier unit, and using

sponge pieces. Compared to an unmodified system, the amount of clean water collected increased by 13.6%.

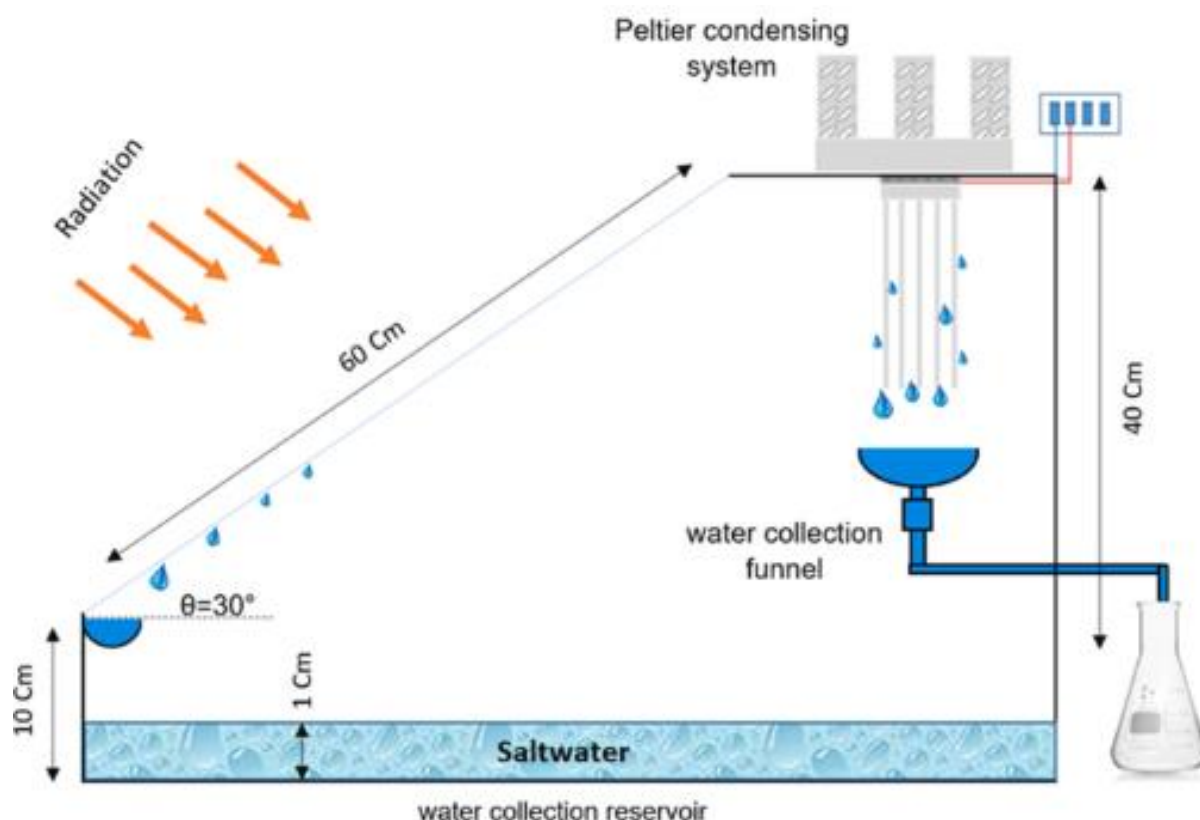


Figure 3 Water distillation system [54].

Özcan and Deniz [55] investigated a solar still integrated with a thermoelectric generator (CSS-TEG), and the results were compared with those of a conventional solar still (CSS). The findings revealed improvements in productivity, energy efficiency, and exergy efficiency ranging from 5 to 40%, 18 to 45%, and 1.69 to 5.31%, respectively. Ahsan et al. [56] designed a triangular-shaped solar distillation system utilizing solar radiation and a heater driven by a PV panel to enhance water evaporation and distilled water production. The water productivity results were compared with those from existing models in the literature, showing improved performance.

Saada et al. [57] investigated the development and performance of an improved solar still incorporating a metal plate. Comparative analysis was conducted between the improved system and a traditional solar still. The results demonstrated significant improvements in productivity and efficiency. The findings highlight the efficacy of integrating a solar collector into the solar still design.

Further studies in the literature explore various enhancements to solar thermal distillation systems. These include the incorporation of evacuated tubes to improve efficiency [58], the impact of adding aluminum balls to increase distillate productivity [59], the development of porous photo-thermal fiber felt to enhance the water evaporation rate [60], and the analysis of a hemispherical solar distillation system [61]. Additional details on water solar distillation systems can be found in [62-64]. Table 4 summarizes the presented studies.

Table 4 Water solar distillation.

Reference number	Subject	Main Remarks
[53]	Hybrid solar distillation using direct salty water heating	Efficiency improved from 23.04% to 33.04%, with higher freshwater production and reduced costs.
[54]	Inclined solar distillation system with thermoelectric module	Black sponges enhanced water output by 14%; insulation improved water production efficiency.
[55]	Solar still integrated with a thermoelectric generator (CSS-TEG)	The thermoelectric generator increased productivity and efficiency by 18-45%.
[56]	Solar distillation integrated with a PV panel	Performance is enhanced by using a combination of solar radiation and a water heater, improving evaporation rates.
[57]	Solar still with an inserted solar collector	The findings highlight the efficacy of integrating a solar collector into the solar still design.

2.5.1 Remarks

Water distillation systems are improving through hybrid designs that combine solar stills with additional components such as thermoelectric generators, low-concentration collectors, and direct current water heaters. These hybrid systems improve freshwater output and energy efficiency while reducing the cost of water production. Future research should explore scaling these systems for community and industrial use and optimizing designs to function effectively in regions with low solar intensity. Additionally, integrating solar distillation with agricultural irrigation offers a sustainable approach to water management in arid areas.

3. Moderate Temperature Demands

Besides meeting a building's low-temperature energy needs, solar energy has enormous potential to meet moderate-temperature demands and services such as absorption air conditioning c, collectors by moderate-concentration vacuum-tube solar collectors, and window-type air conditioning units driven by solar photovoltaic panels, besides other applications.

3.1 Cooling and Heating Applications

Loem et al. [65] conducted a study on using phase change material (RT18 HC) and 320 W PV modules in conjunction with electrical grid power to operate a 1 TR inverter air conditioner. The operation of the proposed system involved both charging and discharging modes. During the charging mode, cool air from the evaporator coil, maintained at 5°C during early morning hours, was used to cool and solidify the PCM. In the discharging mode, air at 25°C was directed through a PCM-packed bed for cooling before reaching the evaporator coil, thereby reducing the cooling load on the evaporator. Using only PCM, daily electrical energy consumption from the grid could

be reduced by approximately 13.84% in winter and 16.13% in summer. When PV modules were added, the air conditioner's daily grid power usage with the PCM bed could be reduced by around 99.44% in winter and 84.62% in summer, compared to 98.83% and 72.86%, respectively, without the PCM bed.

Sulaiman et al. [66] conducted a study on the implementation of low-Global Warming Potential (GWP) refrigerants as alternatives to conventional refrigerants in a solar air conditioner using R32, R410A, R134a, R22, R290, and R600a. Results demonstrated that R290 outperformed R134a, achieving a 2.42% higher coefficient of performance (COP), 2.31% energy reduction, and a 2.37% enhancement in exergetic efficiency.

Due to the high energy consumption of air conditioning systems [67], the exploration of alternative technologies, such as liquid desiccant regeneration systems, has gained significant attention. As the desiccant solution becomes diluted during operation, regeneration becomes essential for continuous system operation. The regeneration process involves heating the diluted desiccant solution, enabling water vapor desorption from the solution [68]. A solar-based regeneration process is viable as demonstrated by Bhowmik et al. [67], who investigated solar-powered desiccant regeneration systems. Their research examined the phase change phenomena within the regeneration system and analyzed the corrosion rates of various desiccant solutions.

Ullah et al. [69] investigated a system that utilizes a solar evacuated tube electric heater for desiccant wheel regeneration, while employing a combination of Desiccant Wheel (DW) and Maisotsenko cycle (M-cycle) technology for separate management of latent and sensible loads, respectively. Results indicated that integrating the M-cycle with the solar-assisted desiccant air conditioning system significantly outperformed conventional desiccant evaporative cooling (DEC) systems. Under identical inlet conditions and regeneration temperatures, the hybrid system achieved a 60-65% higher thermal coefficient of performance compared to the traditional desiccant.

Akyüz et al. [70] compared a solar air conditioner and a conventional AC unit (12,000 BTU cooling capacity with dual inverters). The experimental setup comprised two identical rooms with equivalent internal volumes and thermal insulation properties. Results showed that increasing the compressor input temperature reduced energy consumption by 8-28% and decreased emissions by 7.74-28.27%.

Sandong et al. [71] integrated a solar air conditioning and a parabolic trough concentrator (PTC). A comprehensive energy analysis model was developed to evaluate system performance and quantify potential energy savings. Under peak solar irradiation conditions of 1000 W/m², the system demonstrated remarkable performance, achieving energy savings of up to 48%.

Rebelo et al. [72] compared a photovoltaic solar air conditioner and a conventional unit in Teresina, Piauí, Brazil. The experimental setup comprised two identical rooms: one equipped with a traditional unit and the other fitted with the solar photovoltaic (PV) system. The assessment encompassed multiple performance parameters, including energy consumption, temperature control efficiency, and overall system performance. The findings support the feasibility of PV systems as alternatives to conventional air conditioning units.

Martínez et al. [73] conducted an experimental investigation focused on both thermal and electrical efficiency parameters. Results demonstrated that the evaporative pre-cooling mechanism successfully reduced the condenser inlet air temperature by approximately 6°C, and the peak power demand by 23%. Furthermore, the solar component contributed more than 30%

of the system's total power requirements, while the overall system achieved a 43% energy reduction. These findings highlight the significant potential of combining solar power with evaporative pre-cooling technology for enhanced air conditioning performance in hot climatic conditions.

A solar photovoltaic air conditioner was installed in a 36 m² research laboratory at The University of Jordan. The experimental setup comprised a 2.67 kWp photovoltaic array integrated with a battery storage system, charge controller, inverter charger, and air conditioning unit. The investigation encompassed two operational scenarios: an on-grid configuration with utility connection and an autonomous off-grid system. The off-grid system demonstrated complete self-sufficiency during summer cooling periods and November heating demands, while maintaining substantial heating load coverage during winter months. The off-grid configuration showed a reduced payback period of 6.4 years [74]. More relevant studies and information can be found in [75-81].

Li et al. [82] investigated a compact rooftop stationary medium-temperature solar collector for air-conditioning applications. The design incorporated an innovative tracking/concentrating platform. The results showed that by incorporating three prism arrays and a TiNO_x coating, it was possible to cover 50% of the demands of a large building in Sydney, Australia, using solar energy.

Bai et al. [83] developed a solar-based cooling, heating, and power system. Numerical simulations showed that the system's energy and exergy efficiencies were 82.0% and 58.72%, respectively.

A hybrid system integrating a Parabolic Dish and a Linear Fresnel Concentrator that automatically tracks the sun to concentrate solar radiation proved to be capable of operating at temperatures up to 250°C, which is enough for a solar cooling system and also can satisfy residential hot water demands [84].

Chen et al. [85] developed a thermo-photovoltaic (TPV) system for medium-temperature solar energy storage, incorporating a molten salt energy storage system. The system operated at temperatures between 800 and 1000 K, achieving a 37% increase in spectral efficiency from 51% to 88%. This design demonstrated enhanced performance in small-scale distributed energy applications by combining solar energy storage with thermo-photovoltaic conversion.

Noferesti et al. [86] investigated the use of a solar absorption cooling system to reduce the energy consumption of buildings. The cooling demand of a building was considered to evaluate the system. The building's existing cooling system was planned to be replaced with a solar absorption chiller using evacuated tubes, glazed flat plate, and unglazed solar collectors. The findings indicated that the solar absorption chiller can reduce power consumption by 83.18%, 63.6%, and 47.73%, respectively, when operating with the different solar thermal collectors during office hours.

Bai and Wang [87] conducted a study to develop novel materials for solar energy applications in the medium temperature range. A composite phase change material (PCM) consisting of MXene/D-mannitol (DM) aerogel was synthesized. The material achieved a solar-thermal conversion efficiency of 88.1%. The composite maintained excellent shape stability, effectively addressing common limitations of conventional PCMs, such as low energy conversion capacity and leakage issues that typically hinder their practical implementation.

Further related studies on solar energy medium temperature applications can be found in [85, 88-95]. Table 5 summarizes the studies of solar moderate temperature applications.

Table 5 Solar moderate temperature applications.

Reference number	Subject	Main Remarks
[65]	Solar air conditioner with PCM	Combined PCM and PV modules for a solar-powered AC. Notable reductions in energy consumption.
[66]	A solar air conditioner	Evaluated energetic and exergetic performance of refrigerants. R290 showed higher COP and lower input work.
[67]	Solar packed bed regenerator	Studied liquid desiccants in air conditioning, showing potential for significant moisture removal using solar-powered regeneration.
[69]	Solar-assisted desiccant air-conditioner	Showed that the hybrid system with M-cycle improves thermal performance by 60-65% over conventional systems.
[70]	Solar-assisted air conditioner	Achieved 8%-28% energy savings and reduced emissions with a solar-assisted AC modification.
[71]	Solar-assisted air conditioner	Proposed a novel design integrating a PTC with a vapor compression cycle, achieving 48% energy savings under peak solar conditions.
[72]	Photovoltaic air conditioner	Compared PV and conventional AC units, showing marginally higher energy use but significant economic viability with a 3.7-year payback.
[73]	Hybrid solar air conditioner with evaporative pre-cooling	Evaluated pre-cooling's impact, resulting in an 18.3% increase in EER and 43% reduction in energy consumption.
[74]	Experimental Evaluation of a Solar-Powered Air Conditioner	Demonstrated off-grid self-sufficiency during peak cooling periods and significant energy savings.
[75]	Solar absorption air conditioner with CO ₂	Developed a solar thermal absorption system for near-zero energy consumption in buildings.
[77]	Light-duty vehicle with solar air conditioner	Focused on solar-powered AC for vehicles, reducing fuel use and emissions.
[82]	Medium-temperature solar thermal collector	Developed a rooftop solar collector covering up to 50% of energy needs.
[83]	Solar thermochemical technology	Created a system using methanol decomposition to meet cooling, heating, and power demands of buildings, achieving 82% energy efficiency.

[84]	Fresnel solar concentrator	Developed a hybrid solar concentrator, suitable for medium-temperature heating needs in Moroccan conditions.
[85]	Thermo-photovoltaic metamaterial emitter	Achieved improved spectral efficiency and TPV performance using novel materials for solar storage applications.
[86]	Solar integrated absorption cooling system	Evaluated solar absorption chiller for buildings, achieving significant reductions in power consumption.
[87]	MXene/d-Mannitol aerogel PCM	Developed novel PCM materials for medium-temperature applications.
[88]	Solar gas-fired power system	Analyzed a hybrid solar and gas power system with significant environmental benefits and improved thermal efficiency.
[89]	Relocatable solar power tower for industrial heat supply	Evaluated the feasibility of a solar power tower for industrial heat applications.

3.1.1 Remarks

Solar cooling/air conditioning of buildings is attractive because the cooling loads and availability of solar radiation are in phase. In addition, the combination of solar cooling and heating greatly improves the use factors of collectors compared with heating alone. Solar air conditioning can be accomplished by three types of systems: absorption cycles, adsorption (desiccant) cycles, and solar mechanical processes. Solar thermal cooling is an important market in countries and regions with high cooling demands.

Solar air conditioning has progressed considerably over the past few years as a result of efforts to protect the environment and new developments in components and systems, and significant experience has been gained from demonstration projects. The main obstacles to extensive-scale application, besides the high first cost, are the lack of practical experience and familiarity with the design, control, and operation of these systems.

4. Electricity Demands

As mentioned earlier, the energy demand of a building includes not only low- and moderate-temperature requirements but also electricity for powering appliances and other services, such as illumination, ventilation, and building security systems. A building's electricity demand depends on factors like size, type, climate, and usage patterns, with residential and commercial buildings having different needs. Office buildings often have higher energy demands than residences due to space heating and cooling. Primary energy uses in residences include space heating, cooling, and hot water, and can account for about 80% of a home's energy use in the EU. Factors influencing demand include house size, number of appliances, and household habits, which significantly impact usage.

In 2023, buildings accounted for 32% of the global energy demand and 34% of CO₂ emissions. In 2024, buildings remained significant energy consumers, driven by factors such as increased

electricity demand from cooling and electrification. Global energy use in buildings accounted for nearly 60% of the growth in overall electricity consumption. Efforts are underway globally to improve energy efficiency in buildings. Embodied carbon from materials like steel and cement remains a significant source of emissions, accounting for 18 per cent of global building emissions.

Rural and isolated areas usually suffer from quality and irregular electricity supply. Although rural areas produce more than 85% of food served for urban areas, the public services destined to them are usually inferior in quality compared to that for metropolitan areas, as in the case of electricity supply (due to long distances and increased losses besides low consumption), collection of solid waste (usually because of long distances), and other similar services. Solar photovoltaic electricity generation offers golden opportunities for local governments correct these situations and extend electricity supply to rural areas by adopting adequate public policies, financial incentives, and low-cost grants for installations. A large number of the global population in Africa, Asia, and Latin American countries, and others, can benefit from these inclusion efforts. Notable experiences are ongoing in countries like China to include the rural and isolated areas for distributed photovoltaic electricity generation and consumption.

Yin et al. [96] conducted a study that examines the decision - making logic and strategy optimization among local government, photovoltaic enterprises, power grid enterprises, and farmers to advance rural photovoltaic industry growth. The results showed that the cooperative interest of the involved entities is an important mechanism for the robust development of the rural photovoltaic industry. Local governments can effectively stimulate the enthusiasm of the other parties by subsidizing photovoltaic enterprises, power grid enterprises, and farmers. Direct subsidy policies from the local government to farmers can more effectively stimulate farmers' enthusiasm for installing photovoltaics.

Yin and Yuan [97] presented a study that examines the relation between energy, the economy, and the environment in rural China. The authors provided an integrated assessment and analysis of the influencing factors of the energy-economy-environment (3E) system in rural China. They offered a scientific basis for policies aimed at promoting sustainable rural development by optimizing the energy structure, improving efficiency, and reducing pollution. The findings showed overall improvement in 3E development, room for energy improvement, rapid economic growth, and more balanced environmental development.

Sections 2 and 3 showed that low- and medium-temperature demands in a building can be met satisfactorily by well-developed, high-efficiency solar thermal equipment with proven thermal performance and a well-established market presence at reasonable prices. Electric energy demands, such as for controls, electric equipment and other devices needs equipment which transform solar incident radiation into electric energy, such as solar photovoltaic panels (PV panels). These devices received intensive dedicated research and developments which led to improving their conversion efficiency, and reducing their cost besides improving its working life. Irrespective of these advancement the cost is still high and some public policies and financial incentives are required to avail their use in moderate cost buildings. In hot climates these equipment show degradation in performance and their useful life is reduced. More research and development are currently dedicated to provide efficient cooling kits in the market. Another crucial problem is what to do with these panels at the end of their working life? How to recycle the materials in a safe way without affecting the environment? Again this problem is being

investigated and new results show that it is possible to reuse the recovered materials in the production of new PV panels and new products, which provide a safe disposal solution.

Solar PV worldwide application is still facing challenges; some are related to surroundings such as dust and ice [98], while others are inherent to the solar cells such as overheating and fabrication, and materials costs. Overheating significantly impacts PV cell performance, reducing it by about 5% for each 10°C increase in temperature [99]. Cooling of PV panels is necessary to maintain efficient operation and a long useful life. Panel cooling can be achieved in various ways, including circulating cooling fluids, adsorption, absorption, and the application of PCMs.

4.1 Passive Cooling of Solar PV Panels Using PCM

Photovoltaic panels and concentrator photovoltaic systems, as well as building-integrated photovoltaic (BiPV) and thermal photovoltaic collectors (PVT), are being developed for practical integration into clean power generation schemes. Cooling is necessary for the performance improvement of PV systems. In addition, cooling the solar cells reduces thermal stress and extends their lifespan [99]. PV cooling can be made in various ways, classified as active and passive techniques. The former requires power input, whereas the passive technique does not. In this section, the focus is on the passive approach using PCM [100].

The cooling potential of PCM for different climate zones was addressed in [101]. Paraffin and inorganic PCMs were used in two different climate conditions. However, the PCM fusion temperature is essential to ensure high thermal performance of PCM [102]. The two PCM types proved their thermal regulation potential. PCM-based cooling was shown to increase the annual power yield of PV systems [103]. Arici et al. [104] reported a PCM-induced cooling effect of about 10.26°C, resulting in an efficiency enhancement of 3.73%. Karthick et al. [105] showed the effect of PCM in reducing the PV panel temperature by 8°C and increasing the efficiency by 10%, while Li et al. [106] reported a reduction of the surface temperature by 23°C and an enhancement of the efficiency by 5%. Rezvanpour et al. [107] obtained 38% of cooling effect upon the application of PCM to a solar PV unit. Other studies reported yield increases of 5% [108], 7.3% [109], and 7.7% [110] resulting from PCM integration in PV panels.

The heat recovered from solar cells can be used for other domestic applications, such as water heating. Therefore, this new version of thermal solar PV systems (PVT) is currently being investigated [111]. Preet et al. [112] indicated that PCM can increase the power yield of a PVT system. Khanna et al. [113] conducted a parametric investigation on the performance of a PCM-PVT system where the melting temperature, ambient temperature and wind velocity were the main investigated parameters.

PCM-based cooling of solar PV systems can be made in a greener way [114] by using natural-based materials. In recent years, some research studies have focused on bio-PCM, particularly for cooling PV panels. Animal fat was the main bio-PCM investigated for the cooling of PV panels. For instance, pork fat was investigated and showed higher thermal performance than organic PCM [115].

The cooling performance of PCM depends on the material and its thermo-physical properties, while economic and environmental issues [116, 117]. However, Yang et al. [118] suggested including post-application performance information on the selected material in the selection process to ensure reliability.

The low thermal conductivity of PCM limits its cooling effect. The cooling effect of PCM can be improved by enhancing the thermal characteristics of the material. Various techniques were investigated, including dispersion of nanoparticles, metallic powders, conducting metal foams, and incorporation of fins within the PCM, Figure 4. For instance, SiC nanoparticles showed high thermal performance when dispersed in paraffin for cooling solar PV systems, increasing thermal efficiency by 72% [119], while Al_2O_3 nanoparticles decreased the PV panel temperature by 10.6°C . Various nanoparticle types were investigated [120] at different concentrations, but Al_2O_3 showed the highest impact. Singh et al. [121] verified the impact of nanoparticles on the PCM-cooling performance of photovoltaic panels for both summer and winter and reported significant cooling potential achieving 8.3% for winter conditions and outperforming that of summer. Abdollahi & Rahimi [122] showed that nanoparticles increased the power output by 48.23%. Siahkamari et al. [123] illustrated the higher performance of sheep fat over conventional industrial wax used to cool down solar PV panels. To further increase the cooling effect and hence the power generation, the PCM was dispersed with CuO nanoparticles; 26.2% higher power was obtained due to heat transfer enhancement.

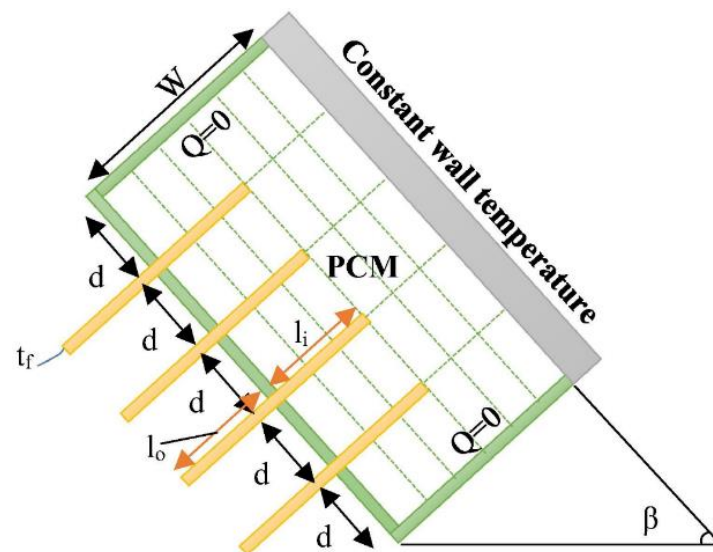


Figure 4 Schematic of finned PCM-based cooling of solar PV panel [124].

A fair number of investigations focused on enhancing the PCM performance by incorporating fins in the cooling system, as in [124-128]. Wongwuttanasatian et al. [129] employed finned PCM and compared it with conventional fluid cooling techniques. The fins combined with PCM showed a higher cooling effect and efficiency, with an enhancement of 5.3%. The impact of fin shape was addressed by Desai et al. [130] for the cooling of PV panels in the presence of PCM. Various shapes were studied, rectangular, triangular, circular, and prismatic. The latter yielded the best thermal results. Yıldız et al. [131] also analyzed the effect of fin shape for the cooling of solar PV systems with PCM. The authors investigated conventional and non-conventional shapes, including tree-like fins, which showed a significant cooling effect.

Porous media such as metal foam can be used for air enhancement of solar PV efficiency. The porous medium can be integrated in the air channel [132] as well as in the PCM, which can be placed as well in the back of the panel. Abdulmunem et al. [133] combined both metal foam and

nanoparticles to enhance the thermal conductivity of PCM integrated for cooling solar PV systems. This technique reduced the cell temperature in the panel by 13.29% and increased efficiency by about 5.68%. Kiwan and Khlefat [134] investigated the combined effect of fins and porous media applied to solar PV and reported up to 8.34% increase in efficiency. Asefi et al. [135] addressed the improvement of solar panels by using nanoparticles in the cooling fluid and PCM enhanced by integrating porous media (Figure 5) achieving a thermal efficiency of about 43.1%.

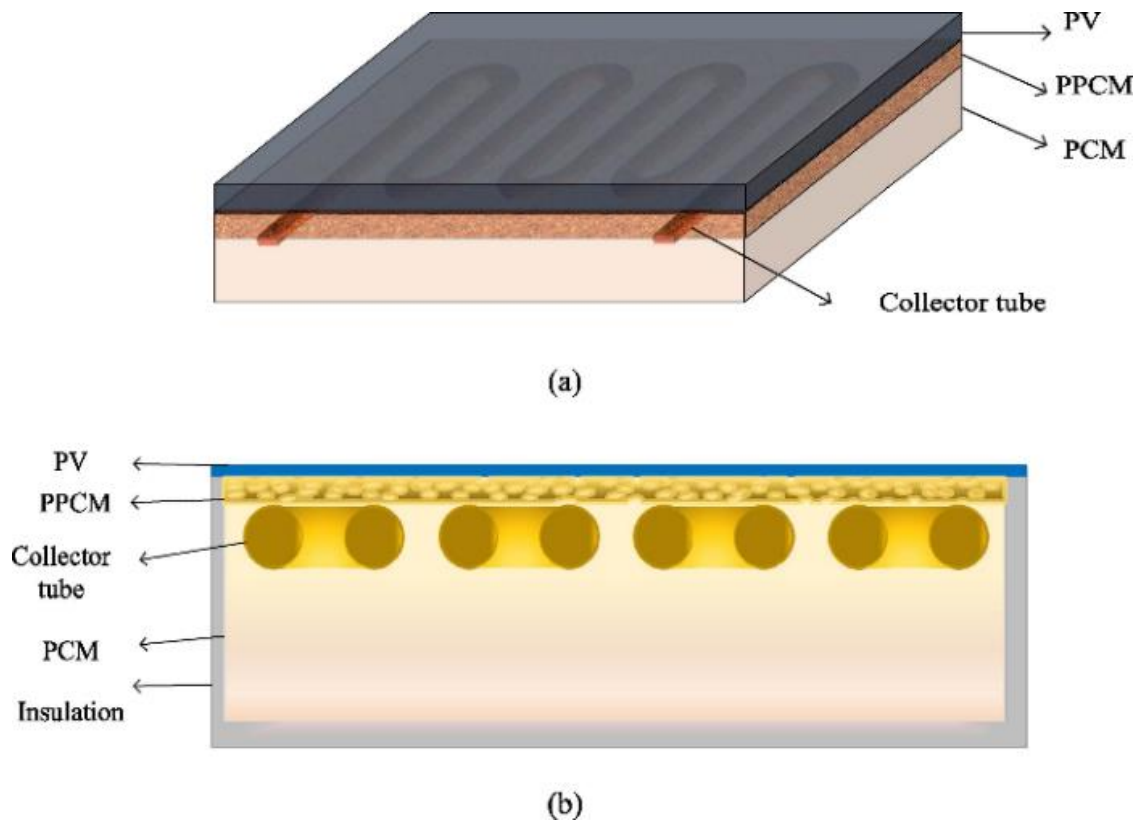


Figure 5 Solar PV panel equipped with PCM enhanced with porous medium (PPCM) [135].

Further enhancement of cooling fluids can be achieved by improving the thermal conductivity. Conventional cooling fluids, such as water, have low thermal conductivity and can be enhanced by dispersing high thermal conductivity nanoparticles. Numerous research studies have been dedicated to these enhancement techniques, such as [136-141].

5. Conclusions and Future Research Opportunities

5.1 Conclusions

1. The reviewed literature covers a wide range of studies on solar water heating systems, focusing on both technological advancements and performance optimization. Key improvements include the use of twisted-tape inserts in evacuated-tube collectors, hybrid solar collectors incorporating photovoltaic systems, and direct/indirect heating. The integration of PCMs has shown significant potential to reduce storage volume and enhance system efficiency. While many

studies have focused on improving heat storage and minimizing energy consumption under varying solar radiation conditions, several gaps remain.

2. Solar cooking systems have seen innovation through the development of hybrid thermal-electric cookers and systems that incorporate PCMs for heat storage. These advancements have enabled both efficient solar cooking and cooking during off-sunshine periods. However, there is still a need for more robust and efficient systems.

3. Solar based energy equipment integrated into building heating and cooling systems has demonstrated significant energy savings and improved thermal efficiency.

4. The performance of bright windows and façades is vital to reduce solar heat gains and thermal losses and maintain thermal and visual comforts. This can contribute significantly to the decarbonization of buildings. Further research and development are required to reduce costs.

5. Significant improvements of solar water distillation efficiency and yields were achieved by combining solar stills with thermoelectric generators.

6. Research in solar-powered air conditioning has focused on integrating photovoltaic systems and PCM with traditional AC units to enhance energy efficiency. Studies show significant reductions in grid energy use and operational costs, particularly when using PV systems and innovative cooling methods like liquid desiccants and hybrid cycles.

7. Solar PV power is continuously increasing due to technology development and relative cost reductions. There is a need to popularize domestic and isolated communities' installations by adequate public policies, tax incentives, and financial installation grants.

5.2 Future Research Opportunities

1. Future research is required to explore the optimization of PCM compositions and investigate Bio PCMs to further enhance thermal storage capacity. Additionally, off-grid solar water heating systems still require advancements in reliability and cost-effectiveness, especially in remote and isolated areas.

2. Recent advancements in solar cooking systems include the development of hybrid thermal-electric cookers and systems that incorporate PCMs for heat storage. Further research is needed to optimize the thermal storage materials used in solar cookers, as well as to develop solutions for low-income regions where the use of traditional fuels (wood, agricultural residues) remains dominant.

3. The cost of bright windows is still prohibitive for moderate homes and should be decreased to popularize their installation in moderate residences and buildings. Additionally, further research is needed to explore novel materials that enhance the thermal storage capacity of PCM systems and reduce costs. Extending these applications to commercial and industrial buildings would help reduce emissions and electricity consumption.

4. The literature review showed substantial innovations in water distillation, including improvements in efficiency through hybrid systems that combine solar stills with thermoelectric generators to reduce freshwater production costs and increase system efficiency. However, further research is needed to develop large-scale industrial applications of these systems and to optimize their use in regions with low solar intensity. Another promising area for future research is integrating solar distillation systems with agricultural irrigation, which could provide a sustainable solution for water-scarce regions.

5. Future work on solar-powered air conditioning should focus on optimizing solar PV and PCM integration to improve energy savings. Additionally, there is a need for further research on hybrid systems combining solar energy with other renewable sources. Long-term performance evaluations and life cycle assessments will be crucial to the economic viability of these systems.

6. There is a need to explore more cost-effective materials and designs for solar thermal collectors to improve their adoption in industrial processes. Research could also target hybrid systems that combine thermochemical reactions with PV technologies to improve energy storage and efficiency. The scalability of these technologies in different industrial contexts, as well as their integration with existing infrastructure, should be a priority for future studies.

7. A number of cooling techniques have been investigated including cooling fluid and phase change materials. Further research can be carried on other cooling techniques such as adsorption, absorption, radiative, as well as evaporative cooling. Self-cleaning and maintenance are worth research focus as well.

Nomenclature

CSS-TEG	A solar still integrated with a thermoelectric generator
DASC	Direct absorption solar collectors
EC	Electro chromic
GWP	Global Warming Potential
NEC	Near-infrared switching electro chromic windows
PBLHS	Packed-bed latent heat storage
PCM	Phase change material
PTC	Parabolic trough collector
PTSC	Parabolic trough solar collector
PV	Photovoltaic
PV-EC	Photovoltaic electro chromic
STEPCO	A hybrid solar thermal-electric powered cooking oven
SWH	Solar water heating

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Competing Interests

The authors have declared that no competing interests exist.

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