Solar energy utilisation: Current status and roll-out potential

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Abstract

To meet the well-known energy transition challenge, a rapid shift from fossil fuels to the broader exploitation of renewable energy sources is needed; solar energy represents the most abundant and readily available resource amongst the renewable energy sources. This vision paper aims at shedding light on the current knowledge and emerging pathways for solar energy utilisation. Specifically, after a general introduction and a brief overview of the current knowledge, open issues are discussed regarding photovoltaic/thermal (PV/T) collectors, building integrated PV/T systems, concentrating solar power plants, solar thermochemistry, solar-driven water distillation, and solar thermal energy storage technologies. Subsequentially, this vision article defines key fundamental challenges that need to be addressed for these technologies to play a significant role in future sustainable energy systems. The identified challenges include developing new materials, enhanced performance, accelerated system installation and improved manufacturing processes, combining solar energy with other clean energy production and storage systems, and integrating solar energy utilisation with local energy utilisation patterns.

Keywords: concentrating solar power; PV/T; solar distillation; solar thermal energy storage; solar thermochemistry.

Nomenclature

Abbreviations

BIPV	building integrated photovoltaic	NF	nanofluid
BIPV/T	building integrated photovoltaic/thermal	PCM	phase change material
BIST	building integrated solar thermal	PDC	parabolic dish collector
CCHP	combined cooling heating and power	PTC	parabolic trough collector
CSP	concentrating solar power	PV	photovoltaic
HVAC	heating, ventilation, and air conditioning	PV/T	photovoltaic/thermal
LFC	linear Fresnel collector	SPT	solar power tower
		TES	thermal energy storage

1. Past

Defining and pursuing sustainable decarbonisation pathways has become a general concern to the international community: at present, many countries worldwide have set goals for achieving carbon neutrality by the middle of this century. In this perspective, it is generally accepted that decarbonisation pathways will rely on the smooth integration of a portfolio of clean energy technologies and ad-hoc demand-side and supply-side management strategies: this vision article focuses on the solar-energy source as part of the portfolio. Indeed, solar energy utilisation represents a tangible way for our society to continue developing and progressing since the total annual solar radiation received by Earth is more than 7500 times the world's total annual primary energy consumption of approximately 450 EJ [1]. The major challenge regarding solar-energy sources is deploying the most appropriate technologies to harvest and utilise a relatively diffuse and distributed resource.

This article provides an overview of emerging solar-energy technologies with significant development potential. In this sense, the authors have selected PV/T [2], building-integrated PV/T [3], concentrating solar power [4], solar thermochemistry [5], solar-driven water distillation [6], solar thermal energy storage [7], and solar-assisted heat pump technologies [8]. Although the technologies mentioned above have made some progress, they still face technical challenges and barriers to widespread implementation so far [9-11]. As such, this vision paper aims to provide an up-to-date discussion on the advances in these solar energy utilisation technologies, give an outlook for what further improvements are needed in these technologies, and recommend specific directions for future research activities.

2. Present: Challenges and opportunities

This section provides an overview of the aforementioned technologies. Firstly, it focuses on PV/T collectors, identifying contemporary designs, manufacturing and implementation challenges. It the turns to the possibility of integrating solar PV technologies (and their variants) with existing domestic or non-domestic buildings, exploring the significant advantages they offer when implemented effectively. This part also highlights the key challenges and issues of their extensive integration on building facades and structures. The section continues by introducing concentrating solar power and thermochemistry technologies. Compared to the first two parts of this section, the last topic has not received as much attention from the research community in recent decades; the authors consider the reasons for this gap. Finally, this section examines cutting-edge research topics and challenges in solar-driven water distillation and solar thermal storage.

2.1 Solar-thermal or PV/T collectors

Solar energy can be harvested as either heat or electricity, with the thermal collection being simpler and (historically) more affordable than the photoelectric conversion. However, solar-to-heat conversion leads to a lower exergy efficiency in most solar-thermal collector designs, thus limiting their application in many scenarios. On the other hand, solar-to-electricity conversion (e.g., PV cells) can be used directly as high-grade electricity or can be converted to heat. Nevertheless, photoelectric conversion can only be effective for photons with energy above the bandgap of PV materials [12]; thus, the major part of the solar spectrum is wasted. To improve the overall efficiency, many researchers have developed numerous PV technology variants that can harvest solar energy simultaneously in the same component as electricity and heat (e.g., PV/T technology) [13].

To date, different PV/T collectors are available. For example, Huang et al. [14] compared the performance of solar PV/T-air collectors with traditional solar-air collectors and individual PV modules. The emerging technologies of the three collectors were tested over different airflow rates, inlet temperatures, and solar irradiance levels. The results indicated that, while the thermal efficiency of the PV/T-air collector was approximately 25% lower than a traditional solar-air collector, the electrical efficiency of the PV/T-air collector was higher than with individual PV system by 4.7%. Hence, the simultaneous production of electricity and heat, èprovided by PV/T technologies, ensured the broader applicability of PV/T compared with conventional stand-alone solar collectors or PV systems. Herrando et al. [15] proposed a CCHP system combining a PV/T collector array to an absorption chiller. In this work, the feasibility of this system for application in the food-processing industry was studied, and the technical, economic, and environmental performances were discussed. The authors found that while the individual efficiencies of the PV and thermal elements were very close to the efficiencies of stand-alone units, the PV/T designs offered great potential for integration with other HVAC units with increased overall (thermal and electrical) efficiencies.

Several structural designs of PV/T systems were also investigated to achieve higher solar energy conversion efficiencies. Hissouf et al. [16] investigated the effect of optical, geometrical and operating parameters on the thermal and electrical performance of both glazed and unglazed hybrid PV/T solar collectors. They found that the thermal efficiency of the glazed system was 21.5% higher than the unglazed system, but the electrical production was lower than the unglazed collector by 11.8%. The extinction coefficient of glass is a significant factor that influences system performance, with the glass thickness also having a slight impact. Furthermore, Varmira et al. [17] assessed the energy and exergy performance of a PV/T collector equipped with a sheet-and-sinusoidal-tube collector against a reference case of a PV/T collector equipped with a sheet-and-plain-tube collector. It was found that the overall energy and exergy efficiencies of the sheet-and-sinusoidal-tube collector were 9.1-15.5% and 1.1-2.6% higher than those of the sheet-and-plain-tube collector. Das et al. [18] developed a novel rectangular spiral tube absorber with a transparent multi-crystalline PV module. In this design concept, a novel composite is fabricated and embedded in the enclosure formed by the PV and back cover to improve thermal (i.e., temperature) uniformity. The experimental results showed that this novel structure could improve the electrical output by 18.4% compared with a standard PV module. In general, the optimisation of the design often increases the complexity of the components and the difficulty of the manufacturing process while improving the system’s overall performance. Therefore, consider the module cost and the economic benefits of a system’s lifespan. Such comprehensive evaluations of system performance and cost are therefore of crucial importance.

The application of nanofluids in solar applications is attracting an increasing number of researchers due to their favourable characteristics in terms of high solar absorbance and good heat transfer performance [19]. Wang et al. [20] studied the impact of nanofluids' optical properties (viz., absorption rate and irradiance direction) on the thermal performance of a direct absorption solar collector. They found that the absorption capability of the nanofluids studied increased with the temperature and that the thermal efficiency of the bottom irradiation mode was 45% higher than that of side irradiation. Xu et al. [21] synthesized SiO_2-H_2O nanofluids for PV/T applications under different conditions and using different nanoparticle concentrations, and investigated the nanofluid dispersion stability and optical properties at high temperatures. The results showed that reducing the maximum sonication temperature during the nanofluid fabrication process was beneficial to prolonging nanofluid stability. The absorptance of the nanofluids decreased when the exposure temperature increased from 25 °C to 90 °C due to aggregation. Although nanofluids have many advantages, there are still significant challenges to overcome before replacing conventional fluids. Firstly, the high-volume fraction of nanoparticles inhibits heat transfer due to increased viscosity. Secondly, some negative aspects of metal-based nanofluids have been identified, such as their low physical and chemical stability, which affects their long-term performance in real applications. Thus, the heat transfer mechanism of nanofluids and challenges associated with their use in solar collectors need to be further studied.

State-of-the-art solar thermal and PV/T modules can simultaneously harvest solar as electricity and heat with high conversion efficiency. A prevailing challenge to be overcome in the future the research avitivies concerns the structural design and optimisation and selecting appropriate working fluids to minimise module cost and maximise the economic and environmental benefits that can arise from relevant systems over their life span.

2.2 Building integrated solar systems

To date, energy consumption in building is approximately 40% of the global energy supply [22]. At the same time, the total built environment has considerable untapped rooftop space, which could be used to harvest solar energy. This solution could also help reduce building energy consumption by providing shading. A popular and promising pathway in this context concerns the integration of solar systems with building envelops [23], such as with the use of techniques based on building integrated photovoltaic (BIPV) [24], building-integrated solar thermal (BIST) [25], and building integrated photovoltaic/thermal (BIPV/T) [26] technologies.

Yu et al. [27] conducted a review focused on BIPV/T developments, presenting and discussing their electrical and thermal performance and their impact on buildings' heating/cooling loads for various typical and novel designs proposed over the past two decades. The review indicated that BIPV/T systems provided high levels of total efficiency and a great potential to reduce the heating/cooling loads of HVAC systems. Therefore, they appear to be particularly promising solutions for reducing building energy consumption and leading the way towards developing low-energy and net-zero-carbon buildings. Mao et al. [28] experimentally and numerically investigated the heat transfer performance of a solar double-slope hollow glazed roof. The experimental results indicated that as the roof slope decreased, reducing the inner surface temperature of the top was relatively noticeable.

On the other hand, the numerical results showed that changing the thickness of the hollow roof layer had a more significant impact on the roof's heat transfer performance than changing the thickness of the roof glazing layer. Shakouri et al. [29] presented an energy analysis by simulating a building-integrated PV thermal double-skin façade. The study considered cooling/heating load reduction and power generation over one year. The results indicated that the suggested BIPV/T double-skin façade system had the capability of reducing annual cooling and thermal loads by 252 MWh and 18 MWh, respectively. The building-integrated solar systems can only be used as an auxiliary power source to supplement the electricity and heat consumption of the building (e.g. it is impossible to meet the total energy demand through building-integrated solar systems). In addition, the coupling between the demand-side and the supply-side in building energy consumption is an important challenge because of the mismatch between solar radiation and urban energy usage trends.

Another way to deploy solar energy technologies in buildings is the use of solar-assisted heat pumps. Such technology is a widely accepted alternative to traditional heating and cooling systems, which would pave the path towards electrification of the building heating and cooling. Badiei et al. [8] carried out a comprehensive review on technological advances and at scale implementations of solar-assisted technologies, which suggested integrating such systems into existing buildings is identified as a prevailing ongoing challenge. An open issue as a substantial degree of refurbishment measures in the host buildings might be necessary to achieve desirable efficiencies from the solar-assisted heat pump systems. Liu et al. [30] studied the performance of a novel solar/air-dual source heat pump system under various refrigerant flow rates and ratios of refrigerant. The research suggested that the refrigerant flow rate (related to the refrigerant charge) had a significant effect on the performance of the dual-source heat pumps, and an appropriate balance of refrigerant flowing into the solar collector or evaporator could improve the performance. Zhou [31] conducted a comprehensive thermal and energy performance analysis of a solar-driven desiccant cooling system. The simulation results indicated that the system could provide enough cooling and heating for more than 98% of working time in subtropical and temperate areas. Besides, the proposed system consumed 50% less electricity than the conventional method. Regarding this type of system configuration, it should be noted that a good coupling between the solar collector panels and the heat pump is needed, so to maximise energy efficiency. Therefore, a significant challenge is to solve the matching issues between all system components and control the running of the systems.

The above-reported state-of-the-art building-integrated solar systems provide high levels of total efficiency and great potential to reduce building energy consumption. Prevailing challenges to be overcome in the future concern solving the coupling between the demand-side and the supply-side in building energy consumption, solving the matching issues between all system components, and controlling the systems' operation.

2.3 Concentrating solar power

Concentrating solar power (CSP) has received significant attention among researchers, power-producing companies, and policymakers for dispatchable electricity generation. It can provide a means of overcoming the intermittency of the solar resource with onsite thermal energy storage [32]. There are four general types of CSP technologies according to the different optical concentration ratios: parabolic trough collectors (PTCs), linear Fresnel collectors (LFCs), solar power towers (SPTs), and parabolic dish collectors (PDCs).

The point-focus SPT system has received significant attention as it can achieve high working fluid temperature, provide high solar-to-electricity efficiency and employ thermal storage more readily [33]. For the typical SPT system configuration, the large heliostat field reflects sunlight to a solar receiver at the top of the centrally located tower, which heats the working fluid to a high temperature; subsequently, the heated fluid drives the conventional steam turbine to generate electricity. Hu et al. [34] present a mathematical model describing solar flux distribution on the surface of an external receiver based on ray-tracing and a convolution algorithm; subsequently, a comprehensive optimisation principle was proposed to optimise the optical efficiency of the heliostats field. It was found that the application of this principle increased the average optical efficiency by 2% during daytime and decreased the ratio of maximum solar flux to the minimum one from 8.6 to 7.8. Ying et al. [35] investigated molten salt's turbulent heat transfer performance with or without nanoparticles flowing in a circular tube under a non-uniform heat flux boundary. They found that the temperature profiles of the receiver tube wall showing the non-uniform characteristics were strongly related to the non-uniform cosine or Gaussian-cosine heat flux boundaries. Under both boundaries, the molten salt nanofluid significantly reduced the peak temperature of the tube wall's outer and inner heated surface compared with the pure molten salt. Fang et al. [36] investigated the thermal and mechanical performance of the superheated water/steam solar cavity receiver using an integrated simulation model. They concluded that the superheater had both the higher wall temperature and thermal stress, which was more crucial for the safe operation of the superheated water/steam solar cavity receiver.

Unlike other CSP technologies, the PDC system configuration is readily applicable in remote and small isolated grids. Besides, PDC systems have the highest concentration ratio, ranging from 1000 to 3000, one of the highest among all other CSP technologies. Due to the high concentration ratio, the PDC system can reach very high temperatures (800 °C) and achieve higher efficiency. In the PDC system, a parabolic point-focus concentrator in the form of a dish is used in a system that reflects solar radiation onto a receiver at the focal point. At the focal point, for efficient power conversion, a Stirling/Brayton engine is placed with an electrical generator to utilise the concentrated heat on the receiver. Bashir et al. [37] designed a solar dish-micro gas turbine system with the PCM-integrated solar receiver. They analysed the impact of the main parameters of the PCM on the performance of the solar receiver. The results showed that the latent heat had a significant effect on the thermal storage in the PCM. Conversely, thermal conductivity had a high impact on PCM's solidification/melting rate. Wang et al. [38] proposed a hybrid system of solar-microturbine with the combustion chamber, and its power output and efficiency were simulated for different working and weather conditions in Edmonton, Canada. The results showed that for a 30 m^2 dish collector aperture area, the cycle outlet power was estimated from 3.70 kW in winter to 9.87 kW in summer. In contrast, the lowest and the highest cycle efficiencies were 19.4% 35.1%, respectively, on sunny days.

CSP can generate bulk electricity, and many industrialised nations are investing heavily; PTC is the most technically and commercially proven among the different CSP technologies. It has a high maturity level and can provide the required operating heat energy at the lowest cost and lower economic risks. For this reason, this technology is dominant in operational and under-construction projects. However, currently, there is a trend toward employing the other CSP technologies in future projects because of the improvement in their performance. In particular, SPT technology is preferred for large-scale solar plants and is a competitor to PTC in producing low-cost electricity if the cost of heliostats and receivers decreases. PDC technology has the highest solar-to-electricity conversion efficiency and zero water consumption, but it is commercially unavailable because it is prohibitive.

The above-reported state-of-the-art concentrating solar power can overcome the intermittency of solar resources and realise large-scale continuous power generation. A prevailing challenge to be overcome in the future is improving the system's conversion efficiency while reducing its cost.

2.4 Solar thermochemistry

The thermochemical conversion process is based on employing solar radiant energy flow to drive the thermochemical redox cycles to convert solar energy into storable and transportable chemical energy [39]. Zhang et al. [40] numerically investigated the thermochemical reaction characteristics and their interactions in a porous catalytic material filled dry solar reforming of methane reactor. The results showed that increasing the heat flux of incident radiation contributed to improving CO_2 and CO conversion while, unfortunately, aggravating the carbon deposition in the front of the porous ceramic; meanwhile, increasing the inlet flow rate effectively alleviated this contradiction. From a practical point of view, sunlight usually enters the reactor after being concentrated because solar irradiance has low energy intensity in the range of 300-1000 W/m^2 [41]; thus, it is necessary to analyse high-flux solar irradiation distribution characteristics for a solar thermochemical energy storage. Jiang et al. [42] studied the design method of a solar simulator with Fresnel lens from concentrating solar energy research, high-temperature material testing, and optimal design method of reactor receiving surface. The numerical calculations helped obtain the suitable installation conditions of the multi-disc simulator and reactor temperature distribution. The system designed by the proposed method could meet the needs of the high-temperature solar thermal and thermochemical applications, especially where there is a strict requirement for the shape or uniformity of the spot.

High temperature solar thermochemical processes for fuels and chemical commodities production have been studied for decades, proving their feasibility. However, industrial deployment is limited. One of the main reasons is that the variability of solar energy hinders a priori day and night continuous solar process operation. Besides, it is challenging to consider high-temperature-resistant materials, energy storage materials, design, control, and dynamic simulation of the reactor system in future work.

As mentioned above, state-of-the-art solar thermochemistry can realise solar energy conversion into storable and transportable chemical energy, and its feasibility is now proven. A prevailing future challenge involves overcoming the variability of solar energy to realise the industrial deployment of solar thermochemistry.

2.5 Solar-driven water distillation

Solar stills are the most frequently used desalination systems due to their low cost of water production and the feasibility of use in most climates, and being environmentally friendly, that feature simple construction, low installation, maintenance cost, and long-life operation [43]. However, solar stills are characterized by low productivity, and possible modifications, top tackle this issue have been made to enlarge their productivity. Fallahzadeh et al. [44] studied the effect of a closed-loop pulsating heat pipe and a bubble injection system on the performance of a portable solar still. The experiment results indicated that the daily productivity of the studied solar still was obtained 2,240 mL/m^2, and the production cost of one litre of water was acceptable compared to the other works. Hong et al. [45] proposed a folded structure to increase the light-to-heat conversion efficiency of the solar-driven evaporating cones. The results indicated that the solar conversion efficiency of the cone with 32 folds reached 83.9% under one sun illumination, higher than the plane cone. Their study showed that the rational design of the 3-D cone was a successful attempt to promote the development of high-efficiency photothermal materials. Many models have been proposed for predicting the solar stills' performance, such as numerical methods, regression models, and machine learning models. Wang et al. [46] established four machine learning models and a traditional multilinear regression model to forecast tubular solar still hourly production. The results indicated that the machine learning models can accurately simulate tubular solar still compared with the complex experimental requirements. In general, the performance and water generation of a solar still is affected by the temperature difference between water and glass; increased water temperature augments the water evaporation, and decreased glass temperature increases water productivity. Thus, the current and future challenges of solar distillations are mainly these two aspects.

Solar-driven water distillation can solve the lack of fresh water in remote areas or arid regions, but it achieves low productivity. Prevailing challenges to be overcome in the future are optimising system design, raising the water temperature, and lowering glass temperature to improve water productivity.

2.6 Solar thermal energy storage

The variation of solar radiation over time due to weather impedes the efficient utilisation of solar energy, in which the heat demand and supply are mismatched. Thermal energy storage (TES) is a peculiar technical solution to decoupling the demand-side from the supply-side in different time scales, storing solar energy and reutilising it at other times and places [47]. There are three main types of TES: sensible heat storage, latent heat storage, and chemical heat storage [48]. Compared with sensible heat storage, latent heat storage has a higher capacity and a more stable heat release temperature. The reason is that latent heat storage uses the latent heat of phase change materials (PCMs) to store heat instead of depending on the materials' specific heat capacity and temperature. Cheng et al. [49] fabricated a shape-stabilized reduced graphene oxide sponge-based phase change composite with reduced graphene oxide decorated melamine sponge as a support and paraffin wax as a filler. Compared with the pure sponge, the anti-leakage ability of the composite showed significant improvements. The reduced graphene oxide also gave the prepared phase change composites good solar absorption efficiencies of 95%. A solar-driven thermoelectricity experiment showed that the thermal energy was stored in the phase change materials and released over an extended period. The open-circuit voltage reached 1.30 V.

Although PCMs are widely used in the solar thermal collection, their application is limited due to poor heat transfer, substantial heat losses, and super-cooling [48]. Compared with the previous method, chemical heat storage is a more promising method that stores thermal energy based on physical or chemical bonding principles using a binary working pair. It has the advantages of high energy density, low heat loss, and good storage operation repeatability [50]. Recently, to improve the energy storage density of absorption thermal storage systems, different new cycles, system configurations, and working pairs have been investigated by researchers [48]. Mehari et al. [51] proposed a multi-functional three-phase sorption TES cycle to simultaneously achieve higher temperature lift and energy storage density. Different applications could be completed in this cycle, including interseasonal heating, combined cooling and heating in summer, and heat transformer in summer and winter. Results showed that the multi-functional three-phase sorption TES cycles obtained a temperature lift of 65 °C and an energy storage density up to 1.3 kWh/kg, which cannot be realised with a conventional three-phase process. Moreover, combined cold and heat storage at 15 °C and 60 °C, respectively, and discharging temperatures above 100 °C were achieved. A more comprehensive range of applications could be expected for three-phase sorption TES with these proposed cycles.

The application of TES in the solar field can help alleviate intermittent problems and smooth out fluctuations in energy demand at different times of the day. The main focus areas in TES are the cost reduction of storage material, improvement in energy storage efficiency, and improvement of thermal conductivity. The technologies are mature and already commercialised for sensible and latent heat storage materials, but thermochemical materials are still at the lab stage. Thermochemical materials have great potential as TES materials in the future due to their highest volumetric energy storage capacity.

The above-reported state-of-the-art solar thermal energy storage can store solar energy and reutilise it at other times and places. It can solve the intermittency problem of solar radiation. A prevailing challenge to be overcome in the future is to accelerate the industrialisation progress of thermochemical materials due to their highest volumetric energy storage capacity compared with sensible and latent heat storage materials.

3. Vision

Solar energy utilisation is one of the most promising avenues for addressing the world's energy and environmental problems because of its many advantages, including its abundant and convenient availability, and its pollution-free and sustainable nature. PV panels and solar hot-water heaters are currently the most commercialized solar energy technologies, with significant global markets. However, some inherent shortcomings of solar energy, such as its low energy density, intermittency, and cost issues, are acting to limit the development and further global penetration of these technologies. Key challenges that motivate future research activities include: (1) development of innovative materials and fluids, such as heat transfer media and PV cells, to reduce the cost of solar energy utilization systems; (2) acceleration and refinement of installation and manufacturing process, to improve the reliability of such systems and extend the service life; (3) coupling with other clean energy production and storage systems for better energy resource utilization; (4) development of policies and strategic local, national and international planning to promote clean and sustainable energy use, carbon neutrality and the development, specifically, of solar energy solutions, along with the integration of solar energy with local energy use patterns; and (5) according to the characteristics of natural resources and land use in different regions, vigorously develop CSP technologies in desert areas, complementary technologies for fishing and power generation on rivers, and complementary technologies for agriculture and power generation on agricultural lands to improve the comprehensive and effective utilization of solar energy.

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