Sunlight Harvesting

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REVISED VERSION

December 6, 2022

Submitted for publication in the special issue of *Computers & Chemical Engineering* titled Sustainable Energy: Status and Open Challenges

Key Words: renewable energy, solar cells, solar energy, photovoltaics, solar heating, integrated systems

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Abstract

Solar energy has been an attractive source of renewable energy because of its enormous magnitude and availability everywhere on Earth. The nature has been capturing and storing it on Earth in the form of chemical energy via photosynthesis. Over millenniums, humans have used their creativity to harvest the energy. The creativity has evolved significantly in the past two decades, leading to major advances in solar technologies that have reduced the cost of solar power by more than 70% for the last ten years. These advances together with the public concern about the environmental consequences of using fossil fuels point to the shiny future of solar technologies. This article reviews advances in active solar technologies including photovoltaics, concentrated solar and solar heating, and put them into perspective. The pros and cons as well as the prospect of each technology are discussed.

1. Introduction

The solar energy that reaches the earth includes 50% visible light and 47% infrared [1] . The earth receives solar energy at a total rate of about 1.08×10^8 GW, which amounts to a total annual energy of 3.41×10^{15} GJ. The annual global energy consumption is estimated to be about 5.80×10^{11} GJ in 2022, which is about 13.86 billion tons of oil equivalents [one ton of oil equivalent (toe) = 41.9 GJ [2]]. Thus, the solar energy that reaches the earth annually is between 5,000 and 6,000 times the primary energy that is to be consumed globally in 2022. If 0.1% of the solar energy is transformed into electricity with 8% efficiency, about 8,000 GW of electricity is generated, which is the forecasted total global electricity generation capacity in 2025 [3].

The U.S. Energy Information Administration has forecasted that the total world energy consumption will increase to 2,5000 GW in 2040 [4]. This increase is a consequence of the global population growth, improvement in the standard of living in many countries, and the rapid industrial growth in numerous countries such as India and China. Fossil fuels are expected to maintain their dominance at least until 2040. However, this dominance cannot continue forever, as (a) the currently proven natural gas and petroleum reserves will finish within 50–60 years, if they are consumed at the current rate [5]; and (b) emissions from the use of fossil fuels are known to severely impact the environment and cause global warming [6].

The need for energy sources other than fossil fuels has driven the allocation of enormous amounts of efforts and resources to improve renewable energy technologies, including solar, geothermal, wind, biomass, tide, hydropower, and sea waves. Among these, solar technologies have the greatest potential because the amount of solar energy reaching Earth is much more than those of all the other renewables resources combined [7]. A major challenge has been to find solar technologies that are cost-effective, versatilely adaptable, and easily deployable [8]. As emerging-market countries do not have large-scale power grid systems, there is a need for large-scale affordable efficient power storage systems that allow for local storage of the generated power and thus for continuous availability of locally-generated power [9]. Thus, advances should be made in solar and power storage technologies simultaneously to realize the economic local generation and storage of electricity.

Solar energy is intermittent, and the rate at which it reaches a location on Earth is dependent on weather conditions including solar irradiation, rainfall, climate temperature, air density, and seasonal changes at the location [10]. The rate also depends on the geographical topography such as terrain, altitude and latitude, and air conditions such as the level of smog and the degree of cloudiness [11].

Solar energy harvesting technologies are generally divided into active and passive. This division is based on how a technology captures and distributes solar energy or converts solar energy into another type of energy that can be used or stored directly. Active solar technologies transform the sunlight (solar energy) to electrical, thermal, or chemical energy that can be utilized directly and/or can be stored. Examples of active solar techniques are photovoltaic systems [8, 12], concentrated solar power [13], and solar water heating [14]. Photovoltaics achieve solar energy conversion to electricity, and photosynthesizers (e.g., plants and algae) conversion to chemical energy in the form of carbon-carbon bonds (Figure 1). We would like to coin the term "photothermals" for the solar technologies that achieve the conversion to thermal energy. Examples of passive solar technologies are buildings oriented optimally to the sun [15], materials with attractive light-dispersing or thermal mass properties [16-19], and building architectures that naturally circulate air [20-21].

The efficiency of solar energy harvesting can be improved by using a combination of solar energy harvesting technologies. For example, the power conversion efficiency of photovoltaics (PVs) is still low (15–20%) partly due to the reflection of a fraction of the solar radiation back from their surface. However, when a solar thermal collector (STC) — which can convert the reflected radiation into thermal energy — is used in combination with a PV, the combined system will have a higher conversion efficiency than the stand-alone PV and STC. The thermal energy that the STC generates can be transferred to a working fluid such as air or water, which can then be used directly for space heating/cooling and water heating, or can be stored for when there is a demand for heating or cooling. Furthermore, a PV-STC system can be combined with heat pumps to provide more than 60% of the heating that urban households need[22].

This article reviews active solar technologies and put them into perspective. The pros and cons as well as the prospect of each technology are discussed. Sections 2 discusses the technologies that convert sunlight to electricity. Section 3 reviews the technologies that convert sunlight to thermal energy, including thermal collectors, concentrated solar power systems, solar water heaters, solar assisted heat pumps, solar assisted air conditioning, solar assisted refrigeration, solar cooking, industrial heating, and solar district heating and cooling. Sections 4 focuses on the use of solar energy in built environments and industrial processes including agriculture and water treatment. Section 5 concentrates on the technologies that make use of sunlight in the production

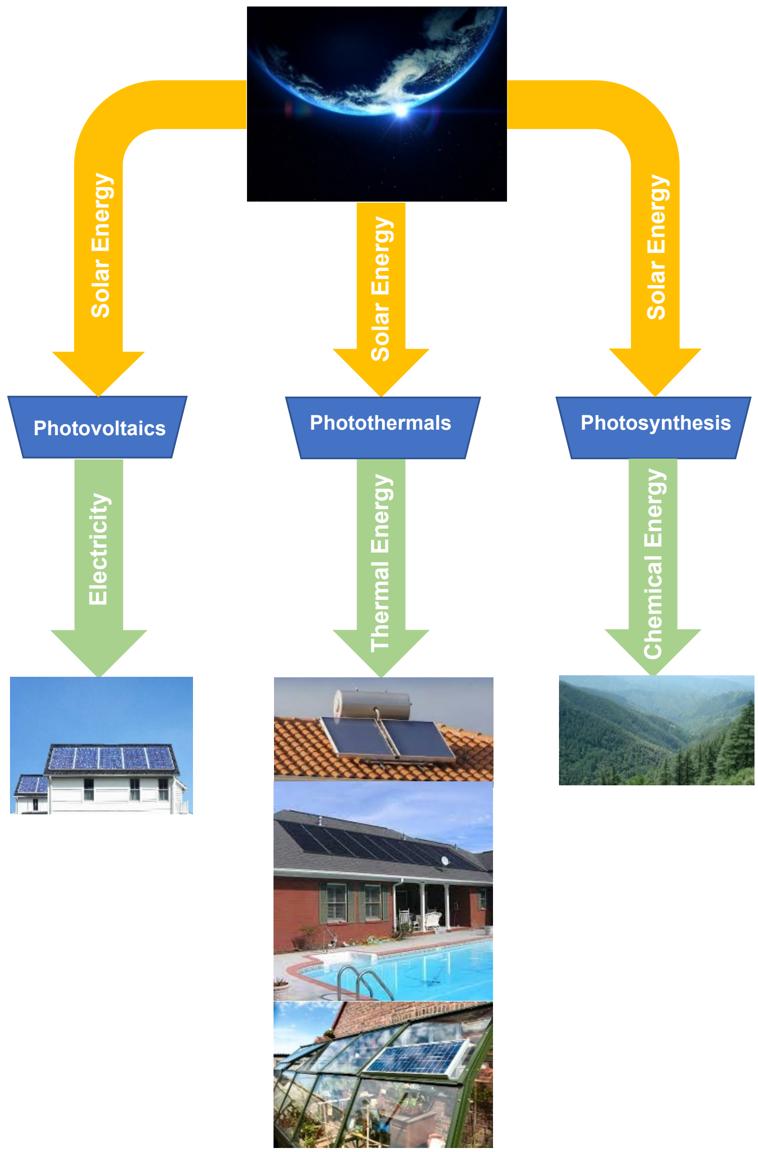

Figure 1. Solar energy conversion methods.

of chemicals including hydrogen. Section 6 discusses solar energy technologies limitations, challenges, and future research opportunities, and also provides some concluding remarks.

2. Conversion of Sunlight to Electricity

This section reviews the solar technologies that convert sunlight to electrical energy. Electricity is generated from sunlight directly using a PV, or indirectly by means of a concentrated solar power

(CSP) technology. As sunlight is available everywhere on Earth, PV and CSP systems can generate electricity locally at any place on Earth. The generated electricity can then be consumed or stored locally, or transmitted via electric grids. A PV produces electricity directly from sunlight by means of the photoelectric effect. However, a CSP system produces a concentrated ray from a large area of sunlight using lenses or mirrors and a tracking system, and it then converts the energy of the ray to electricity directly or indirectly.

2.1. Photovoltaics

The global photovoltaic market is forecasted to grow from US$ 54B in 2018 to US$ 334B by 2026 [23]. Thin film technologies dominated the market in 2018 and are forecasted to maintain this dominance (Figure 2) [23]. The industrial sector was the dominant consumer for PV technologies and is projected to continue this dominance (Figure 3) [23]. Currently most of commercial PVs are still silicon-based. However, in recent years attempts have been made to develop new technologies that are less expensive and more efficient, durable and flexible [24-25]. The new technologies include

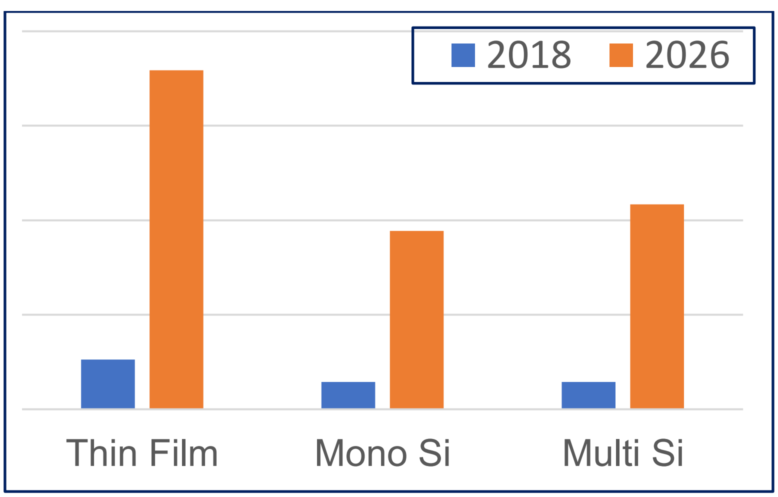

Figure 2. Global PV market, by technology.

Credit: Data from Allied Market Research. Photovoltaic Market by Technology (Thin Film, Mono Si and Multi Si), System (High Concentration Photovoltaic (HCPV) and Low Concentration Photovoltaic (LCPV)), and Application (Industrial, Residential and Commercial): Global Opportunity Analysis and UIndustry Forecast, 2019-2026. https://www.alliedmarketresearch.com/photovoltaic-market solar cells that are based on organometallic perovskites, thin films, quantum dots, oxides nanoparticles sensitized with dye, polymers, extremely thin absorbers, and silicon [26-32].

In every solar cell, major processes are adsorption of photons, generation of excitons, transport of electrons and holes, and recombination. The overall performance including the power conversion efficiency (PCE) of a solar cell depends on the contributions and efficiencies of these individual processes. Research studies are currently being performed to improve minority carrier lifetimes, charge mobility, and photon absorption (which ultimately lead to improvement of PCE of solar cells), as well as cost reduction [8]. Figure 4 shows the PCEs of different research-solar cells reported until 2021 [33]. As can be seen, the PCE of every type of solar cells has increased with time, and a four-junction solar cell solar cell (manufactured by NREL in 2020) with the highest PCE of 47.1% has been reported. The solar cell with the next highest PCE of 46.1% is also a four-junction solar cell solar cell but manufactured by Fraunhofer Institute for Solar Energy [ISE] in Denmark

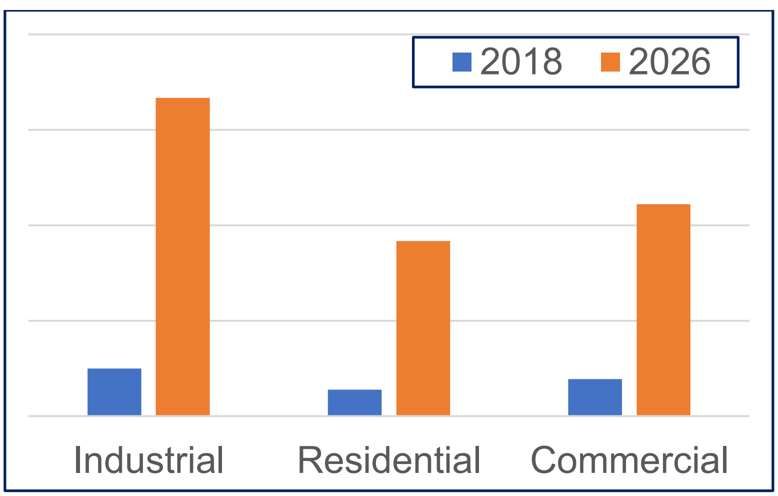

Figure 3. Global PV market, by application.

Credit: Data from Allied Market Research. Photovoltaic Market by Technology (Thin Film, Mono Si and Multi Si), System (High Concentration Photovoltaic (HCPV) and Low Concentration Photovoltaic (LCPV)), and Application (Industrial, Residential and Commercial): Global Opportunity Analysis and UIndustry Forecast, 2019-2026. https://www.alliedmarketresearch.com/photovoltaic-market in 2016. Indeed, Fraunhofer ISE holds several other solar cell PCE world records, such as 26% PCE for a both-sides contacted silicon solar cell [34]. Table 1 compares several types of solar cells in terms of cell efficiency, module efficiency, cost per watt, and thickness[35].

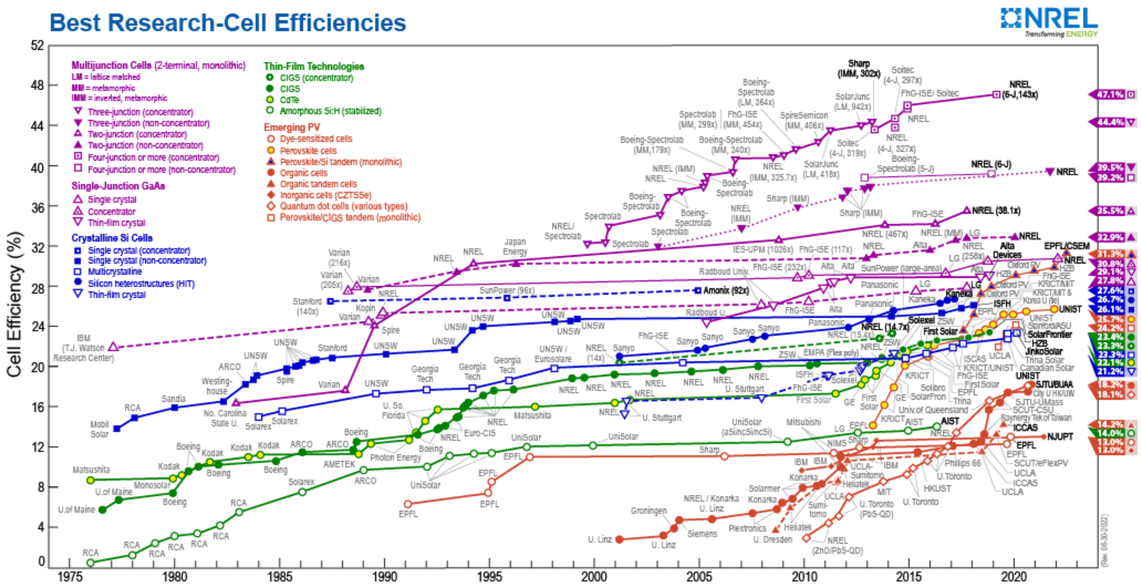

Figure 4. Best research-cell efficiencies.

Credit: Image from Best Research-Cell Efficiency Chart. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/pv/cell-efficiency.html

Table 1. Comparison of several types of solar cells based on four criteria.
Credit: Adapted from Dhilipan, J.; Vijayalakshmi, N.; Shanmugam, D.; Ganesh, R. J.; Kodeeswaran, S.; Muralidharan, S., Performance and efficiency of different types of solar cell material–A review. Materials Today: Proceedings 2022, 62, 1295-1302.

Cell Type	**Cell efficiency %**	**Module efficiency %**	**Cost/watt (US$/w)**	**Thickness**
1st generation: wafer based				
Mono crystalline silicon	26.1	24.4	0.50–0.58	0.3 mm
Poly crystalline silicon	22.3	19.9	0.34–0.43	200 µm
2nd generation: thin film				
Amorphous silicon	13.6		0.37–0.43	0.2–0.5 µm
CdTe	22.1	18.6	0.42–0.49	80–100 nm
CIGS	22.9	19.2	0.39–0.43	0.5 µm
3rd generation: emerging				
Polymer PV	23.3		0.33–0.39	200–400 nm
Perovskite	46.0		0.44–0.47	500 nm

Commercialized solar cells/panels. PCEs of commercially available photovoltaics are around 14–22% [36-37]. PCEs of amorphous silicon-based solar cells are only around 6%. The US-based Alta Devices, Inc. manufactured a single-junction thin-film gallium arsenide (GaAs) solar cell with a PCE of 27.6% [38]. Kayes *et al.* used the same technology platform and fabricated a series-connected, two-junction device with PCEs up to 30.8% [39]. Their work demonstrated the potential of multijunction architectures for achieving higher PCEs. Yu *et al*. [40] fabricated a tandem that coupled a (concentrating) silicon PVMirror with a gallium arsenide receiver. Their device showed a PCE of 29.6% under the outdoor global irradiance. While the PCE of amorphous silicon-based solar cells is about 6%, SunPower Corporation [41] reported that an improved version of its SunPower X-Series technology with a total area efficiency of over 25% well above the 14–19% efficiency of current commercial multicrystalline silicon solar cells.

Solar cells at the research stage. GaAs, CdTe, CIGSe, Si, and perovskite single-junction solar cells with efficiencies of 29.1%, 26.7%, 23.4%, 22.1%, and 21.6%, respectively, have been reported (Figure 4). Single-junction solar cells can gain AM1.5 efficiencies of up to 30%–32%. Stacking solar cell materials with different bandgaps allows for absorbing a wider range of solar spectrum wave length, thus allowing for further increases in PCEs of solar cells [42]. PCEs up to 44.0% have been reported for multiple-junction production cells and up to 47.1% for multiple dies assembled into a hybrid package [33-34, 43].

Among PV systems, perovskite-based (PSCs)[44] and dye-sensitized solar cells (DSSCs) [45] seem to have the highest potential. The production costs of DSSCs are less than those of solar cells made from silicon, and DSSCs can be fabricated from a larger set of materials [46]. Cell efficiencies of more than 14% have been reported for DSSCs [47]. Furthermore, DSSCs can operate under indoor lighting, allowing their use in applications other than rooftop installations; they have shown to have a PCE of 28.9% under indoor lighting and 11.3% under complete sunlight [48]. PSCs are also a promising photovoltaic technology due to their appealing perovskite material that has high charge carrier mobility, high light-absorption coefficient, extended minority-carrier lifetime, and tunable band gaps. PSCs with PCEs up to 26.1% have been reported (Figure 4) [33, 44, 49].

As shown in Figure 5a, a DSSC has a sandwich design; it consists of three main layers: a mesoporous TiO_2 photoanode, an electrolyte, and a cathode. The electrolyte is usually an organic liquid comprised of an iodide/triiodide redox couple. Other types of electrolytes such as polymer electrolytes, hole transport materials, and ionic liquids have also been utilized [50-52]. The fabrication involves coating a photoanode on a transparent conducting oxide (TCO) layer, which is usually fluorine-doped tin oxide (FTO) glass [53]. A single layer of a ruthenium dye is often used to synthesize the TiO_2 photoanode [54]. A hole transport material, an electrolyte, is placed between the platinized TCO cathode and the photoanode. It contains the iodide/triiodide redox couple. Visible

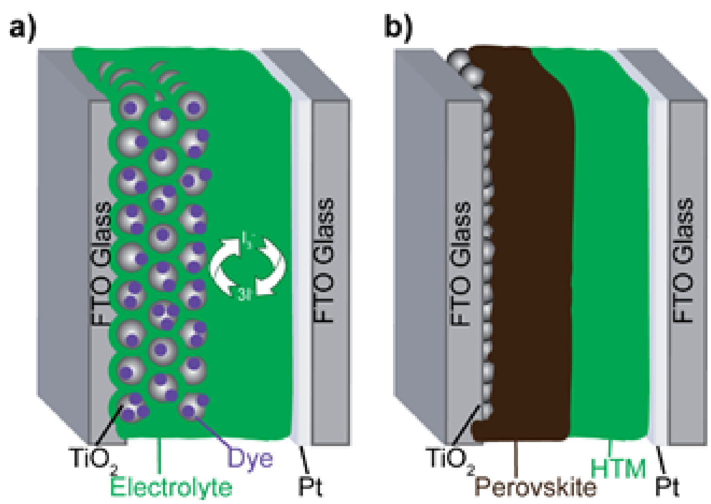

Figure 5. Schematics of a DSSC and a PSC.

light photoexcites the dye. The dye then supplies the TiO_2 layer with electrons, which go through the TiO_2 photoanode, the FTO, an external load, and the cathode, and finally return to the electrolyte. The electrolyte transfers the electrons to the photoanode, allowing the regeneration of the dye. The design of a PSC is similar to that of a DSSC, as depicted in Figure 5b. A thin film of compact TiO_2 is coated on FTO glass to hinder recombination. The perovskite material is placed on top of this layer; it absorbs photons and offers a path for the transport of electrons. A hole transport material is then positioned above the perovskite layer.

2.2. **Concentrator photovoltaics**

The main idea in concentrated PVs is to concentrate a significant amount of solar energy to a tiny zone where there is a PV solar cell. Large lens and/or curved mirrors are used to concentrate solar energy. The concentrated sunlight also generates a substantial amount of thermal energy, which can be converted to more electricity using conventional methods of conversion of heat to electricity [55]. Figure 6 [55] depicts a system that reflects and focuses sunlight on a solar cell receiver. It directs the infrared reflected from the receiver to a fiber-optics light pipe that transports light to a high-temperature solid-oxide electrolysis cell, which uses both solar heat and electricity to split water. Concentrator PVs have been found to be promising due to their advantages such as efficiencies > 40%, absence of any moving parts, no thermal mass, ease of scalability, and speedy response time. There are highly efficient, multi-junction concentrator PVs. Adding a solar tracker and a cooling system to concentrator PVs further increases their efficiency.

2.3. Solar trackers

Energy is transmitted from the sun to Earth via radiation. As such, the rate of the solar energy that a solar panel receives depends on the angle at which the light ray hits the surface of the solar panel; the rate is maximum when the surface of the panel is perpendicular to the incident light ray [56]. A

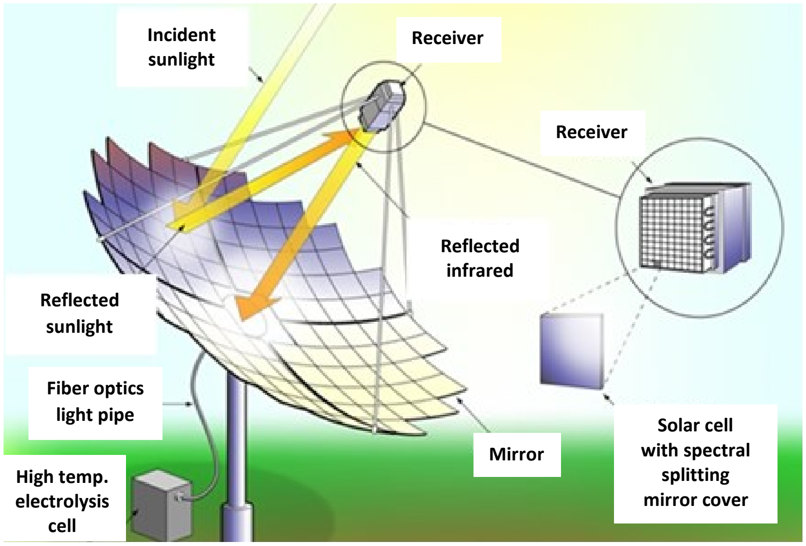

Figure 6. Schematic of a system that uses reflective concentrator PVs and high-temperature electrolysis to generate hydrogen.

Credit: Image from Thompson, J R, McConnell, R D, and Mosleh, M. Cost Analysis of a Concentrator Photovoltaic Hydrogen Production System. United States: N. p., 2005. Web. Copyright permission from the publisher.

solar tracking system can be used to continuously maintain the panel surface perpendicular to the light ray as long as sun is in the sky [57], thus maximizing the conversion of sunlight to electricity. Many different solar tracking systems have been proposed and used to track the position of the sun. Like every control system, they include a sensor (in this case, a light sensor), an actuator, and a controller. The light sensor can be a light dependent resistor or two phototransistors covered with a small plate [57].

2.4. Temperature sensitivity

The temperature at which a solar cell operates affects the performance of the cell. Common performance measures are open-circuit voltage (OCV), fill factor (FF), PCE, and short-circuit current (SCC). For example, the PCE, FF, and output power of a crystalline silicon solar cell have been reported to decrease by 0.08 %/K, 0.2 %/K, and 0.65 %/K, respectively, at temperatures up to 80 °C [58]. An experimental investigation found that in multi-crystalline silicon solar cells, factors such as the base net doping and the cell architecture strongly impact the sensitivity of the performance measures to temperature variations. Figure 7a shows the variation of the P-V and I-V curves of a mono-Si solar cell with cell temperature [59]. The investigation reported that lowering the bulk resistivity can enhance solar cell performance in hot environments. The temperature sensitivity of PSCs has been attributed to the bandgaps of their semiconductor materials [60]. Figure 7b depicts the temperature coefficients and detailed balance efficiencies of several PSCs[61]. photovoltaics at 290 K PSC[62]. There are different losses that limit the efficiency of current commercial cells. A major fraction of the losses occurs at junctions. The sensitivity of OCV to temperature is related to the tradeoff between recombination and generation of carriers and the dependence of this competition on temperature. The sensitivity of SCC to temperature is due to the dependence of the

DSSCs are more temperature sensitive than conventional Si-based solar cells [63]. Taki *et al.* [63] reported that DSSCs with palladacyclic complexes as sensitizers are more durable. Their DSSC with a mono-nuclear complex showed a 20% drop in SCC at 130 ± 5 °C, and their DSSC with di-nuclear complex exhibited the same drop in SCC at 93 ± 2 °C. Their DSSC with N719 as the dye showed the same level of decrease in SCC at 71 ± 5 °C and in OCV at 147 ± 3 °C. Figure 7c shows how SCC density, OCV, FF, and PCE of a bare DSSC and a DSSC coupled with a low concentrating photovoltaic under an illumination of 1000 W/m^2, vary with temperature [64]. A PV panel has a higher efficiency on water than on land, as its operating temperature is lower when it is floating. Another benefit of a floating solar cell is that it hinders water evaporation.

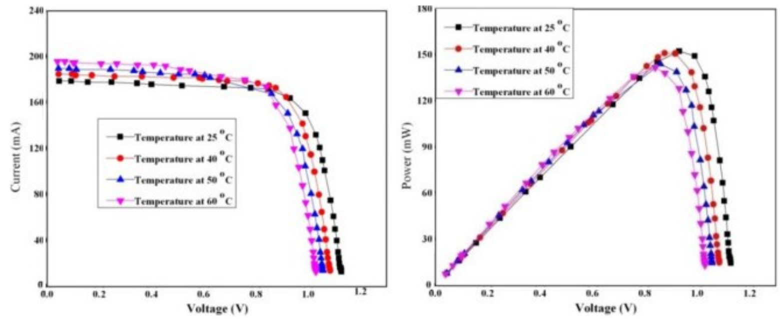

Figure 7a. Polarization and power curves of a mono-Si solar cell at different cell temperatures.
Credit: Image from Chander, S.; Purohit, A.; Sharma, A.; Nehra, S.; Dhaka, M., Impact of temperature on performance of series and parallel connected mono-crystalline silicon solar cells. Energy Reports 2015, 1, 175-180. Copyright permission from the publisher.

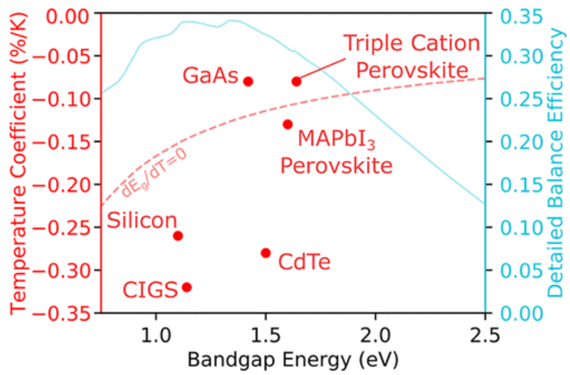

Figure 7b. Temperature coefficients and detailed balance efficiencies of several PSCs at 290 K.
Credit: Image from Moot, T.; Patel, J. B.; McAndrews, G.; Wolf, E. J.; Morales, D.; Gould, I. E.; Rosales, B. A.; Boyd, C. C.; Wheeler, L. M.; Parilla, P. A., Temperature coefficients of perovskite photovoltaics for energy yield calculations. ACS Energy Letters **2021,** 6 (5), 2038-2047. Copyright permission from the publisher.

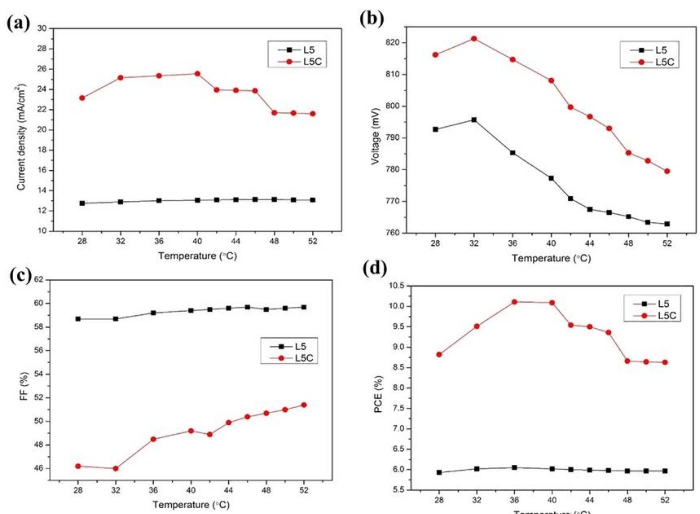

Figure 7c. Temperature dependence of the SCC density, OCV, FF, and PCE of a bare DSSC (L5) and a DSSC coupled with a low concentrating photovoltaic (L5C).
Credit: Image from Selvaraj, P.; Baig, H.; Mallick, T. K.; Siviter, J.; Montecucco, A.; Li, W.; Paul, M.; Sweet, T.; Gao, M.; Knox, A. R., Enhancing the efficiency of transparent dye-sensitized solar cells using concentrated light. Solar Energy Materials and Solar Cells 2018, 175, 29-34. Copyright permission from the publisher.

2.5. Environmental costs of manufacturing solar cells

PV systems are environmentally friendly in the sense that their conversion of sunlight into electricity does not pollute the environment. However, not all current processes that produce the cells and the materials that are used in solar cells are environmentally friendly [65]. For example, lead toxicity has been recognized as a major barrier to the commercialization of PSCs [66]. In recent years, attempts have been made to minimize the environmental impacts of the materials that are utilized in solar cells and the processes that manufacture them. As a result of these efforts, materials are being utilized more efficiently in the fabrication of these systems, and the overall performance of PV systems has improved.

In addition to environmental impacts of manufacturing and using PV systems, their economic impacts should be evaluated as well. Life cycle assessment allows for considering all these aspects of PVs. Measures such as energy pay-back time (EPBT), carbon dioxide equivalents per kWh, net energy gain (NEG), and energy return on energy invested (ERoEI)] [also called the energy return on investment (EROI) have been introduced and used to conduct the LCA. EPBT is the amount of time that an energy system should operate to produce the same amount of energy that had been consumed to manufacture the energy system. NEG is the net energy gained in an

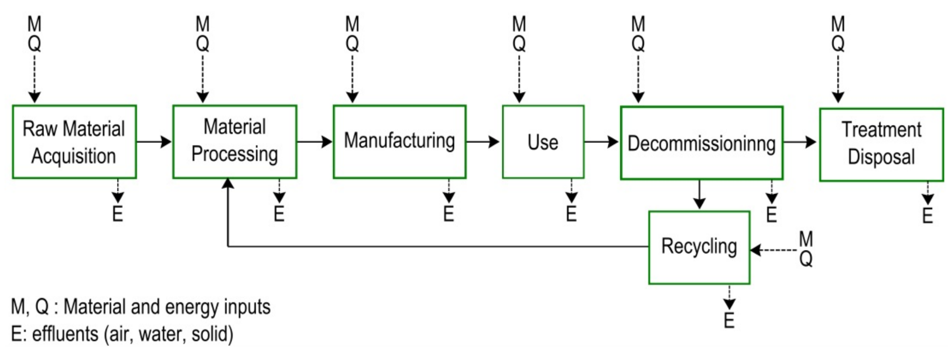

Figure 8. LCA of photovoltaic systems.
Credit: Image from McConnell, R.; Fthenakis, V.; Fthenakis, V., Concentrated photovoltaics. Third Generation Photovoltaics 2012, 167-182. Copyright permission from the publisher.

energy harvest (i.e., energy produced minus energy consumed). EROI is the total amount of usable energy generated by a system during it lifetime, divided by the sum of all energies consumed to generate the usable energy. The LCA should be applied to every solar cell technology to consider direct costs, resource availability, and environmental impacts in a unified framework, as three aspects are closely related [67]. Figure 8 depicts typical steps in the LCA of photovoltaic systems [68]. LCA was performed on high-concentration PV systems [69]. Using measured field data, the team evaluated the usage of land and water, the energy payback times of the systems, and life cycle greenhouse gas emissions, [69]. They reported that high-concentration PV systems have considerably higher maintenance costs, but their environmental liability over an entire life cycle is considerably less, compared to those of c-Si (flat-plate) devices installed in the same regions of elevated insolation. They reported that an Amonix 7700 PV system operating in Phoenix, AZ would generate 27 g CO_2-eq./kWh over 30 years, while the energy payback time would be 0.9 year.

2.6. Process systems engineering opportunities

As interfaces play a major role in both DSSCs and PSCs[70], better understanding of how interfacial processes and surfaces affect cell performance is needed. Specifically, good understanding of the interdependences and synergetic effects among device components and processes will advance these technologies. Multiscale mathematical modeling in concert with experimentation can provide the needed understanding[71]. Mathematical modeling will also enable model-based optimization of solar cell design, operation, and integration with other energy generation systems, power grids, and storage systems[31, 72-77]. The smooth and optimal operation of solar cell panels integrated with power storage systems and power grids requires automation and control[78-81].

3. Conversion of Sunlight to Thermal Energy

This section reviews the solar technologies that convert sunlight to thermal energy. These technologies include photovoltaic thermal collectors, concentrated solar power, solar water heating, solar-assisted heat pumps, solar-assisted air conditioning, solar-assisted refrigeration, solar cooking, industrial heat process, and solar district heating and cooling.

3.1. Photovoltaic thermal collectors

Photovoltaic thermal (PVT) collectors — also called photovoltaic thermal solar collectors, hybrid solar collectors, and solar cogeneration technology — convert solar radiation to electrical and thermal energies. A PVT collector consists of PV solar cells with an STC (Figure 9). The STC transfers untapped waste heat from the PV module to a heat transfer fluid. This combination of electric and thermal energy generation within one component enables the achievement of overall efficiencies higher than those of the PV and the STC alone. Such a combined system can provide about 50% of the cooling and more than 60% of the heating demands in domestic applications [22].

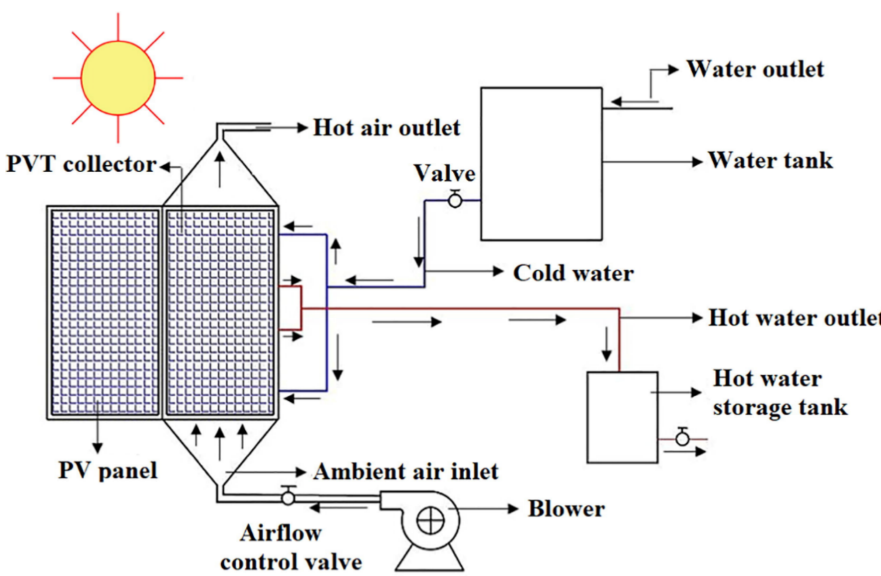

Figure 9. Schematic of a solar-thermal energy system.
Credit: Image from Navakrishnan, S.; Vengadesan, E.; Senthil, R.; Dhanalakshmi, S., An experimental study on simultaneous electricity and heat production from solar PV with thermal energy storage. Energy Conversion and Management 2021, 245, 114614. Copyright permission from the publisher.

PVT collectors are categorized based on their structure or working fluid. Table 2 compares different PVT systems. Water-type PVTs have higher performances because of the higher heat capacity of water compared to air. The design and operation of PVT collector integrated systems strongly affect the thermal and electrical performances of the systems. If water-tube absorbers of the systems are designed optimally, the electrical and thermal efficiencies of the systems can reach ~12%, and 50.1%, respectively [82]. The two performances cannot be maximized at the same time, as they are competing measures. The capital cost of a PVT system includes the costs of its PVT module, the system balance (all components of the PVT system other than the photovoltaic panels), and water storage tank.

Table 2. Comparison of different PVT systems.

Credit: Adapted from Joshi, S. S.; Dhoble, A. S., Photovoltaic-Thermal systems (PVT): Technology review and future trends. Renewable and Sustainable Energy Reviews 2018, 92, 848-882. Copyright permission from the publisher.

PVT	Main advantages	Main disadvantages	Potential uses	Future opportunities
Water-based	• Mature technology • Simple operation • Application flexibility • Many choices for the heat transfer liquid • Availability of working medium (water)	• Water freezing in low temperature geographies • Tedlar absorber may rust • Hard to clean water cooling channels • Power consumption of auxiliary equipment • Power consumption of pump • Shorter lifetime • Higher weight to surface area ratio • Harder to track sun • Corrosion and leakage issues	• Space heating • Domestic water heating • Laundry. • Pool heating • Desalination • Feed water preheater for power cycles	• Improved thermal absorber designs to enhance efficiency • Improved heat transfer in the channels • Use of alternative heat transfer liquids • Large scale installation • Adaptation and design of ancillary equipment for use of PVT at high temperature locations
Air-based	• Mature technology • More compact • Free and abundant working medium (air) • Can be used with a BIPVT system • Minimal corrosion issues	• Blowers / fans are essential for air movement management • Air low heat capacity • Limited use	• Solar Dryers • Space heating • Industrial process heating	• Multi inlet air flow duct needed • The air side heat transfer coefficient needs to be improved • Natural ventilation need assessment to avoid the use of blowers or fans • Roof integration for BIPVT systems

				• PVT evaluation when exposed to high doses of sunlight • PVT installation at scale
PCM-based	• Good performance • Can work in the absence of sunlight • Variety of commercial PCMs are available	• Unmature technology • High costs are associated with PCMs	• Same as PVT systems based on water • Thermal storage in many applications	• Better heat conductivity of PCMs • Development of new PCM and PCM based packaging • Feasibility of PCM-based systems under long periods of sunlight
Heat pipe-based	• Mature heat pipe technology • PVT systems show improved thermal performance • PV module has no direct contact with a coolant • Corrosion free • Works in wide temperature ranges	• Not a well evaluated system • Heat pipe manufacture for PVTs is not trivial • Heat pipe leakage issues • High system costs • Heat pipes leak • Hard to manufacture heat pipes for PVT systems • Technology at its infancy	• Space heating • Domestic water heating • Laundry • Feed water preheater for power cycles • Desalination • Pool heating	• System cost reduction • Need for better wick structures • Need for novel working fluids for heat pipes
Nanofluids-based	• Nanofluid technology is relatively mature • Enhanced thermal performance	• Technology still at its infancy • Nanoparticles sedimentation	The same as for heat pipe-based systems	• Effects of nanoparticle type, shape, size, etc. on the performance • Discovery of novel base fluids and nanomaterials
Heat pump supported	• Improved thermal gain	• Still at start-up stage • Expensive	• The same as for heat pipe-based systems Space cooling	• Enhancing coefficient of performance of heat pumps
PVT system in combination with thermoelectric modules	• Coolant fluids have no direct contact with PVs	• Still at start-up stage • Insignificant heat	• The same as for heat pipe-based systems	• Enhancement of figure of merit of thermoelectric materials
Concentrated PVT systems	• Considerable heat gain • Decent thermal storage prospects • Flexibility to use a wide range of eutectic salts, HTF, PCM, etc.	• Many cell materials may not be suitable • Costly construction materials, operation and maintenance • Low lifetimes • Temperature of operation usually high • Issues related with material corrosion leading to damage to structures • A key challenge involves attaining uniform optical performance	• The same as for heat pipe-based systems Absorption coolers • Solar cooking • Production of fresh water	• Novel solar cell materials suitable for high temperature • Studying transparent plastics as glazing • Better receiver designs • Lower cost concentrators and reflectors • Less tracking needs • Decreasing system weight
Beam split technology	• Operation of PV modules at low temperatures	• The technology in its infancy • Partial blockage of radiation by glasses	• The same as for heat pipe-based systems	• Less expensive filter glasses • Filter degradation (in sunlight) analysis

	• The ability to convert existing systems to BSPVT • Compatible with concentrated PV systems	• High costs of filter glasses • Utilization of liquid spectrum filters in its infancy		• Novel liquid spectrum filters • Study of system reliability in practice • Feasibility of using coalesce luminescent phosphors and spectrum filtration in PVT • More study of BSPVT systems via simulations

PVT technologies have significant advantages over PV-only technologies. However, they are more expensive. Studies have shown that with a feed-in tariff support rate of 58 US$/kWh for a 20 year period, an optimized PVT system has a discounted payback period of 11.2 years, compared to 6.8 years for a PV-only system [11] . When a domestic renewable heat incentive of 11.5 US$/kWh in quarterly payments was applied, the payback time decreased by about one year. The payback time decreased by about 2 years when this incentive was applied as a one-off voucher at the time when the system was placed in service for the first time. When a renewable heat incentive rate of 27 US$/kWh was applied, the PVT and PV systems had similar payback times [11].

3.2. Concentrated solar power

A CSP system looks more like a thermal power station such as gas, geothermal, or coal. Typically, these systems include thermal energy storage, for storing thermal energy as latent or sensible heat, allowing for generating electricity on-demand. Therefore, CSP systems are dispatchable. In recent years, there have been advances in collector and reflector materials and design, thermal energy transport and absorption, thermal energy storage, and power production [83]. However, since 2010s, a sharp decrease in the price of PV systems has led to forecasts that CSP systems will not be economically attractive in the future [84]. As a matter of fact, the capital cost of a utility-scale PV power station was 20% of the capital cost of the least expensive utility-scale CSP station in 2020 [85]. Consequently, the deployment of CSP systems has decreased considerably. However, Schöniger *et al.* believe that CSP systems when used together with thermal energy storage systems are less expensive than PV systems with lithium batteries [86].

3.3. Water heating

Solar water heating (SWH) is a promising alternative to water heating with natural gas, as it has no fuel consumption and zero greenhouse gas emissions [87]. Theoretical studies have shown that SWH has the potential to lower natural gas consumption by 50 to 80% [88]. Savings would be larger for multifamily and industrial installations than for residential setups for single families [88]. Most residential SWH systems have the following six main components (Figure 10):

- STC(s): evacuated-tube and flat-plate collectors are usually common.
- A storage system that provides heat when solar radiation is not enough or accessible.
- A heat transfer system that typically consists of heat exchangers, valves, pipes, pumps, and fans. A fluid flows through the collector to absorb the heat.
- An energy management system to control the collection, storage, and distribution of the thermal energy.
- A supplemental storage tank. Since there is a mismatch between when the demand for hot water is highest (i.e., mornings and evenings) and when solar radiation is highest (i.e., noon), an SWH system is typically integrated with another system that delivers added thermal energy whenever needed. This another system is usually a standard electric or gas heater.

Solar water heating uses a variety of energy systems, including integrated collector storage, thermosyphon, direct circulation, and indirect air and water heating.

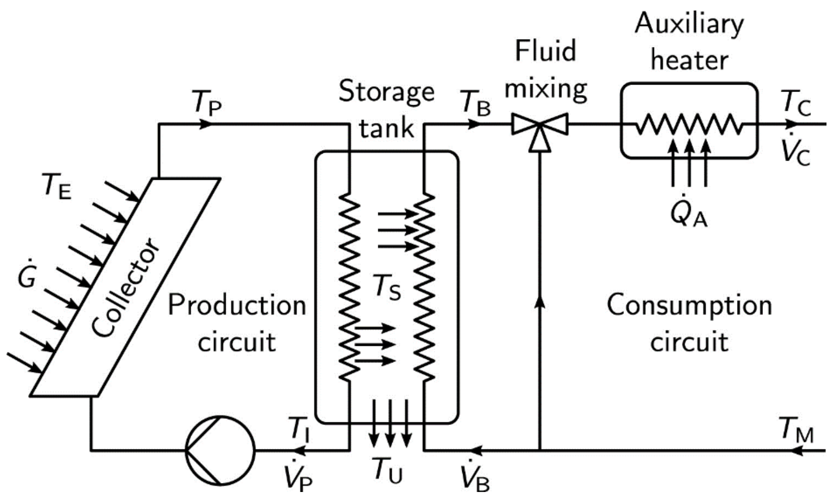

Figure 10. Schematic of an SWH system.

Credit: Image from Araújo, A.; Ferreira, A. C.; Oliveira, C.; Silva, R.; Pereira, V., Optimization of collector area and storage volume in domestic solar water heating systems with on-off control—a thermal energy analysis based on a pre-specified system performance. Applied Thermal Engineering 2022, 119630. Copyright permission from the publisher.

For an SWH technology to succeed, it should have broad market impacts. Of great importance is that the technology should be competitive with natural gas water heaters in low temperature geographies [87]. The widespread use of the technology has been hindered by the high cost of an installed SWH system [87].

3.4. Heating, cooling, refrigeration, and ventilation

Integrated solar energy and heat pump systems. A solar aided pump combines a heat pump cycle with thermal solar panels. These two technologies are used in parallel to heat water. Here, the solar thermal panel is considered as the low-temperature thermal energy source, and the generated thermal energy supplies the evaporator of the heat pump cycle. In this way, the system is more efficient and cost-effective, and has a high coefficient of performance (COP). Depending on the desired temperatures in the heating system and the thermal source temperature, the COPs of these systems are from 2.0 to 4.7. Table 3 lists the COPs of various heat pumps operating under different conditions.

Table 3. COPs of different heat pumps.

Credit: Adapted from Redko, A.; Redko, O.; Di Pippo, R., 3-Effective use of heat pumps for various heating applications. Low-Temperature Energy Systems with Applications of Renewable Energy 2020, 87-133. Copyright permission from the publisher.

Heat source & temperature	**Hot air system (25–30 °C)**	**Hot water "radiators" (70–95 °C)**	**Hot water supply (40–55 °C)**
Air −10 – −5 °C	3.9	–	3.2
Ground 5–10 °C	3.9	2.0	3.2
Groundwater 8–15 °C	4.0	2.2	3.6
Lake, river 4–17 °C	4.0	2.2	3.6
Wastewater 10–17 °C	4.2	2.2	3.8

Several concepts have been developed for integrating heat pumps with solar collectors to improve the energy conversion efficiency. One concept involves using a PV panel to supply electric power to the compressor of a heat pump system [89]. In this concept, as the thermal energy that the PV panel generates is not used, the energy raises the operating temperature of the PV panel, lowering the panel power output[90]. This is a disadvantage of this concept. A second concept involves the integration of a heat pump cycle with a solar thermal collector. As this concept does not include PV cells, the solar thermal collector supplies thermal energy to the heat pump, and an external source provides electric power to the compressor [91]. The main disadvantage of this second concept is that it needs an external energy source. A third concept is the integration of a PVT collector with a heat pump cycle. The PVT collector supplies only heat to the heat pump, and an external source provides electrical energy to the compressor [92-94]. In this integrated system, a refrigerant flows through the PVT panel, allowing this panel to act as the vaporizer in the heat pump cycle. A different approach is to pass a non-vaporizing working fluid through the PVT panel to capture the thermal energy for later use in the heat pump. A fourth concept (Figure 11) is the use of a PVT collector with a heat pump. The collector provides thermal and electrical energies to the heat pump [94-97]. The excess electricity is stored in a rechargeable battery or is sold to the grid. The relative complexity of this fourth concept is its drawback. However, it has been reported that the system is very efficient and has economic and environmental advantages [98].

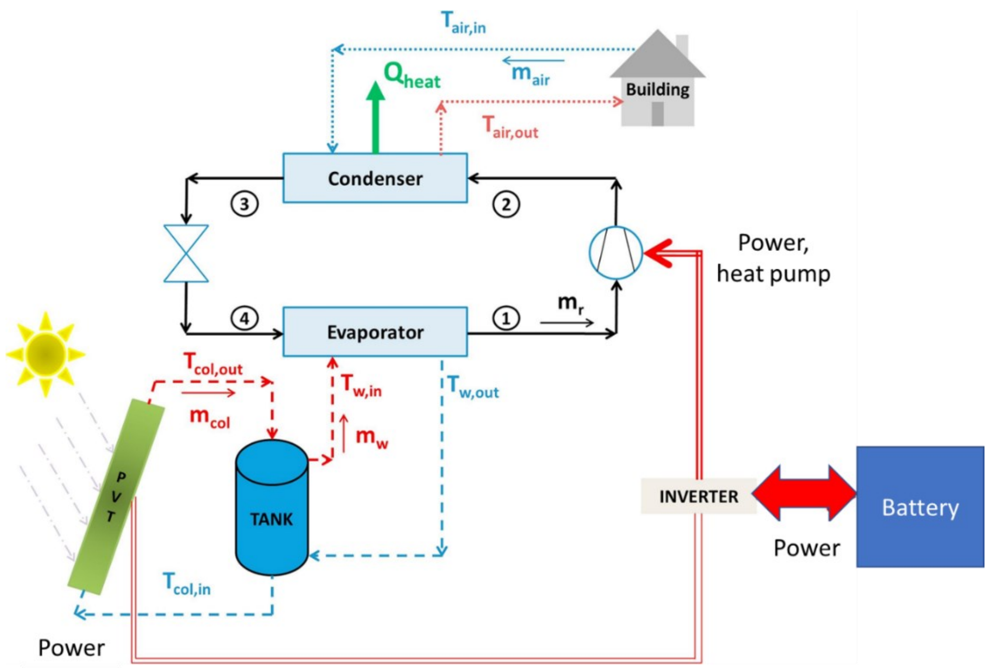

Figure 11. A PVT panel provides thermal energy and power to a heat pump.

Credit: Image from Bellos, E.; Tzivanidis, C., Multi-objective optimization of a solar assisted heat pump-driven by hybrid PV. Applied Thermal Engineering 2019, 149, 528-535. Copyright permission from the publisher.

Solar air conditioning. Heating and cooling have usually been achieved separately, e.g., cooling via vapor compression air conditioning and heating via gas /oil burning units. Recently, cooling technologies driven by thermal energy have attracted attention due to their sustainability and reliability attributes. These systems consume less energy than vapor compression systems. Furthermore, they do not require the use of refrigerants that are usually not environmentally friendly.

For air-conditioning systems employing solar thermal cooling, a solar thermal collector along with a supplementary heating system (backup boiler for when there is low or no irradiation) are used to supply thermal energy to a heat driven cooling machine to produce chilled water needed for air-conditioning or cooling (Figure 12). Heat driven systems can be divided into two types: open cycle (such as direct air treatment to control humidity and temperature) and closed cycle (such as chilled water systems).

In a closed-cycle system, a heat driven sorption chiller produces chilled water for space cooling or air-conditioning by means of chilled beams, air management units, chilled ceilings, fan-coils, and so on. The COP range of such a system with single-effect chillers is between 0.4 and 0.7 [99]. A solar-driven absorption chiller used a commercial building in the Middle East has been reported to have a ~5 year payback period [99]. The energy consumption of a vapor-compression air conditioning system is higher than that of solar-assisted absorption chiller. It has been reported that energy saving with an integrated solar-supported cooling system can be up to 58% during the summer season, and the system has an annual levelized cost of energy-savings of around US$ 140,000 [99].

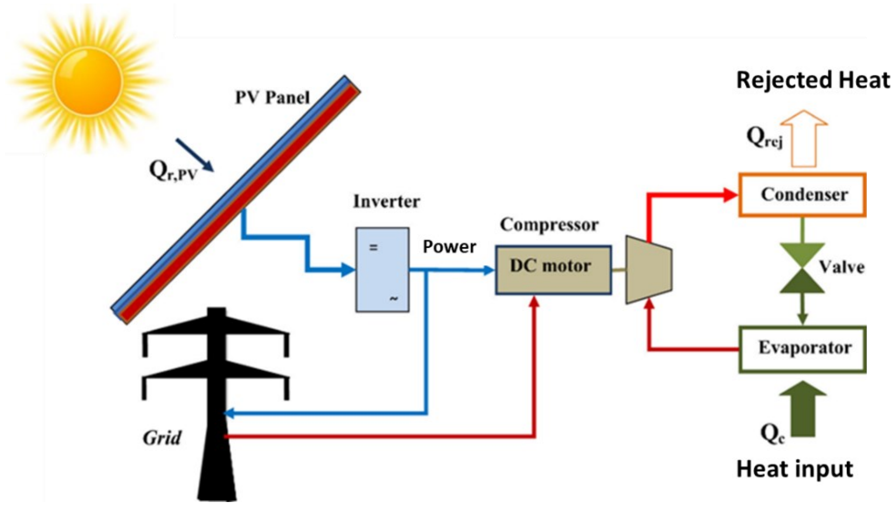

Figure 12. A solar air conditioning (closed-cycle) system.

Credit: Image from Ghafoor, A.; Munir, A., Worldwide overview of solar thermal cooling technologies. Renewable and Sustainable Energy Reviews 2015, 43, 763-774. Copyright permission from the publisher.

Solar refrigeration. Solar refrigeration systems have received a considerable attention, because the demand for cooling is usually strongest when sunlight is strongest, and solar refrigeration can be available at locations where grid electricity is not accessible. Solar refrigeration has been reported to help protecting permafrost foundations [100]. It can also be used to preserve temperature-sensitive goods such as medicines and foods and achieve cooling. Two major types of solar refrigeration systems are PV refrigeration and solar thermal refrigeration [101]. PV refrigeration is more efficient and has a more stable operation, compared to solar thermal refrigeration. As a consequence of its working principle limitations, thermoelectric refrigeration is appropriate for cold storage only within the temperature range of 5 to 10 °C [102].

A vapor compression refrigeration system (VCRS) is of the PV refrigeration type and comprises of a compressor, an evaporator, an expansion valve, and a condenser (Figure 13). A PV panel supplies the power that the system needs. A VCRS consumes around 15% of the total generated energy to run the whole cooling cycle [103]. The COP of a VCRS can be enhanced vastly by optimally controlling the evaporator temperature [104].

A vapor absorption refrigeration system (VARS) is of the solar thermal refrigeration type and uses heat from the Sun to run the vapor-liquid circulation of a refrigerant (Figure 14). This system has a low COP of 0.4 to 0.7 and is noiseless, environmentally benign, and long-lasting [105]. The thermodynamic cooling cycle of a VARS consists of a condenser, a heat source, and an evaporator. The heat source of a VARS should be at a temperature between 70 and 150 °C. Thus, the heat source can be sunlight [100]. VARSs are more economically viable than VCRSs [106]. Both systems are economically more attractive at larger scales (Table 4). Table 5 compares VCRSs to VAESs. Solar PV and PVT technologies are suitable for driving vapor compression and adsorption refrigeration, respectively.

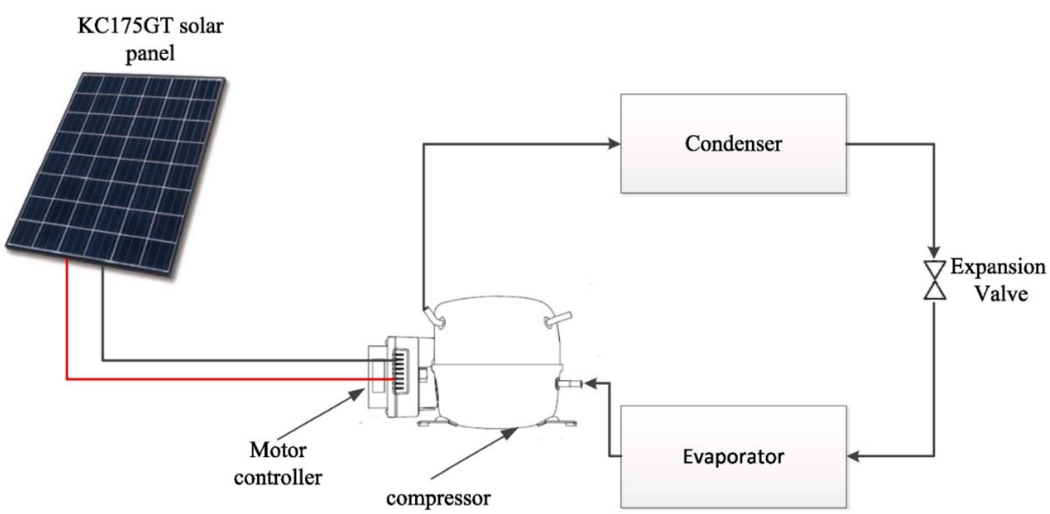

Figure 13. Schematic of a vapor compression refrigeration system driven by power supplied by a PV panel.
Credit: Image from Salilih, E. M.; Birhane, Y. T., Modelling and performance analysis of directly coupled vapor compression solar refrigeration system. Solar Energy 2019, 190, 228-238. Copyright permission from the publisher.

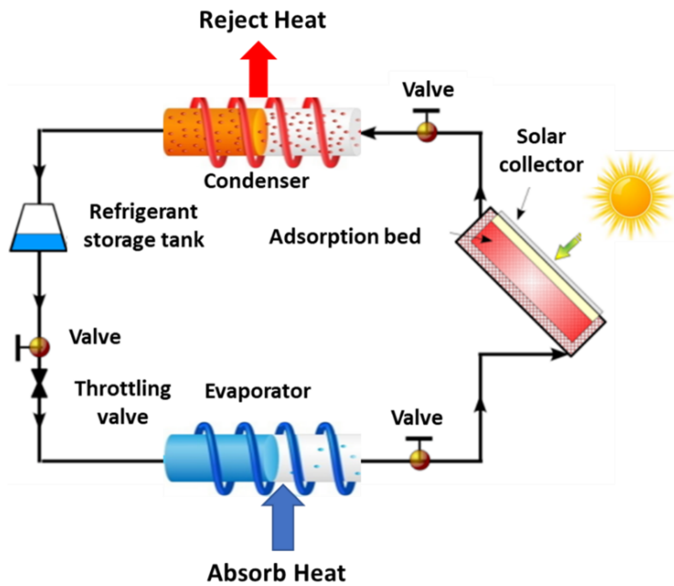

Figure 14. Schematic of a solar vapor absorption refrigeration system.

Credit: Image from Hassan, H.; Mohamad, A., A review on solar-powered closed physisorption cooling systems. Renewable and Sustainable Energy Reviews 2012, 16 (5), 2516-2538. Copyright permission from the publisher.

Table 4. Payback periods (PBPs) of vapor compression refrigeration and vapor absorption refrigeration systems at different electricity prices.
Credit: Adapted from Al-Ugla, A.; El-Shaarawi, M.; Said, S.; Al-Qutub, A., Techno-economic analysis of solar-assisted air-conditioning systems for commercial buildings in Saudi Arabia. Renewable and Sustainable Energy Reviews 2016, 54, 1301-1310. Copyright permission from the publisher.

Electricity price (¢/kW h)	PBP (years)	
	VARS	VCRS
3.2 (0–4000 kW h)	32.1	51.6
5.3 (4001–8000 kW h)	22.6	31.0
6.9 (> 8000 kW h)	18.5	23.9
16 (International mean)	09.1	10.3

3.5. Solar cooking

A solar cooker or solar oven converts solar energy to thermal energy to cook food (Figure 15[107]).

They have also been used to achieve other tasks, including sterilization and pasteurization.

Different types of solar cookers have been manufactured. Common types are solar panel cookers, solar parabolic cookers, and solar box cookers [108]. Wilson Solar Grill is a cooker that is able to store solar energy to cook later in the absence of sunlight[109].

Firewood, cow dung, agricultural waste, and kerosene are still the primary energy sources of thermal energy in many developing counties, as they are locally available and are still affordable. However, their use has negative side effects. For example, the use of wood has caused major ecological problems such as deforestation and can be accompanied by major health problems, including eye disorders, lung diseases, and burns [110]. Furthermore, according to the World Health Organization (WHO), indoor air pollution is responsible for about 1.6 million deaths annually [111]. Thus, solar cookers can be used in these countries to provide affordable energy with little or no negative side effects. Other advantages of solar cookers include no recurring costs, no labor costs, and high durability [112].

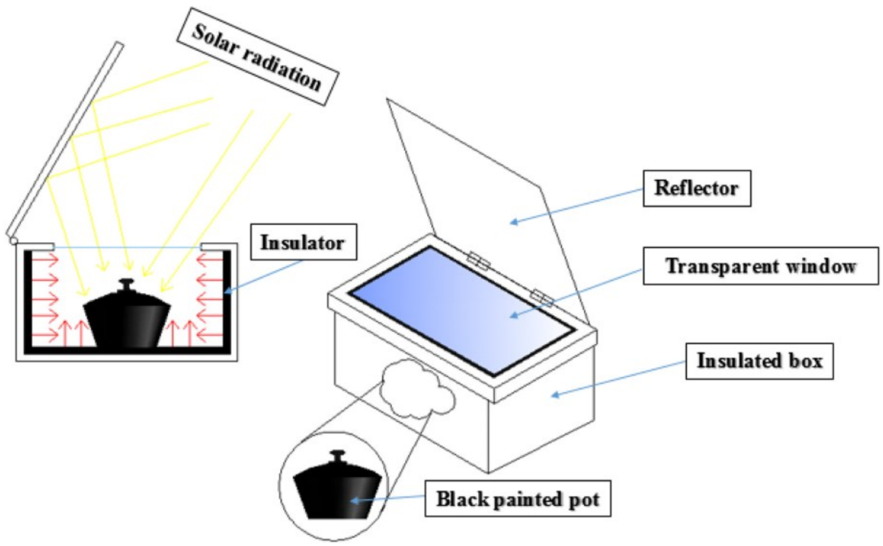

Figure 15. Solar box cooker with reflector.
Credit: Image from Herez, A.; Ramadan, M.; Khaled, M., Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios. Renewable and Sustainable Energy Reviews 2018, 81, 421-432. Copyright permission from the publisher.

For the past five hundred years, many have attempted to cook food with sunlight. Tschirnhausen in the 1600s seems to be the first to experiment with solar cookers [113]. Others include Horace de Saussure in 1767 [114] and John Herschel in 1830. Governments in developing counties have promoted and invested on the use of sunlight for cooking whenever fossil fuel prices have increased significantly. For example, after 1970s when the fuel prices increased sharply due to an oil crisis, the Indian and Chinese governments encouraged the use of box-type solar cookers. Attempts have been made to propose guidelines, tests, and standards for evaluating solar cookers [115-116]. Recent attempts have mostly focused on enhancing the power capacity of solar cookers by introducing novel designs. These advances in the solar cooking technology are expected to lead to increased efficiency and affordability of these cookers.

Solar pasteurization is the process of killing harmful microorganisms with the aid of sunlight; a solid or liquid is pasteurized by heating the matter to temperatures high enough to kill microorganisms. For example, milk can be pasteurized using solar energy (Figure 16 [117]). The first

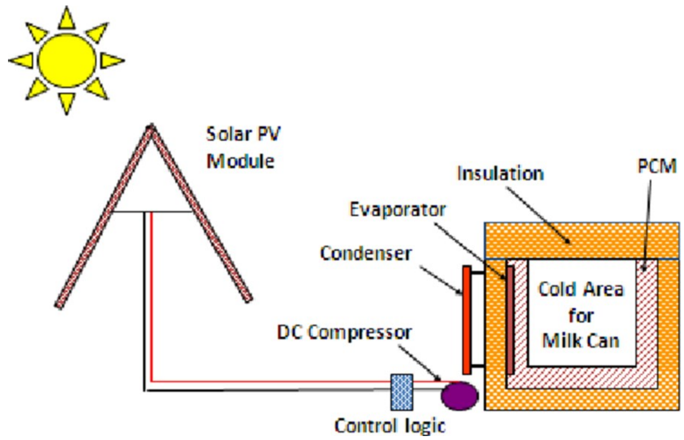

Figure 16. Schematic of a solar milk-pasteurization process.

Credit: Image from Panchal, H.; Patel, J.; Chaudhary, S., A comprehensive review of solar milk pasteurization system. Journal of Solar Energy Engineering 2018, 140 (1). Copyright permission from the publisher.

water pasteurization using box-type solar cookers was attempted in 1979. Ciochetti and Metcalf [118] constructed a solar box cooker and successfully pasteurized naturally contaminated water. Solar cookers have potential to be used widely for water disinfection in developing countries [119]. Solar box cookers can also be used to pasteurize soils for disease control [120] and to decontaminate hospital materials before disposal [118].

3.6. Process heat

Currently, not many industries are using sunlight to produce process heat to replace fossil fuels or consume these fuels less. However, there are many industries that can potentially harvest solar energy for their industrial processes, especially industries located in countries with high solar radiation. Benefits of using solar industrial process heat include less greenhouse gas emissions and more sustainability. A study [121] showed that the utilization of solar process heat leads to an annual energy gain of 550 to 1100 kWh/m^2 in the Mediterranean climate. Solar process-heat generation systems are most suitable for processes, the operating temperatures of which are in the range of

60 to 260 °C. Two of the industries that are currently using solar energy for process heating are the food and beverage industries, where the generated thermal energy is used for washing, pasteurization, water heating, cooking, drying, etc. [122] Another one is the textile industry, in which solar thermal energy is used in cleaning, washing, pressing, drying, and fixing.

About 80% of the total energy that a brewing process consumes is thermal energy. Low-pressure steam can be generated by means of solar heat. In addition, solar heat can be used to achieve refrigeration via absorption cooling. In a malting process, solar heat can be used to materials at different steps of the process. Solar heat can benefit the dairy industry greatly. In the milk industry, solar energy can supply the thermal energy needed for pasteurization, sterilization, and milk powder drying. In the food preservation industry, solar thermal energy can be utilized in many processes including vegetable scalding, fish processing, cooking, can cleaning and sealing, and sterilization. Furthermore, solar absorption cooling and refrigeration can be used for cooling. In the textile industry, sunlight can provide the thermal energy needed to heat liquids used in washing, and to perform bleaching, dyeing, and drying. In solar process-heat systems, it is necessary to integrate sunlight collectors with conventional energy supplies and heat storage systems, allowing the process to operate when solar irradiation is low or unavailable[121].

A solar furnace concentrates solar radiation using reflectors and generates thermal energy. A small solar furnace can be used to cook food, while a large one can generate thermal energy enough to heat a gas to generate electricity. Solar furnaces can be employed in space to provide energy for manufacturing purposes. Like every sunlight-based technology, their disadvantage is the dependence of their operation on the intensity of sunlight, which can be addressed by integrating them with thermal energy storage systems[123].

A solar pond is a man-made pond that is open to the atmosphere from the top (Figure 17 [124]). It receives solar energy from the top. The received thermal energy is stored in the form of sensible heat. The stored energy is then extracted from water at the base of the pond. Water evaporation is a major challenge in the operation of solar ponds [125]. The main idea in such a pond is to cause a significant temperature rise in the bottom region of the pond by inhibiting convection via using salt water in the ponds. These ponds are known as “salt gradient solar ponds”. In the past two decades, many such ponds with difference sizes have been built in many countries [126]. The efficiency of a solar pond, the percent of solar energy that a pond collects, is over 20%. About 4% of the energy can be transformed into electricity utilizing a Carnot power cycle [127].

3.7. **Solar district heating and cooling**

District cooling (DC) and district heating (DH) systems have received more attention recently [128]. The idea is to heat/cool all the buildings in a neighborhood using a central heating/cooling facility; the heat/cold created in a central place is distributed by means of insulated pipes to buildings in a neighborhood. Solar thermal plants are increasingly integrated with DH networks. In Europe, domestic hot water (DHW) and space heating (SH) counts about 80% of the energy demands of

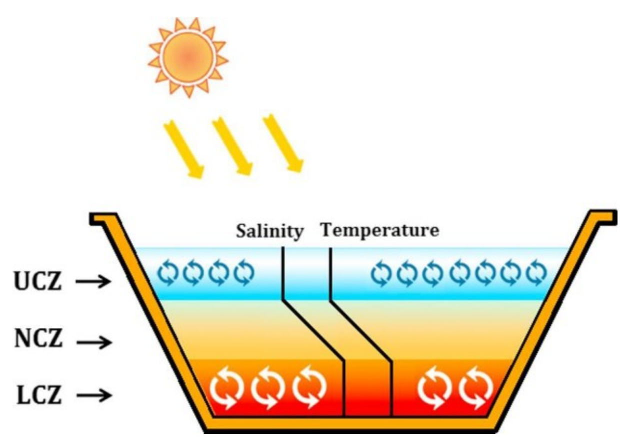

Figure 17. Schematic of a solar pond. NCZ = non-convective middle zone; UCZ = upper convective zone; LCZ = lower convective zone

Credit: Image from Khalilian, M., Energetic performance analysis of solar pond with and without shading effect. Solar Energy 2017, 157, 860-868.Copyright permission from the publisher.

the built environment [129]. Since the range of temperatures needed for these applications are relatively small, there is a great incentive to exploit solar thermal plants. Successful coupling of a solar thermal plant with a DH system strongly depends on the operating temperature of the DH. In order for solar thermal plants to function at high efficiencies and thermal energy losses from the DH network to be minimized, supply and return temperatures need to be feasibly low [129]. Large solar DC and DH systems have been used increasingly in Europe, particularly in Germany, Austria and Denmark, for the last decades [130].

The installation of long-term and short-term thermal energy storage (TES) systems and their integration with solar plants allow for addressing two main problems caused by the time delay that exists between supply and demand. The first problem is the lag between the daily heat demand and daily solar irradiation. The second problem is the large amount of heat that is available in summer and the small amount of solar irradiance during winter when the heat demand is high [131]. The implementation and installation of a long-term thermal energy storage system costs 50–500 €/m^3 [128]. A simulation study indicated that the installation of a TES system integrated with a solar DH system reduces the principal energy consumption by 6%, thus reducing CO_2 emission by more than 4% [128]. Germany has built eight central solar thermal plants with seasonal thermal storage from around 1995 [132]. It has been reported that solar DH systems coupled with seasonal thermal storage are techno-economically viable in Germany [133]. A solar DH system with underground thermal energy storage and assisted by biomass energy, has been proposed for installation in the Mediterranean's regions with low to medium population densities [134].

The successful implementation of a solar DH system is dependent upon key factors, including the quality of the DH networks, the cost of the land, the economic viability of ground mounted collectors, the efficiency and durability of the collector, and the level of tax on fossil fuels [135]. The main aim of DH is to provide heat to customers at the lowest feasible prices. Because the large size of a solar collector field, the limited capacity of thermal energy storage, and the dynamic profile of the annual heat demand affect each other, these key parameters need to be optimized when a solar DH plant is planned and designed [135].

3.8. Process systems engineering opportunities

The design, operation and integration of every solar system discussed in this section can benefit from mathematical modeling studies. The operation and integration of these systems can be enhanced greatly by the development and use of novel control and automation methods. For example, the coefficient of performance of a vapor compression refrigeration system can be improved greatly by optimally controlling the evaporator temperature [104]. Thus, the process systems engineering community can substantially contribute to the advancement of these sunlight harvesting technologies.

4. Sunlight in Built Environments and Industrial Processes

4.1. Building integrated photovoltaics/thermal

Building integrated photovoltaics/thermal (BIPV/T) is recognized as the most effective way to exploit vertical and horizontal built environments for the decentralized production of renewable energy [136]. By replacing the vertical surfaces of building skin (façades) with active PV claddings, utilizing BIPV/T systems, it is possible to make buildings nearly-zero or plus energy (Figure 18)[137]. The utilization of BIPV/T systems can reduce the external heating and cooling energy demand of buildings and decrease heat accumulation in PV systems, enhancing PV power conversion efficiency [136]. Moreover, the BIPV/T potential depends not only on the latitude and elevation of the location but also on the surrounding obstacles as well as seasonal variations and climatic conditions. For instance, hot and humid climate conditions would favor an opaque and high- efficiency BIPV/T and a cold and dry climate a semi-transparent BIPV/T [138].

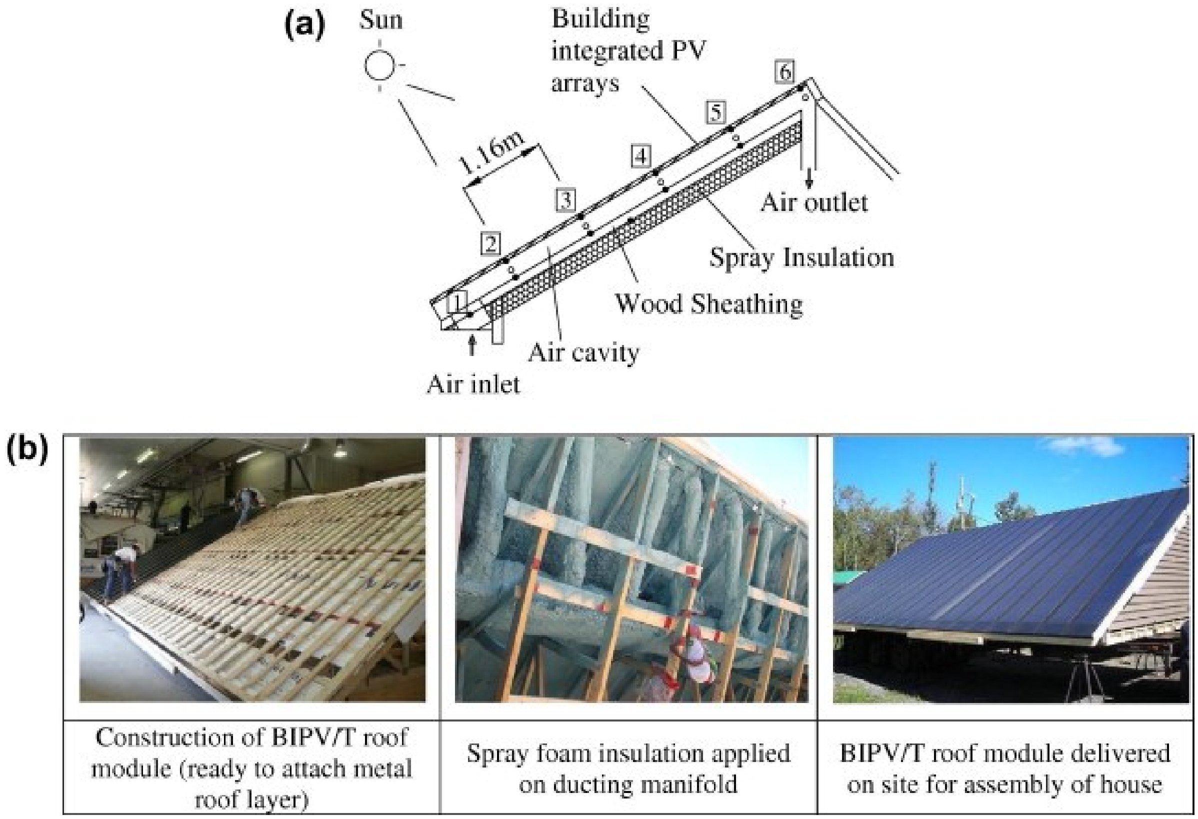

Figure 18. (a) Schematic of the BIPV/T system and temperature monitoring points and (b) construction of BIPV/T prefabricated module in the factory.
Credit: Image from Chen, Y.; Athienitis, A.; Galal, K., Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept. Solar Energy 2010, 84 (11), 1892-1907. Copyright permission from the publisher.

4.2. Agriculture

Solar energy is currently utilized in several regions to supply water to crops economically, especially in the regions where there is no access to grid electricity [139]. Solar-powered irrigation systems use solar energy to pump water; they are clean technology options for irrigation. The initial capital cost of the solar-powered system is more than a diesel generator. However, solar powered irrigation can be more economic in the long term [140].

Drying is a process that is widely used in agriculture and other sectors including diary, textile, cement, timber and wood, wastewater treatment, and biomass processing. For example, drying is used to preserve agricultural crops. Solar energy allows industries to lower their grid-electricity consumption and enhance energy sustainability. Hot air is typically used for all drying processes. Air can be heated by a solar collector. Therefore, the amount of solar thermal energy that a collector generates is a key factor in the technoeconomic analysis of any process integrated with a solar collector [141]. Solar dryers have received more attention in recent years. Novel designs and concepts have been developed and are being studied. For instance, solar air heating has been reported for tea processing [142]. Air can be pre-heated with solar energy and further heated by a traditional furnace. The use of the solar air heating system lowers the fuel consumption of the furnace by 25% [142]. A roof-integrated solar air heating system coupled with a batch drying system is an efficient and cost-effective way for drying fruits [143]. The cost of fruit drying aided by solar energy is approximately 20% lower than drying without using solar energy [143].

4.3. Water treatment

Many industrial processes consume a considerable amount of water. The water that industries use typically requires treatment before returning it to the environment or reusing it. The treatment often requires considerable water pumping, which consumes electric power. PV panels can generate the electricity that the pumps and other equipment need to operate [144]. Some treatment plants also need energy to heat streams.

Solar distillation. Water distillation has been used to remove contaminants from water. The evaporation process that is involved requires a large amount of thermal energy. Also, pumping water requires electricity. Solar distillation allows for the use of solar energy to aid the evaporation, allowing for sustainable production of freshwater. Specifically, a PVT system can provide both the thermal energy and electricity that these processes need. For small-scale freshwater production in rural locations, solar distillation is an economical and reliable option.

Solar desalination. The simplest solar-powered technology for desalination is a solar still that makes use of a big pool, which is kept under a transparent screen. Solar energy helps water evaporate, water vapor condenses on the screen, and liquid water is collected. This technology needs a very large piece of land, but it is inexpensive to install and maintain. A simple solar still can typically produce distillate at a rate of up to 3.5 kg m^{-2} day^{-1} [145]. A solar still can be integrated with PVT panels. In this integrated system, thermal energy from PVT panels are used for water preheating and electrical energy from PVT panels for running pumps [146] (Figure 19). This design makes sustainable off-grid system and can provide distillate at a higher flow rate than a passive solar still. Basic solar stills offer limited distillate flow rates. This can be addressed by developing more advanced systems that integrate evacuated and multi-staged solar stills with STCs [147].

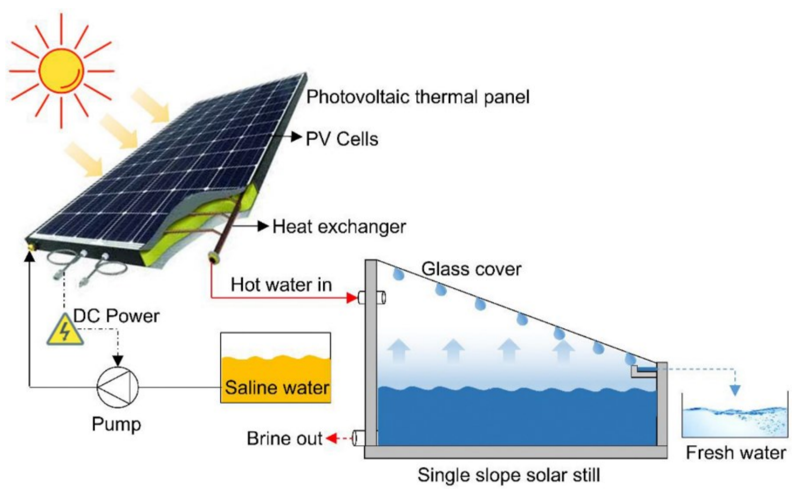

Figure 19. Schematic of a solar still integrated with PVT.
Credit: Image from Anand, B., R. Shankar, S. Murugavelh, W. Rivera, K. Midhun Prasad, and R. Nagarajan, A review on solar photovoltaic thermal integrated desalination technologies. Renewable and Sustainable Energy Reviews 2021, 141 (110787). Copyright permission from the publisher.

Reverse osmosis (RO) is another technique that is used in the desalination of salt water. The interest in the RO technology has grown substantially in recent years. Its 2022 market size has been forecasted to be US $9.2 billion [95]. Advances in this technology in the past four decades have led to a significant drop in its specific energy consumption from 20 kWh/m^3 to less than 3 kWh/m^3 [95]. The significant improvement in energy efficiency of RO systems is a result of advances in energy recovery units, membrane materials, and pumps [96].

An RO system can be integrated with a PV system to directly supply the power to the RO system [148-149]. The integration of an RO system with a PVT system leads to further improvement in efficiency [96]. In solar thermal desalination, sea water desalination is achieved using solar heat. However, RO requires large initial investment and significantly more water pre-treatment in comparison to distillation methods [145]. The average energy demand for distillate water production by means of RO with recovery of energy amounts to 4 kWh/m^3 [149]. RO integrated with PVT is particularly attractive for small communities, as its environmental impacts are low and it is easy to design and implement for different demand profiles [150-151].

Desalination processes are energy intensive, and their energy demand is an important parameter in assessing their cost-effectiveness. Sample energy usage of several desalination processes are listed in Table 5. These processes require both thermal and electrical energies. Thermal energy is utilized to warm up seawater, and electricity to run pumps, compressors, and supplementary units. If the cost of heating is low, then multi-effect distillation is more attractive [149]. Table 6 summarizes results recently reported from economic analyses of solar assisted desalination units. These studies considered system components, operating temperature range, mass of water, electrical and thermal energy production, process efficiency, specific energy usage, payback period, and water price.

Table 5. Energy demands of various desalination systems.
Credit: Image from Tzen, E.; Morris, R., Renewable energy sources for desalination. Solar Energy 2003, 75 (5), 375-379. Copyright permission from the publisher.

Desalination Systems	**Thermal Energy (kJ/kg)**	**Electrical Energy (kJ/kg)**
	Seawater	
Multi-stage flash	190–290	4–6
Multi-effect distillation	150–290	2.5–3
Vapor compression	–	8–12
RO without recovery of energy	–	7–10
RO with recovery of energy	–	3–5
	Brackish water	
RO with recovery of energy	–	1–3
RO without recovery of energy	–	1.5–4
Electrodialysis	–	1.5–4

Table 6. Results from economic analyses of solar assisted desalination units.

System components	**Operating temperature**	**Water produced**	**Power produced (or capacity), system efficiency, payback period, SEC**	**Water prices**	**Ref.**
PVT modules	40 °C	0.2 L/h/m^2	SEC: 0.34 kWh_t/kg water, 0.15 kWh_e/kg water	3.7–6.8 \$/m^3	[97]
PVT panel, MED, heat storage tank	40–70 °C	30.7 L/m^2/day	N/A	N/A	[145]
PVT module	30–60 °C	0.8 L/h	Unit efficiency: 43.15%	N/A	[152]
PVT panels	N/A	1.1 L/h	Unit efficiency: 31.54%	98.1 \$/m^3	[153]

5. Chemical Production

Solar energy can also be used to drive chemical reactions. A process that achieves this is called a solar chemical process. The product of the reactions can be a chemical fuel, often called a solar fuel, that is easily storable, or a chemical precursor or product. Solar fuels can be produced through (a) the photochemical (activation of chemical reactions by photons) application of sunlight, (b) the thermochemical application of solar heat supplied by a concentrated solar heat to drive chemical reactions), (c) photoelectrochemical reactions (using the electricity power from solar energy to drove an electrochemical reactions), and (d) photobiological (artificial photosynthesis) [154]. These reactions can produce a variety of chemicals including fuels such as are hydrogen, hydrocarbons and ammonia [155]. For example, hydrogen can be generated from water hydrolysis using electricity from a PV system, nitrogen can be obtained from air using a gas separation technology and electricity from a PV system, and the chemical reaction of hydrogen and nitrogen then produces ammonia, which is storable fuel. The current yield of solar ammonia processes is in the nmol $g_{cat}^{-1}h^{-1}$ to μmol $g_{cat}^{-1}h^{-1}$ range, which is not attractive to scale up the process [156]. A photoelectrochemical (PEC) reaction is straightforward but is challenging to adopt in practice due to the complex interactions among sunlight, a semiconductor, and a liquid solution [157]. A PEC system can produce chemical and electrical energies.

5.1. Hydrogen production technologies

Photoelectrochemical Processes. A PEC system can be used to produce hydrogen. A semiconductor in a PEC system works similarly to a semiconductor in a PV cell. In both systems, photons, the energies of which are higher than the band gap produce electron-hole pairs. This electric field is then utilized for water oxidation or reduction [158]. Thus, in a PEC system, both solar energy absorption and water electrolysis occur. This compact design does not need a separate power generation system like PV cells. The semiconductor material absorbs solar radiation efficiently and generates sufficient photovoltage for hydrogen production.

In the PEC technology, there research problems that need further investigation. These include the compatibility of the semiconductor-liquid interface [157], improved efficient, and lower costs. Addressing these problems will enable future large-scale deployments of PEC systems [159]. The optimal design, fabrication, and operation of these systems need good skills in electrochemistry, controls, engineering design, thermodynamics, system integration, transport phenomena, materials, and performance monitoring [160].

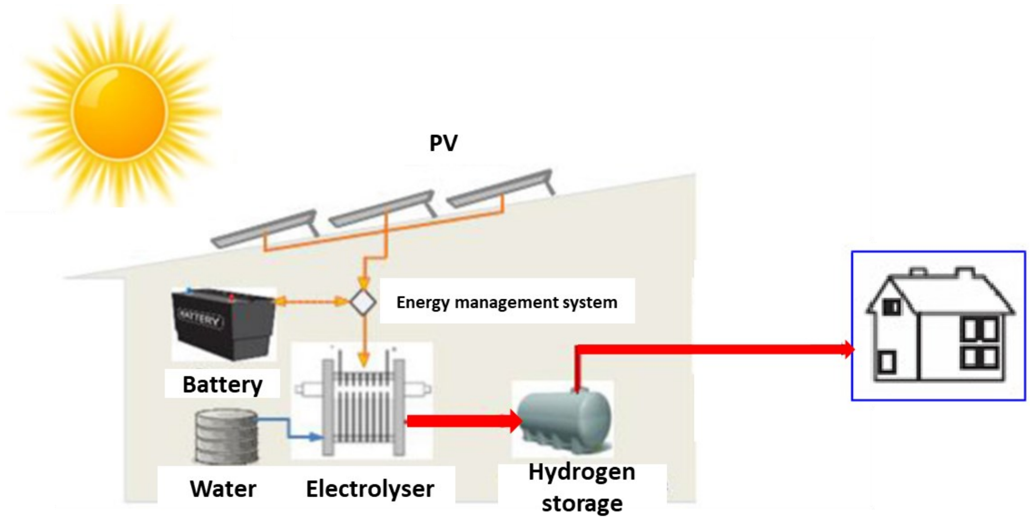

Figure 20. Schematic of a PV-assisted electrolysis system.

Credit: Image from Gutiérrez-Martín, F.; Amodio, L.; Pagano, M., Hydrogen production by water electrolysis and off-grid solar PV. International Journal of Hydrogen Energy 2021, 46 (57), 29038-29048. Copyright permission from the publisher.

PV-Assisted Electrolysis. PV-based electrolysis is a highly efficient method of producing hydrogen. A PV system can be integrated directly to an electrolyzer without any intermediate elements, thus removing the need for expensive power converters and associated electronics [161-162]. A battery-assisted operation can facilitate the use of solar off-grid power by compensating for the intermittency of sunlight (Figure 20).

A PVT system can be integrated with an electrolysis process to efficiently generate thermal and electric energies from sunlight and use the energies in hydrogen production. In this configuration, the feed water is preheated by a PV panel. This preheating reduces the temperature of the PV panel and thus improves the efficiency of the panel. The generated electricity is then used for the electrolysis of water [163]. By preheating the feed water, the amount of electricity needed for heating water is decreased, leading to more than 60% increase in the solar-to-hydrogen efficiency [164]. The excess heated water can be used in other applications [163]. The temperature of the feedwater and PV panel, which have strong effects on the device performance, can be controlled by adjusting the preheater length, water flow rate, and sunlight intensity [163]. As the PV and water electrolysis technologies are mature now, PV-assisted electrolysis is now more attractive than water splitting by means of PEC systems. The efficiencies of current commercial PV panels and electrolyzers are more than 18% and 60%, respectively. Therefore, a solar-to-hydrogen production efficiency of more than 10% is now possible [165]. PV-assisted electrolysis is now the most economically viable technology among all solar-driven hydrogen production technologies [165]. Table 7 lists key advantages and disadvantages of various solar H_2 making methods.

Table 7. Main advantages and disadvantages of solar H_2 production methods.
Credit: Adapted from Agyekum, E. B., Christabel Nutakor, Ahmed M. Agwa, and Salah Kamel, A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. membranes 2022, 12. Copyright permission from the publisher.

Method	Advantages	Disadvantages
PC water splitting	Most attractive for solar H_2 production	Poor light-conversion efficiency
	Simple	Poor stability
	Sustainable and environment-friendly	Need for H2/O2 separation
PEC water splitting	Excellent efficiency	Expensive
	Environmentally attractive	Complex
		Poor stability
PV-EC water splitting	well-established technology and ready for industrial use	Expensive
	Facile scalability	Complex
	High efficiency	Environmentally not attractive
	High durability	

5.2. Carbon dioxide capture and storage

A concerning side product of power generation from fossil fuels is carbon dioxide, the emission of which is the world's most serious environmental problem. Thus, major efforts are being made to lower the level of the emission and mitigates the consequences of the emission. These include the more use of renewable energy sources, CO_2 capture and storage (CCS), and the improvement of the efficiencies of energy generation, conversion and consumption systems[11]. In their regeneration stage, the majority of gas-separation processes use a considerable amount of energy that is usually supplied by a fossil-fuel power plant. Alternatively, solar aided CCS can be used to completely or partially supply and use the needed energy [166]. Various integration of CSSs and solar thermal collectors have been reported (Figure 21). Solar-assisted CCS systems have high potential to supply the extra heat by means of solar thermal collectors. A solar thermal assisted-carbon capture system can be used to supply the heat energy needed for the gas separation process. An appealing feature of solar aided CCS systems is that they can be used as energy storage, as they can use the extra solar energy during excessive irradiation times to drive the endothermic CCS process and store the product for use when the solar irradiation level is low [166]. Studies focusing on different solar driven CCS are listed in Table 8 [167].

There are three main technologies to capture and separate CO_2 from flue gases: (i) post-combustion capture, (ii) pre-combustion capture, and (iii) oxyfuel combustion. The selection of each option depends on several parameters such as the availability of resources and land geography[166]. In the post-combustion carbon capture, CO_2 is captured from the outlet gas of a combustion process. Solar-assisted post-combustion capture can be direct or indirect based on how the thermal and electric energies generated by the solar thermal collector system is supplied to the carbon capture and gas separation processes (Figure 22). In the direct solar-assisted carbon capture,

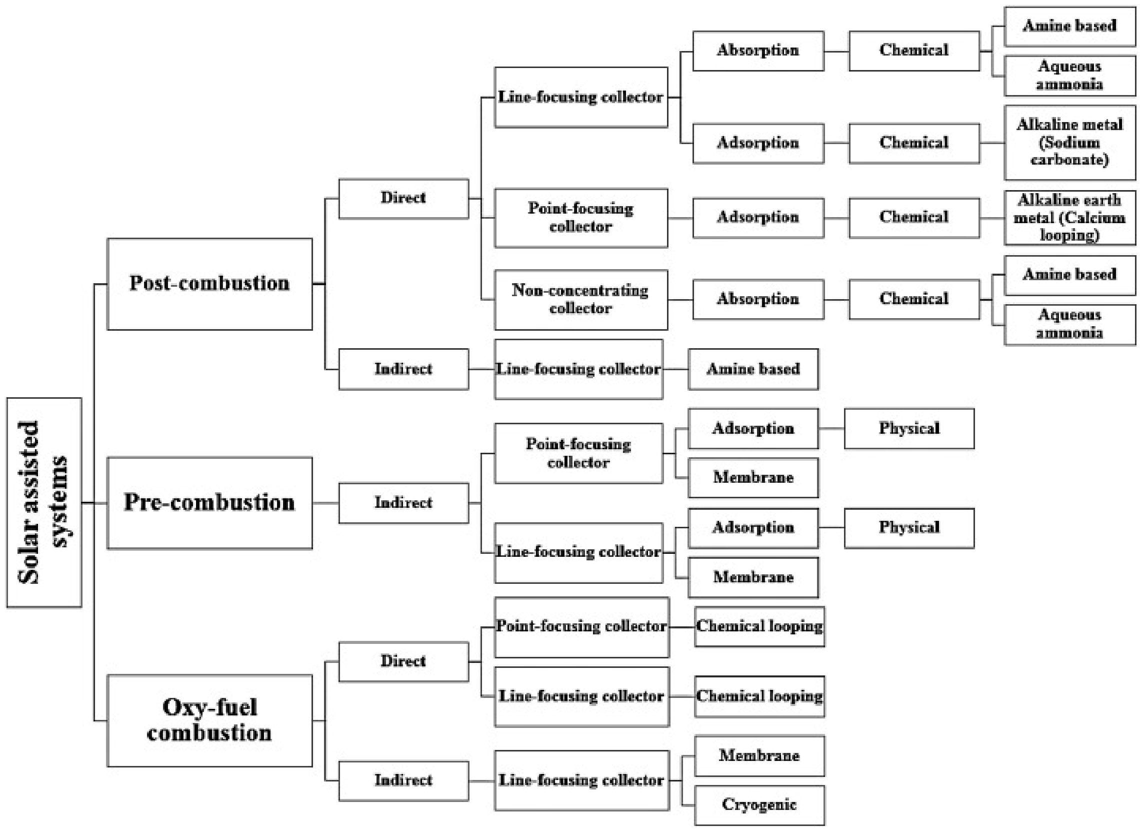

Figure 21. Solar-assisted CCS systems studied in the literature.

Credit: Image from Saghafifar, M.; Gabra, S., A critical overview of solar assisted carbon capture systems: Is solar always the solution? International Journal of Greenhouse Gas Control 2020, 92, 102852. Copyright permission from the publisher.

the PVT supplies the energies directly to the carbon capture and gas separation processes, while in the indirect method, the PVT system integrated with a power plant to provide the energy [168].

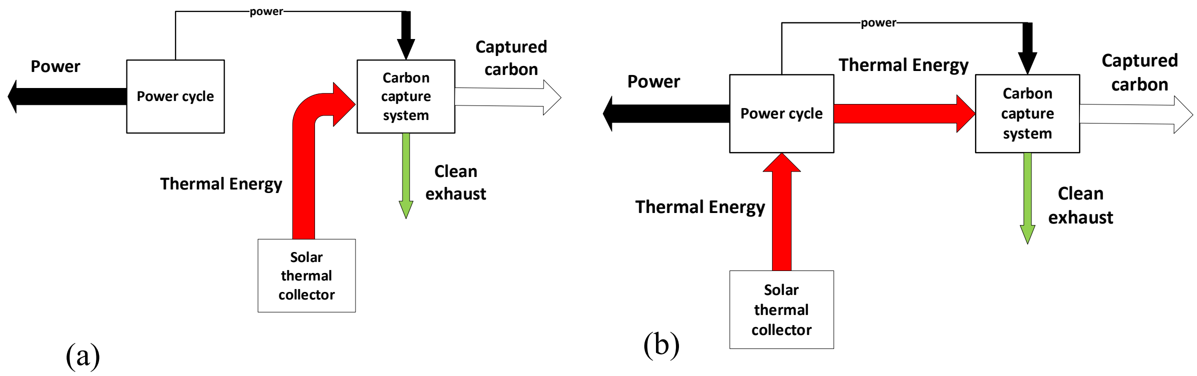

Figure 22. Solar thermal energy integration with a post-combustion capture system. (a) direct solar-assisted CCS and (b) indirect solar-assisted CCS.

In the pre-combustion carbon capture, a fuel is first converted to a non-carbon fuel, the combustion of which is not accompanied with any CO_2 emissions. This conversion is via gasification and reforming processes which generate CO_2 and syngas, and via water-gas shift reactions that convert CO and steam to CO_2 and H_2. Finally, CO_2 is separated from hydrogen. The pre-combustion carbon capture process is less expensive is simpler. In solar-assisted pre-combustion carbon capture, solar thermal energy is utilized in thermochemical and carbon capture processes where hydrogen/syngas production and separation take place simultaneously[169]. In the oxyfuel combustion, pure oxygen from air separation is provided to a combustion chamber to increase CO_2 yield. The produced CO_2 is separated, compressed, and stored simultaneously[168].

Table 8. Studies on solar-driven CCS.

Credit: Adapted from Saghafifar, M.; Gabra, S., A critical overview of solar assisted carbon capture systems: Is solar always the solution? International Journal of Greenhouse Gas Control 2020, 92, 102852-102852. Copyright permission from the publisher.

Carbon capture system	**Thermo-dynamic cycle**	**Capacity**	**Solar thermal collector**	**Energy analysis**	**Economic analysis**	**Environmental analysis**
Amine-based	Subcritical multi-pressure Rankine cycle	520 MWe	Parabolic trough collector (steam)	net capacity can amount to 483 MWe	Price sensitivity to the cost of the PVT	The improvement of CO_2 recovery caused a higher boiler heat duty requirement and therefore needed bigger solar field collectors.
Amine-based post-combustion capture	Subcritical multi-pressure Rankine cycle	1000 MWe	Parabolic Trough (steam)	Indirect integration improved the plant net capacity from 878.5 MW for direct solar integration to 896.67 MWe.	-	Indirect solar integration system can slightly improve the CO_2 avoidance cost in comparison to the direct solar assisted system by 0.84 US$/t$CO_2$.
Chemical looping	Trigeneration gas turbine with cooling water and domestic heat generation	-	Heliostat field	System energy efficiency of 67%	-	-
Indirect oxyfuel solar assisted CCS	Transcritical and subcritical CO_2 Rankine cycle	-	Parabolic trough	System energy: 57.2% Exergy efficiencies: 60.7%	-	-

5.3. Photosynthesis

Photosynthesis has been occurring on Earth for millions of years. It transforms the solar energy into chemical energy and stores this energy in the form of chemical bonds in trees and plants. For thousands of years, humans have benefitted for this process and have tried to optimize it by improving crop productivity and performing plant breeding.

In recent years, efforts have been shifted to improving photosynthesis efficiency through using concepts from synthetic biology. The purpose is to create new pathways that can provide higher yields. Synthetic biology can also be applied to optimize our use of carbon sources and solar energy, and thus our production of fibers, fuels, and food [154]. Our improved understanding of photosynthetic systems is expected to enable us to engineer and redesign photosynthetic systems.

6. Concluding Remarks and Prospects

Solar energy systems are becoming mature and are increasingly accepted by the public. The public support has motivated governments and the private sector in many countries to make large investments on these systems. While being more expensive than the PV systems, the CSP technology is more suitable for the regions that experience less clouds or fog. Currently, PV technologies provide most of the solar power generated. There is a large untapped market for off-grid solar systems, which needs support from research institutions, the private sector, and governments.

Although the cost of solar energy harvesting systems has decreased considerably, the cost of solar power generation is still high. High capital costs are still a major drawback of solar energy systems. For instance, according to the Solar Energy Industries Association, before tax credits, the national cost of a residential solar panel system in the U.S. is $2.94 per watt in 2022 [170]. Moreover, the efficiencies of the majority of solar panels are still in the range of 10–20%. Of course, solar panels with higher efficiencies (ca. >20%) are also in the market but they cost more.

Solar energy can be harvested only when sunlight is present, and the amount of the harvested energy depends on time and weather conditions (level of air pollution, temperature, degree of cloudiness, etc.). Climate change projections indicate that solar irradiation will change in many regions. For example, there will be less clouds over subtropic regions [171]. Therefore, subtropic regions can benefit more from CSP technologies [172]. As solar energy systems usually need a large land to produce solar power at an appreciable scale, the large-scale production of solar power is favorable where land is not expensive.

There are sustainability problems that need to be addressed. As solar panels are fabricated from precious metals that include silver, indium or tellurium, enough infrastructure is still not available for recycling spent panels. Moreover, the efficiency of these systems is lowered by cracks within PV modules, intrusion of water, dust exposure, and algal growth. A side product of the polysilicon manufacturing process is silicon tetrachloride, which is poisonous and expensive to process and reuse (it costs ~$84,500 per ton to process this side product). Because of its high recovery cost, silicon tetrachloride is often discarded without adequate pre-disposal treatment [173].

Adequate skilled workforce is needed to meet the increasing demand for solar power systems. Additionally, as these systems are complex, either the technical understanding of the end customers should be improved or the operation, maintenance and repair of these systems should be simplified [173]

The process systems engineering community can substantially contribute to the advancement of sunlight harvesting technologies. The design, operation and integration of solar systems can benefit from mathematical modeling studies. Multiscale mathematical models can provide insights into the design of materials and the fabrication of devices, and can be used in model-based design, operation and integration (with energy storage systems and other energy generation systems) of solar systems. Furthermore, given the intermittent nature of sunlight and many other renewable energy resources, the optimal operation and integration of renewable energy systems require the development and use of novel control and automation methods.

Acknowledgement

M. Soroush would like to acknowledge financial support from the U.S. National Science Foundation under Grant No. CBET–1804285. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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