CHAPTER

1 Solar energy: direct and indirect methods to harvest usable energy

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1.1 Introduction

The global energy demand is increasing substantially due to increasing population, industries, and technological development. The renewable energy sources can play vital role to cope up with the rising demand for energy and reduce greenhouse gas emissions. Solar radiation is a source of renewable energy from sun, and it can generate electrical and heat energies using appropriate harvesting techniques [1]. The solar energy can be employed in two forms, which are solar thermal and photovoltaics. The solar energy can be directly converted into electricity (by solar photovoltaics) or indirectly converted into heat energy (by solar thermal collectors). Although photovoltaic (PV) requires high capital cost, this technology is accepted worldwide due to less maintenance and operating cost [2]. The International Energy Agency reported that more than 16% of share in total energy production would be photovoltaics by 2050. The cumulative production of photovoltaic energy was 653 GW until 2019, and it is expected to reach 4.674 TW by 2050 [3]. Solar PV production is expected to increase among all the renewable energy sources by 2020. There is still uncertainty about any increase in renewable energy sources by 2021, particularly for give out solar PV applications. However, in the last year, individuals and small-to-medium-sized business together produced 1/5th of total renewable energy globally. In several countries, the construction of distributed solar PV was stopped or significantly slowed down as lockdown actions blocked access to building [4]. The annual growth of renewable electrical energy generation from 2018 to 2020 is shown in Fig. 1.1 [4].

The modern technology needs higher grade solar energy to generate greatest productive power with a compact power plant and a minimum pay-back time for capital investments. Concentrated solar power (CSP) technology is capable of satisfying both the thermal and electrical demands [5]. The solar irradiation from the sun is concentrated using CSP technologies on comparatively slight target area by

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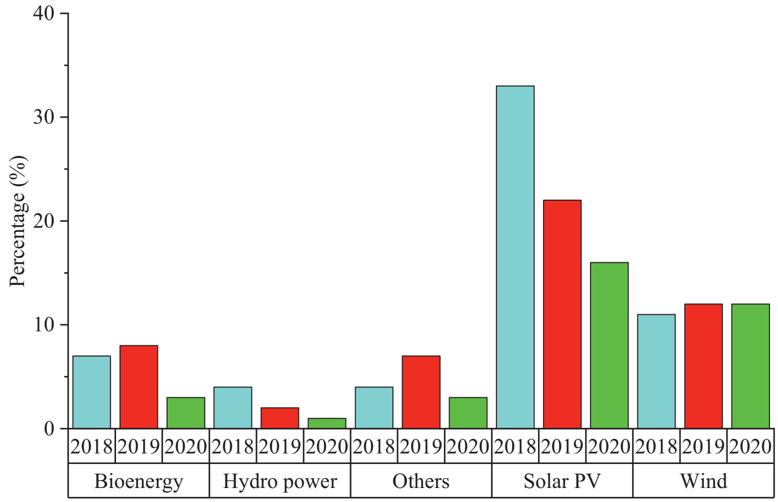

FIGURE 1.1

Global annual growth for renewable electrical energy generation [4].

lens or mirror and generates medium to higher temperature of heat energy. The rise in functional temperature and the quantity of heat obtained per unit area provide greater thermodynamics performance and lesser surface area, resulting in a substantial reduction in conductive and convective heat loss [6]. Based on temperature, solar concentrators are classified into three types as shown in Fig. 1.2, which are high, moderate, and low temperature solar collectors. Flat plate collectors are mostly low temperature series; hence, it is applicable in residential purposes. Central receiver solar collector is mostly high temperature solar collector, which is not suitable for residential or commercial uses, as large area for installation and high solar irradiation are required [7]. Solar collectors are categorized based on their concentration as nonconcentrating and concentrating solar collectors as shown in Fig. 1.3 Also, concentrating collectors are further classified into line focus and point focus solar collectors [8].

Collectors such as evacuated tube and flat plate collectors work under nonconcentrating types, while concentrated type solar collectors are used for applications with higher temperature. The maximum production performance of flat plate collector is 70%−74%, and the maximum efficiency of ETC is 40%−50% [9].

Dwivedi et al. [10] studied various feasible methods of cooling technology of PV modules and analyzed. Fuqiang et al. [5] studied the progress in CSP system with parabolic trough collector, and recent advances in CSP technologies with PTC device heat transfer improvement strategies have been discussed. Jie et al. [11] comprehensively analyzed the historical background, recent advancement, technological features, applications and economical analysis of parabolic trough collector and linear Fresnel reflector. De Sa et al. [12] reviewed the comprehensive analysis of direct steam production from linear solar concentration system.

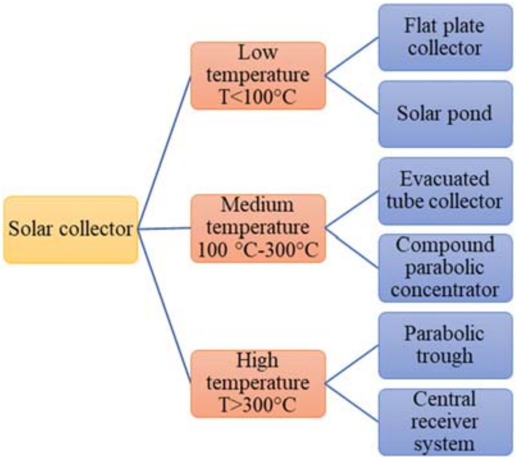

FIGURE 1.2

Classification of solar collector based on achievable temperature.

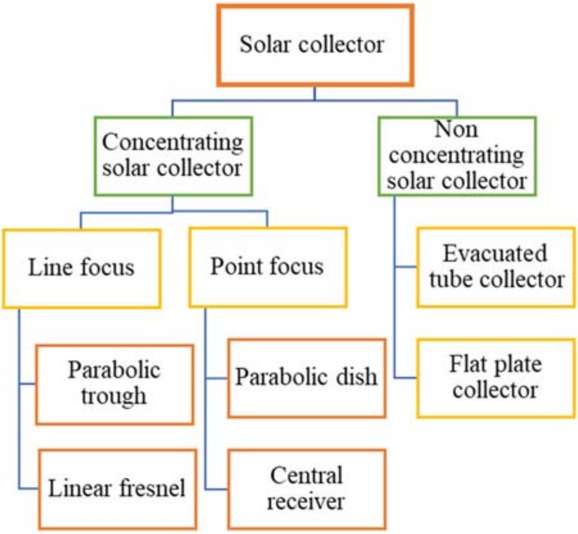

FIGURE 1.3

Classification of solar collector based on concentration type.

This review shows an overview of the main experimental studies carried out and simulation models found in the literature. This chapter briefly explains the different types of energy harvesting techniques such as PV, concentrating and nonconcentrating solar thermal collectors, and hybrid solar collectors.

1.2 Solar energy

Renewable energy typically uses the direct forms of energy from the sun [6]. With the characteristics, these resources have enormous energy capacity of intermittent, distributive, and distinct geographic variability. These characteristics cause usage problems, technological, and economic challenges. Sun releases a massive amount of radiation energy in the upper atmosphere of earth around 1.7×10^{17} W [5]. As sunrays hits the earth surface, because of absorption, reflection, water vapor, scattering by carbon-di-oxide and atmosphere suspensoids, it would be multi-attenuated. The cumulative falling solar radiation on earth accounts for around 51% of inward solar irradiation. This is still enormous quantity after multi-depletion [13]. Solar energy is a combination of radiant light and heat that is harvested using different methods such as solar thermal collectors and photovoltaics. Furthermore, the solar energy solutions are a feasible choice for all. The interesting aspects of these technologies are moderately lighter weight and residential installation. Solar energy is an acceptable source of energy for residential users, as it can be mounted on the roof tops, moved around, and even modified by various arrangements. But the major drawback of this device is the noncapability to work at night time because of the absence of solar energy during night time [8]. Solar energy is utilized in two ways: the visible light converted into electricity known as photovoltaic effect and the heat transfer of component for heating purpose, which is known as solar collector. Throughout the chapter, these two types are discussed extensively. In addition, solar energy sources generate less emission, no mechanical moving parts, no vibration, and no noise in the case of photovoltaic system [14].

1.3 Direct method of solar energy harvesting techniques

The conversion of solar energy into human usable energy takes place in electric or thermal energy forms. The solar energy converted into electrical energy is accomplished primarily using a PV cell. Such cell can function under 1-Sun ($100\ \mathrm{mW\ cm^{-2}}$) conditions in which they are exposed to diffuse radiation and concentration, but attention must be taken to ensure that the operation at extreme temperatures does not damage the cells.

1.3.1 Solar photovoltaics

Solar cells transform solar energy into direct current through the photovoltaic effect in the wavelengths of visible radiation. For many applications, singe solar cells cannot produce enough power. In solar panels, cells are bounded in series and sandwiched between highly transparent and beneath opaque/transparent shelters to shield against unfavorable climate conditions. The packaged solar cells connected in series are called photovoltaic modules. Photovoltaic modules available in various forms for the required electrical power output. Solar cells are divided into three generations, first, second and third generation solar cells. Currently, research and development programs for enhancing efficiencies and minimizing cost for each solar cell generation are made in various research groups worldwide. The first generation solar cells meet the demand for the solar cells [15].

The activity of a solar cell depends on the semiconductor's fundamental property known as its bandwidth. This bandwidth is a function of the semiconductor atomic structure, and this results in an energy difference between the top energy levels to empty energy levels. The difference of energy due to the thermal activation is too high for electrons to move from the lower to higher regions. Electrons in the bottom level can be stimulated by the absorption of photons of electromagnetic radiation from the bottom to the upper level, through the spectrum. Solar cells are made up of semiconductors and have bandwidths to absorbs photons inside the visible area of the spectrum, also the energy is lower than the bandwidth will not absorb any photons. The bandwidth of semiconductor such as Cadmium telluride, Silicon, Gallium arsenide and Copper indium gallium diselenide were 1.11, 1.43, 1.44 and 0.9–1.7 eV respectively. The silicon semiconductor is the most common solar cell material with 1.11 eV [15]. The semiconductor absorbs photons and captured by the electron. So the electron gets electric potential, and the current is generated at a constant voltage known as cell voltage [15]. Lower the bandwidth decreases absorption threshold, but discharges more energy as heat, whereas the semiconductor with higher bandwidth allows more energy passes through it without any absorption. Solar cell material has the maximum bandwidth of 1.43 eV. The silicon bandwidth is below the maximum at 1.11 eV, but it has proven to be the most efficient solar cell material till date and its market share is also high. Three different forms of silicon used in PV are amorphous, crystalline, and semi crystalline. The most effective but costly silicon to manufacture is crystalline silicon, while the least effective and the cheapest is amorphous silicon. One of the alternatives to silicone is cadmium telluride, which is economically cheaper but in amorphous form. The bandwidth exceeds the optimum. Gallium arsenide semiconductor is more efficient than silicon, but it is more expensive and of partially crystalline form. Also the following factors affect the power generation of solar cells as shown in Fig. 1.4 [15,16].

1.3.1.1 First-generation solar cells

Silicon wafer technology is used to produce the first-generation solar cells. Most of them are made from mono and polycrystalline silicon. These first-generation solar cells are single junction solar cells with a theoretical efficiency of 33%. The engineering methodology involved to produce first-generation solar cells need several resources and laborers. The maximum energy conversion performance of these cells are 15%–20% [17].

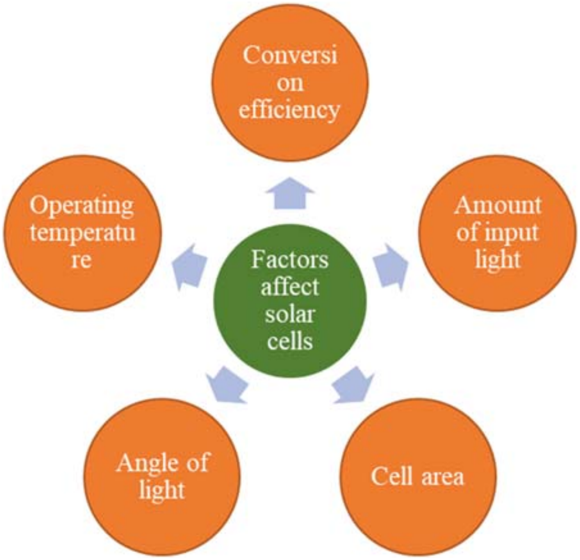

FIGURE 1.4

Factors affecting the solar cell performance.

1.3.1.2 Second-generation solar cells

The second-generation solar cells are amorphous solar cells such as a-Si, CdTe, CIGS, and micromorphous silicon. The production cost and efficiency of second-generation cells were lesser than those of first-generation solar cells, and this technology needs lower temperature for manufacturing. Generally, these solar cells are produced by depositing a thin film of the above materials on the substrates (glass or ceramics, Si) using either chemical vapor deposition or spin coating techniques [17].

1.3.1.3 Third-generation solar cells

Commercially, crystalline, thin film devices and organic and dye-sensitized solar cells are used for first, second, and third generation solar cells, respectively. The third-generation technologies are primarily geared toward improving the energy conversion performance and second-generation light absorption coefficient solar cells though retaining development costs similar to second-generation solar cells. Performance can be improved by producing multijunction solar cells, raising the coefficients of light absorption and the use of carrier aggregation techniques [17]. The organic semiconductors work on similar to conventional semiconductor rather than electric conductivity. Therefore, there is a need to find an effective way to extract the electrical power when the organic semiconductors are produced. While this may be drawback, the simplicity of their processing is appealing to organic materials. The printing of the semiconductor onto a substrate is required to make it highly flexible. But organic semiconductor performance is still very poor with the best 6% theoretical value and 4% producing efficiency. Dye-sensitized solar cells use specified colors for absorbing sunlight and transferring the emitted electron to the material during the process. These devices are comparable with photosynthesis, but the complex series of exchanges make them to work and look similar to electro chemical devices like batteries. As with organic semiconductors, because of simplicity of manufacturing these are appealing, as they can printed too. Maximum theoretical efficiency is 31% and functional efficiencies have been reached by 13% [15].

The solar cell electrical efficiency can be calculated in two different ways.

1. Indoor conditions that is, Standard test conditions (STC)

   Under STC, the solar cell electrical efficiency is given by [18]

$$\eta_{ee} = \frac{P_{\max}}{P_{in}} = \frac{V_{\max} \times I_{\max}}{\text{Incident solar radiation } \times \text{ Area of solar cell}} = \frac{V_{oc} \times I_{sc} \times FF}{I(t) \times A_c} \tag{1.1}$$

   where I_{sc}, V_{oc} and FF were short circuit current, open circuit voltage, and fill factor (the maximum value of fill factor is 0.88) respectively.

2. Open field circumstances (for variable solar irradiation in terrestrial areas wave length ranges from 0.23 to 26 μm).

   The solar cell electrical efficiency under open field condition is given by

$$\eta_{ee} = \frac{P_{\max}}{I(t)} = \frac{I_{\max} \times V_{\max}}{I(t)} \tag{1.2}$$

The energy of the photons $E = \frac{hc}{\lambda} = hv$ belongs to the wavelength ranges from 0.40 to 0.70 μm has enough energy more than the energy of the band gap. The energy content is 47% from 0.40 to 0.70 μm. This means that solar cells generating electrical energy from silicon (Si) and gallium arsenide (GaAs) cannot be efficient and Germanium (Ge) exceeding 47%. Therefore, electrical efficiency of solar cells is lesser than 47% [18].

1.4 Indirect method of solar energy harvesting techniques

The indirect method of solar energy harvesting can be categorized into two categories viz. no-concentrating collectors and concentrating collectors.

1.4.1 Nonconcentrated solar collectors

Solar collectors are categorized in two ways: (1) concentrating and (2) nonconcentrating. Generally, flat plate collector (FPC) and evacuated tubes (ETC) are working based on nonconcentrated type. These collectors are primarily designed for applications involving solar water heating and industrial heating process that require 60°C–250°C of temperature. These collectors use diffuse and radiant solar radiation and do not require sun tracking [19]. These are mechanically humbler than concentrating solar collectors, and it need less maintenance.

1.4.1.1 Flat plate solar collector (FPC)

Fig. 1.5 shows the schematic diagram of flat plate collector. It comprises absorber, heat transfer fluid pipe, transparent cover, casing, and insulation. The absorber is a thin copper or steel sheet deposited selective solar coating, and a solar safety glass is used as transparent cover. The solar irradiation enters the transparent glass and reaches to absorber. The absorber converts the solar irradiation into heat energy and the heat energy is absorbed by highly conductive heat transfer fluid. The housing safeguards and protects the absorber and insulation from impacts on the environment. In order to minimize the thermal losses on the rear side of the absorber rock wool or mineral wool is used [21,22]. The FPC thermal productivity can be improved by minimize the thermal and optical losses. This may be accomplished by (1) use of anti-reflective multi glass, (2) hermetically sealed evacuated tube collector, and (3) hermetically sealed FPC with a noble gas.

In recent days, FPCs are substituted by ETCs, as they offer certain benefits. The ETCs have evacuated tubes, which heats the absorber and eventually heats the working fluid for water heating or space heating applications. The vacuum in the ETCs decreases heat losses in conduction and convection, allowing them to achieve significantly highest temperature than most FPCs. Balaji et al. [23] analyzed the thermal

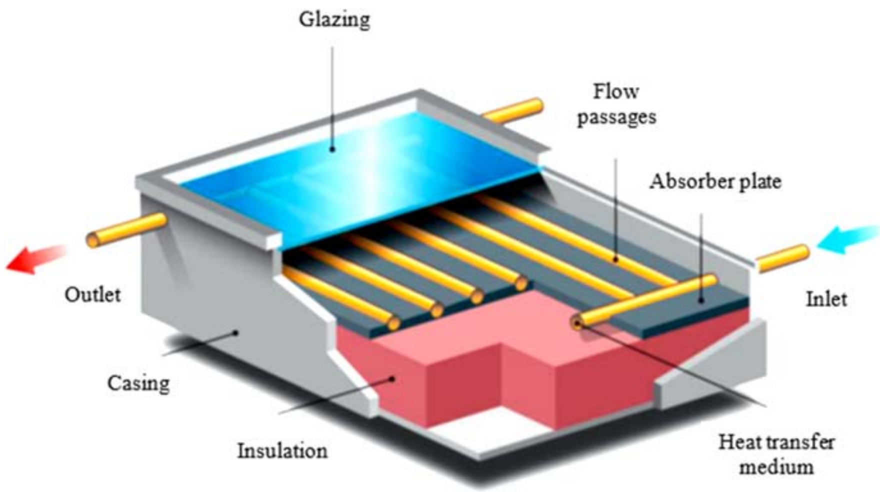

FIGURE 1.5

Flat plate solar collector.

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performance enhancers used in flat plate solar water heater with and without absorber transformation. The result showed that the free convection dominates inside the collector. The rise in flow stability, conduction heat transfer, and turbulence showed the need for thermal performance enhancer in heat transfer applications.

1.4.1.2 Evacuated tube solar collector (ETC)

The schematic diagram of the evacuated tube solar collector is shown in Fig. 1.6. Each ETC has two tubes made up of tremendously strong borosilicate glass with a high thermal and chemical shock resistance. The outer tube of the ETC is transparent, with minimal reflection allowing solar rays to pass through it. The outside of the tube is coated with a selective sputtered solar coating that shows exceptional solar absorption and lower thermal emittance. The tubes are merged together at the top side, and the air between the two layers of glass in the annular space is evacuated to minimize the convective and conductive heat losses. The upper side of the parallel tubes is fixed to the inner storage tank [21].

A barium getter is introduced into the base of the exterior glass tube in the process of producing vacuum. The inside glass tube is fixed into the outer tube and centering the inner glass tube with the getter. The tubes are heated at high temperature and it induces vacuum. On the open end, the two-glass pipe are then

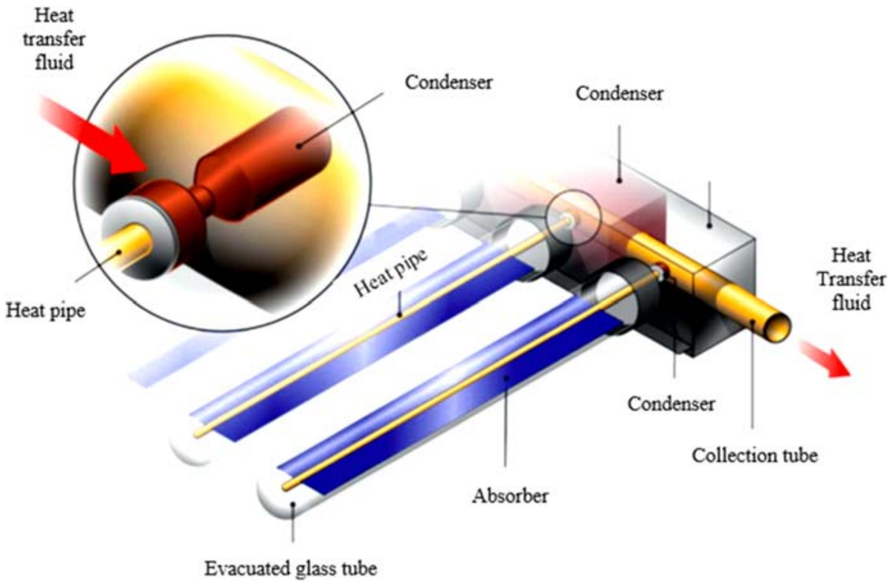

FIGURE 1.6

Evacuated tube solar collector.

Adapted/reproduced from with permission from K. Hudon, Solar energy - water heating, Future Energy: Improved, Sustainable and Clean Options (2013) 433–451 [22] Elsevier, copyright 2014.

fused together. The barium getter serves a different purpose. When the glass tubes are heated, the barium getter also become very hot before the ends are fused together and a pure layer of barium is coated at the bottom of the tube which looks like a chrome plate inside the outer glass tube. Compared to the FPC the main advantage of the ETC is that the constant profile of the round evacuated tube is always nearly perpendicular to the rays of the sun. Therefore, the energy observed is roughly constant over the course of day [24]. ETCs are further classified in to two groups: (1) direct flow ETC (2) heat pipe ETC.

The thermal efficiency and economic evaluation of evacuated solar water heater for rural area were examined by Yanhua et al. [25]. It was observed that the indoor temperature can meet the heating demand. It was concluded that ETC solar water heating system for room heating is economically cheaper than air-conditioning system and coal fired boiler. The thermal performance of evacuated tube solar collector was examined by Xu et al. [26]. The experiments were conducted with various parameters such as steam temperature, solar irradiation, and climate conditions. It was showed that ETC collector has exceptional collecting efficiency and steam needs to supply for a long time. The thermal performance of ETC-SWH was studied by Shafieian et al. [27]. The results indicate that water temperature was increased significantly by improving overall thermal efficiency and decreasing exergy destruction. Sedeghi et al. [28] analyzed ETC by using Gene-Expression Programming. It was reported that the thermal output was improved to 72% and evacuated tube collector is reliable and trustworthy.

1.4.2 Concentrated solar collectors

In concentrating solar collector, different kinds of mirrors and concentrators are used for concentrating the solar radiation to deliver higher temperature varying from 400°C to 1000°C. Parabolic trough, parabolic dish, solar tower or central receiver and compound parabolic concentrator (CPC) are the concentrated solar collectors. The concentration ratio varies from less than unity to the 10^5 order higher values. Concentrated solar collectors are classified in to two types: (1) line focusing (2) point focusing. Line focus solar collectors have lower concentration ratios, and point focus collectors have higher concentration ratio. The CPC collector is a concentrated collector which is non imaging. Whereas line and point concentrating collectors are parabolic trough and solar tower respectively [29].

1.4.2.1 Line focus collectors

Line focus collectors have reflectors that focus solar irradiation on a linear receiver. Line focus collectors are categorized into linear Fresnel and parabolic trough. A linear Fresnel solar collector is approximately a parabolic trough and having independent reflectors instead of continuous one. Whereas there may be some optical performance loss due to independent reflectors used, this may be some other benefits to pay to increase the overall performance and economic benefits.

1.4.2.1.1 Parabolic trough

The parabolic trough solar collector primarily contains tubular reflector and reflecting mirrors at the focal line. The solar energy is collected on the surface of the receiver tubes by parabolic reflecting mirrors and transformed into thermal energy to heat energy and this heat transferred to the fluid flowing through the receiver tube. Normally, the heat exchanging fluid enters one side of the parabolic trough and discharge to another end. Some of the parabolic trough collectors tube in tube arrangements to allow heat transfer fluid to enter and exit [30,31]. The schematic diagram of the parabolic trough is shown in Fig. 1.7.

Normally, parabolic trough is installed to get maximum energy, and the collectors are aligned from north to south to allow tracking from east to west direction. The parabolic trough maybe fitted to get maximum energy in winter, with the collector aligned direction from east to west. The commercially available parabolic trough concentrator achieves concentration ratio ranges 50–80 [29].

1.4.2.1.2 Linear Fresnel

The linear Fresnel collector consists of flat or slightly parabolic reflectors with single axis solar tracking frame and fixed receiver comprising single or multiple linear receiver tubes and often with secondary reflectors to attain higher concentration ratio [32]. In addition to parabolic trough collector, linear Fresnel collector is also considered as an interesting substitute line focus technology, which has tremendous potential to reduce initial investment to a large extend. The primary reflectors monitor the location of the sun while the assembly of the receiver remains unchanged. The line diagram of linear Fresnel collector is shown in Fig. 1.8. Linear Fresnel development history traces back 1957, when Baum first suggested the original idea of splitting a large parabolic trough collector into separate small ones. The concept was later first put into effect. A prototype of linear

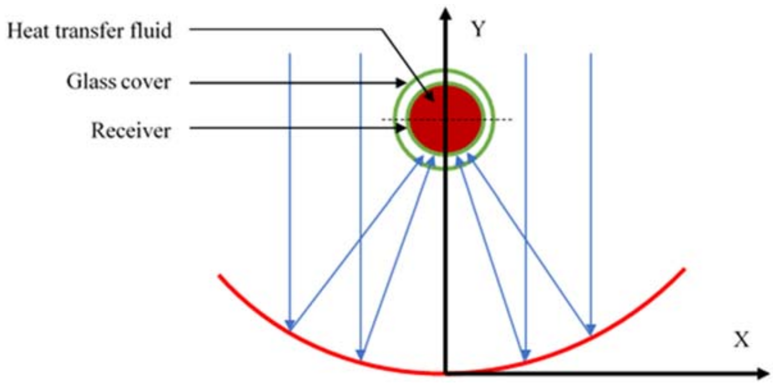

FIGURE 1.7

Parabolic trough.

Fresnel biaxial tracking was constructed in Italy by Francia [33]. Numerous optimization projects were carried out in the 1970s with the goal of improving performance, but most of them remained in the experimental stage [31].

In the early 1990s, PAZ company, Isreal established an innovated linear Fresnel collector with a secondary reflector, which was of great significance to increase the concentration ratio. Solarmundo from Belgium had the linear Fresnel collector prototype designed and tested of 2500 m^2 and subsequently stated that the overall cost of investment was reduced by nearly 50%. In addition, linear Fresnel technology was also more cost effective than other established concentrated solar technologies which attracted the interests of scientists around the world. Australian company built the first linear Fresnel collector of 1 MWt which is produced steam in 2004 [31].

In Spain, the solar power group created the Fresdemo pilot collector in 2007 and achieved numerous important experimental output results. The first commercial linear Fresnel receiver Novatec Solar AG was constructed Spain in 2009, it was 1.4 MWe. While linear Fresnel collector was the latest concentrator solar technology to be used to appear and linear Fresnel creation is still lagging to some degree that of the parabolic trough collector for historical reasons [32]. Currently there are an increasingly growing number of linear Fresnel plants and more plants under construction worldwide. In the meantime, increasing research interests have been shifted into design, development, optimization and system integration of linear Fresnel collector.

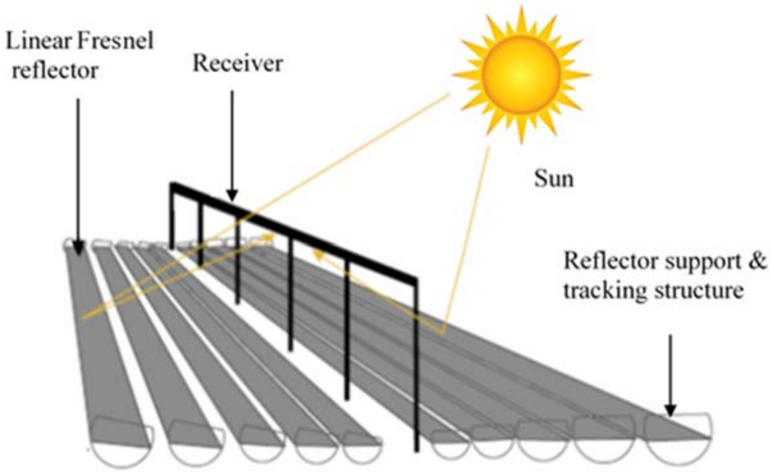

FIGURE 1.8

Linear Fresnel collector.

Adapted/reproduced from with permission from A.B. de Sá, V.C. Pigozzo Filho, L. Tadrist, J.C. Passos, Direct steam generation in linear solar concentration: experimental and modeling investigation – a review, Renewable and Sustainable Energy Reviews 90 (2018) 910–936 [12] Elsevier, copyright 2018.

A fixed receiver is attached on the linear tower of the Fresnel collector in which linear mirror strips are concentrated solar radiation. For example, there are many linear Fresnel receiver designs including plates, simple pipes, secondary concentrating devices, and evacuated tubes. A fixed linear cavity, with single or multiple number of tubes is in the linear Fresnel collector where inside of the cavity, the tubes are surrounded by air but not in contact with ambient [34]. The linear Fresnel concentrator concentrate the solar irradiation into the tubes and a heat transfer fluid is flowing through the tubes and heat transfer fluid absorb the heat. Several researchers were examined the performance of trapezoidal cavity in linear Fresnel collector systems. Besides that, direct steam production, the linear Fresnel collector work with molten salt and conventional thermal oils. Linear Fresnel concentrator using evacuated tube and compound parabolic reflector as a secondary reflector was designed by Qiu et al. [35] with molten salt as a heat transfer fluid. The overall performance of the linear Fresnel collector field has been examined by using Monte Carlo ray tracing method with self-developed 3D optical model. In addition, the thermal efficiency was analyzed by a combination of the finite volume method and Monte Carlo ray tracing method [31].

1.4.2.2 Point focus

Point focusing collectors have a reflector, which concentrates the solar radiation at the central assembly of the receiver. Central receiver system and parabolic dishes are two dominant technologies known as solar towers. Instead of a more uniform reflector base, the solar tower has individual facets of the reflector known as heliostats. Although there may be some losses in optical output due to heliostats, but there may be other benefits that pay to the overall performance or cost benefit.

1.4.2.2.1 Parabolic dish

Parabolic dish includes a receiver, parabolic reflector with solar tracking, and pipe work to carry the heat transfer fluid. The parabolic dish may be continuous or consists of discreate elements to confirm the shape of parabolic. The receiver is attached to the support system of the reflector, So that the sun is monitored by both the dish and the receiver as shown in Fig. 1.9. The shadow can be minimized by optimizing the size of the receiver, and its support structure can be built on the reflector. Also, the receiver mass can be optimized to reduce the mass needed for tracking the sun. The utmost common attention is to position a Stirling engine at the receiver for a parabolic dish [30]. Alternatively, the heat transfer fluid from the receiver is used to operate heat engine independently. The parabolic dishes are arranged as solar field with a small space to reduce the collisions and protecting the collectors, whereas enabling ample maintenance and minimizing the heat transfer fluid pipe work and parasitic pumping capacity. Commercially available parabolic dish collectors attain the concentration ratio of greater than 2000 [29].

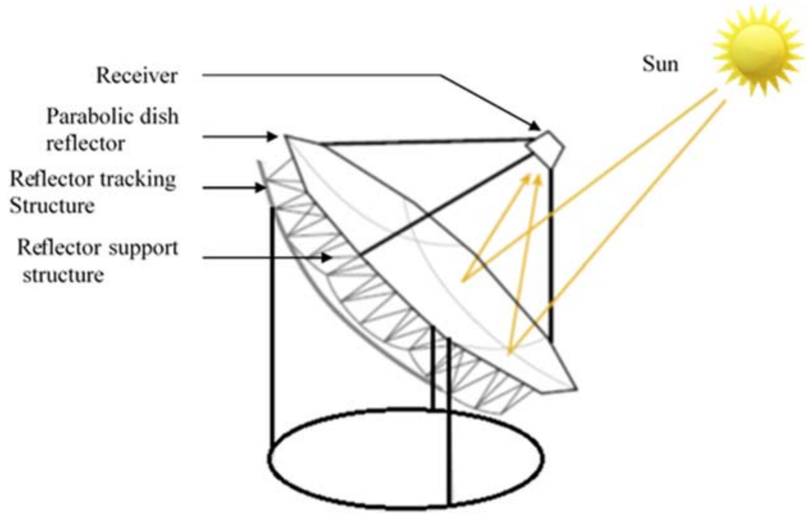

FIGURE 1.9

Parabolic dish.

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1.4.2.2.2 Solar tower

Solar tower adopts a slightly different method for producing solar thermal energy. Although a heat collection system distributed around the solar energy is used by the parabolic trough array, the central receiver concentrates the heat collection in a single central facility, which contains a huge solar receiver and heat collector is mounted on the top of the tower. The tower is fixed on the center of a special mirrors known as heliostats; each heliostat is managed to concentrate the sunlight and reaches it onto the central receiver installed on the pole. The Fig. 1.10 displays the schematic illustration of solar tower. This type of solar plant is known as point focus solar thermal power plant [30].

The earliest solar tower built in Spain in 1981 was 500 KW, which uses sodium as the heat transfer fluid. In 1982 solar-1 was installed in Barstow, California, with 10 MW power production capacity which was water/steam based heat transfer cycle. In 1996 solar-1 was developed to solar-2, and the heat transfer fluid used as molten salt. Tests were carried out in different places until 2007 and the world's first commercial solar tower in Spain named Planta solar 10 (PS10) [15].

The solar tower plant is basically an approximation of a huge parabolic dish. Every reflector belongs to somewhat different size parabola. But every mirror must be capable of independently tracking the sun, construction of this solar collector comparatively costlier than solar trough plant. The advantage is that it can reach higher temperature between 800°C and 1000°C [29].

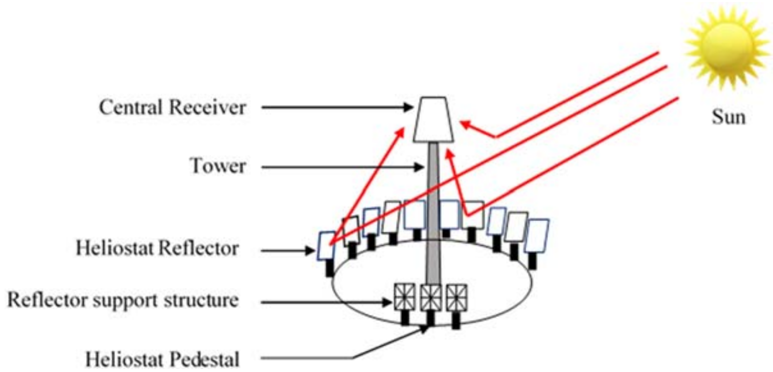

FIGURE 1.10

Solar tower or Central receiver system.

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The size of the solar tower can be estimated by solar field size, which can be constructed. This will be limited, as the distance between the central receiver and the heliostat is too large and the efficiency will fall. The biggest single field tower seems likely to be around 200 MW or less. The larger plants require multiple fields and towers. Generally, flat type heliostats used in larger towers, which is economical to assemble than solar trough. The nature of the solar tower construction flat terrain is not necessary. But a flat site is important for solar trough plant. The heliostats usually have an area of up to 120 m^2. A 11 MW PS10 plant built in Spain has 624 heliostats and occupied 60 ha or 5.5 ha/MW. A second Spanish solar tower PS20 with 20 MW has 1255 heliostats and occupied 90 ha area. These both Spanish solar towers are producing steam using direct steam system. The steam condition of the system is 250°C and 40 bar relatively low overall thermal efficiency [15]. The largest solar tower plant is Ivanpah in California. This plant producing direct steam of 392 MW and has three towers. Moreover, Crescent Dunes solar tower in USA, generating 110 MW heat energy. Furthermore several larger solar towers are under construction in china, using both heat transfer and heat capture [15].

1.5 Photovoltaic thermal systems

The solar energy is converted into direct electric current through photovoltaic panels. Amongst 7%–19% of the solar energy is transformed into electricity, while the remaining energy is reflected or absorbed by the photovoltaic panel in the form of thermal energy [37]. This heat energy reduces the electrical efficiency of the PV module. Every rise of 1°C temperature of Panel decreases 0.5% of electrical efficiency of crystalline silicon PV panel and 0.25% drop in amorphous silicon PV cell [38]. As a remedy researchers have recommended that the performance of the PV system can be improved by reducing the heat from the PV panel by using some cooling medium such as water, air, bi-fluid, oil, etc. [39]. Besides that the extracted heat can be employed for some useful applications like, space heating, water and air heating, small scale industries, medical applications, etc. [1]. As a remedy a system simultaneously convert solar energy in to electrical and heat energy is known as hybrid photovoltaic thermal (PVT) system [7,40]. This PVT system requires smaller area than separate photovoltaic and thermal collector systems. The performance of the PVT system depends on the type of PV panel used, dimensions, type of heat transfer fluid, type of technology, rate of flow and climate conditions. Normally PV module is reserved at lower temperature for maximum efficiency, durable and lower chance of decay of silicon [41]. Dwivedi et al. [10] reported that the performance of PV system adversely affected by rise in surface temperature. Also, humidity, wind, dust/shading, ambient temperature and solar irradiation were affects the performance of the PV system. The combined effect of solar irradiance and temperature results in over heating of the solar panel, which may result in increase in cell degradation, decrease in performance, decrease in conversion efficiency, and reduce the life of PV panel.

Fig. 1.11 displays the working principle of hybrid PVT system. This system includes photovoltaic panel, heat exchanger, battery, heat transfer fluid, and pump. Once the solar radiation falls on the photovoltaic panel, 7%—19% of the irradiation is transformed into electricity [37]. The remaining energy is converted into heat energy. The heat can decrease the panel life and efficiency of the PV panel [42]. So, PV panel should be cooled by using any one of the cooling methods. Generally, the pipes are arranged on rear part of the photovoltaic panel and heat transfer fluid (water) passes through these tubes. This fluid extracts the heat energy from the PV module and this heat energy used for some other useful applications. The electrical energy can be stored in the battery. Generally, various methods of cooling the PVT systems are practically used. The classification of PVT systems are shown in Fig. 1.12 [43].

1.5.1 Classifications of PVT systems

In air-based PVT system, the heat transfer fluid is air, which works either by active or passive methods. Normally, fan or blower is used for passive mode to achieve higher flow rate. The air extracts the thermal energy from the photovoltaic and the extricate energy can be used for useful applications. So that the temperature of the photovoltaic panel get reduced and the efficiency and life of PV panel improved [43]. Normally, higher temperature applications, air-based cooling system do not work efficiently. But water has the best thermal properties compared to air. In water-based PVT system the water tubes are mounted back side of the PVT system. The water flows through the tubes and extract the heat from the PV panel so that heat of the PV module reduced, life and output of the photovoltaic panel improved. The hot water used for domestic need for most of the case [44].

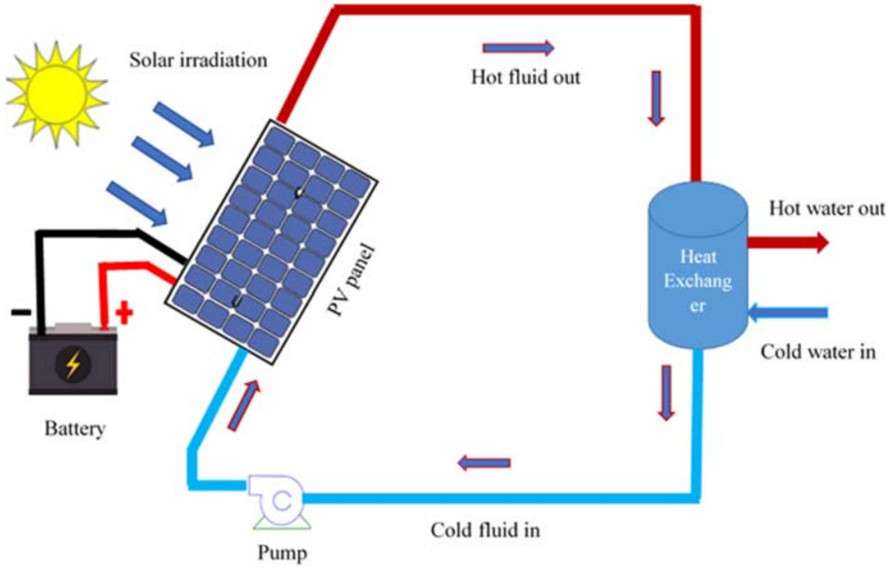

FIGURE 1.11

PVT system.

Adapted/reproduced from with permission from R. Reji Kumar, M. Samykano, A.K. Pandey, K. Kadirgama, V.V. Tyagi, Phase change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: a futuristic approach and its technical challenges, Renewable and Sustainable Energy Reviews 133 (2020) 110341 [39] Elsevier, copyright 2020.

The output of the water or air-assisted PVT systems were not reached the projected one. Owing to this, more investigators [45–47] were suggested that using two fluids simultaneously in single PVT system is known as bi fluid PVT system. In this system both fluids are passes through separate channels. Most of the configurations are one fluid passes through rear side and another fluid passing through the channel of the photovoltaic panel. This bi-fluid PVT system cool the panel, obtain hot air, hot water and electrical energy simultaneously [41,42].

Jet impingement is the efficacious approaches of heat transfer between photovoltaic module and the heat transfer fluid. In this technique the high velocity of fluid is sprayed on the back side of the photovoltaic panel. The heat transfer fluid extracts the heat energy from the photovoltaic module so that the photovoltaic module cool down and the heat transfer fluid get rise the temperature. This is an excellent technique of improving conductive heat transfer methods and is beneficial for cooling electronic equipment, turbine blade cooling, food processing, etc., and jet impingement method enhances the thermal and electrical efficiency of the PVT system [43]. Jaaz et al. [48], had developed a CPC with water impingement PVT system. The results confirmed that increase in mass flow rate of water, improves the electrical output. It was reported that PV panel electrical

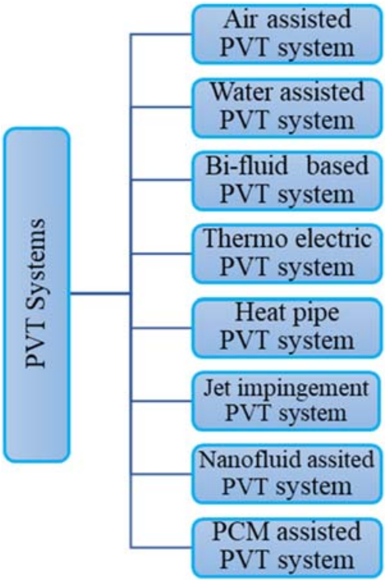

FIGURE 1.12

Classifications of PVT systems.

performance had increased by 7.0% with the use of CPC and water jet impingement. In addition, Belusko et al. [49], studied the experimental investigation of jet impingement on solar collector. The results concluded that the thermal energy had improved by 21% when jet impingement was used. Hasan et al. [50], had studied on water jet array nanofluid in PVT system with various nanofluids (SiC, SiO_2, TiO_2). The results concluded that nanofluid (SiC/water) jet array impingement had a higher efficiency and the thermal, electrical and overall efficiency was 85%, 12.75%, and 97.75% respectively at the flow rate of 0.167 kg/s.

Thermo electric PVT systems works on the principle of see back effect. According to see back effect, two different metals or semiconductors that maintain different temperatures produce emf between two metals. In this system one end of the junction is coupled to the photovoltaic panel other end of the junction is cooled by working medium like air or water, the cooling medium temperature is lesser than the PV panel temperature. Thermo electric cooling is normally used in electronic cooling like microprocessor [43]. More researchers are implementing this method in PVT systems. He et al. [51], examined the experimental investigation of thermo electric cooling and heating in PVT systems. It was reported that the Coefficient of performance of the system is 1.7. Correspondingly, the thermal and electrical performance was improved 16.7% and 23.5%. Makki et al. [52], reported that the overall performance of thermo electric PVT system is higher than conventional PVT system.

Heat pipe is a collection of principles of condensation and evaporation to transfer heat efficiently from two solid surface without any outside assistance. In the evaporator section the working fluid absorbs heat from the photovoltaic module and converted into vapor state due to the adiabatic section pressure difference. The vapor state enters into the condenser section and reject the heat and transformed into liquid state again return back to the evaporator section through wick assembly.

Heat pipe-based PVT systems are passive type PVT systems and used for cooling the photovoltaic module. Few authors [53–55] were investigated on heat pipe assisted PVT systems. Shixiang et al. [53], reported that the power output, thermal and electrical efficiency of the system were 7.24 kWhr, 49.9% and 7.51% respectively when use of vapor injection method (VISHP-PVT). Zheng et al. [54] examined a heat pipe with wire mesh PVT systems with 20 and 40 degrees inclined angle. The results confirmed that heat pipe with wire mesh has higher performance than without wick. Also, it was observed that heat pipe without wick works effectively more than 20 degrees and with wire mesh works effectively at less than 20 degrees inclined angle. A loop heat pipe-based photovoltaic system (PVT-LHP) was developed by Diallo et al. [55], using triple heat exchanger. It was noted that thermal, electrical and overall performance of PVT-LHP can achieve 55.7%, 12.2% and 67.8% respectively. Moreover, the coefficient of performance of PVT (COP_{PVT}) system was 2.2 times higher than conventional PVT system.

Generally, air, water, and EG are used as the working fluid in PVT systems. The main drawback of the conventional fluids is lower thermal conductivity, and the heat transfer capacity is mainly dependent on the thermal conductivity of the heat transfer fluids. Therefore this problem can be solved by dispersing highly conductive nanoparticles in to the conventional fluid [56]. Generally Al_2O_3, TiO_2, CuO, SiC, CNTs are the commonly used nanoparticles [42]. These nanoparticles are dispersed with conventional fluid, which provide higher thermal conductivity nanofluid. Owing to higher conductivity, the heat transfer capacity was improved than conventional fluid. The working principle is same as the water-assisted PVT system. The combination of water and nanoparticles provide significant improvement in thermal properties. Also, there is an enhancement in thermal, electrical, and overall performance of the PVT system [57–59].

The fundamental idea of PVT system has been explained in this section, and important literature review exertions have been dedicated to establishing a vibrant research and development in this area. Applications of PVT on working fluids such as air, water, and nanofluids were observed to be used for water heating and space heating only. In future, for increasing the thermal output of PVT device and the thermal energy, there is a need to use some other higher temperature applications. It can be noted that, there is a lack of storage of heat energy facility in this type of PVT systems. The limitation of this PVT system is that extracted thermal energy cannot be stored in any place, but it can be used immediately for some other applications, whenever solar irradiation is available.

1.6 Conclusions and recommendations

1.6.1 Conclusions

The detailed literature review on direct and indirect energy harvesting and their different methods are discussed in this chapter, which will be very effectual and beneficial for the new investigators. Also, this chapter describes various types of generations of solar photovoltaics used, different methods of solar collectors, and various types of hybrid PVT systems. The increase in solar irradiation decreases the overall performance of the photovoltaic system. The increase in solar cell temperature increases the short circuit current. Also, the increase of solar module temperature decreases the open circuit voltage. Furthermore, low wind speed, higher ambient temperature, and high relative humidity are related to the reduction of overall efficiency of the system. The working methods, operating temperatures, and various applications of different solar collectors are discussed. The thermal performance of solar collectors is highly dependent on the mass flow rate of heat transfer fluid, and the exergy efficiency is dependent on solar irradiance. FPCs are used for lower and medium temperature applications, but ETC systems are used for higher temperature applications. The performance and initial installation cost are high for parabolic trough collector. Linear Fresnel collector has lower efficiency, and initial cost is less than parabolic trough collector. The linear Fresnel collector arrangement is technically user-friendly for large-size collectors. The large-size collector may enhance the collector performance by reducing the pumping power of the system. And the fixed receiver system greatly reduces the leakage of heat transfer fluid and reduces the maintenance cost. Finally, PVT technology is more eco-friendly and will commit to the improvement of an alternative renewable energy source, dependency, autonomy and cost attractiveness with the use of fossil fuel source of energy.

1.6.2 Recommendations

This chapter discusses the detailed review of various solar energy harvesting techniques and different types of solar collectors and various cooling methods. The following recommendations are given for future work.

- It is recommended to use phase change material with high latent heat and surface area to achieve better solar thermal energy.
- It is recommended to use aluminum absorber plate, unless corrosion is a consideration, in which better option is copper absorber plate.
- There is a need to develop a heat transfer fluid with a lower freezing point, higher thermal and chemical stability limits, good heat transfer properties, and negligible environmental impacts.
- The most viable technique to overcome the problem of tube receiver deflection and glass cover rupture would be inexpensive materials with excellent thermo mechanical properties.

- To improve the thermal efficiency of FPCs and PTCs, it is proposed to combine passive methods and nanofluids. To examine the various forms, mixtures and concentration ratios of nanofluids and their effect on the thermal efficiency of FPCs, research studies should be carried out. In addition, studies are required for this subject to decide the optimum mass flow rate and consequential use of pump power.
- To optimize the resultant effect of the solar collector, it is recommended to use solar tracker to detect the optimum solar radiation and temperature.
- PVT system has achieved a major milestone, and still some improvements are needed for the future advancement of this technology such as developing new feasible, energy efficient and economic systems like PCM integrated and nano PCM integrated PVT systems, study long-time dynamic efficiency PVT systems, demonstration of PVT systems in buildings and feasibility study, study the optimization and geometric parameters of PVT system, and 4E (energy, exergy, exergoeconomic and enviroeconomic) analysis of PVT systems.

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References

[1] M. George, A.K. Pandey, N. Abd Rahim, V.V. Tyagi, S. Shahabuddin, R. Saidur, Concentrated photovoltaic thermal systems: a component-by-component view on the developments in the design, heat transfer medium and applications, Energy Conversion and Management 186 (2019) 15−41.

[2] S. Diwania, S. Agrawal, A.S. Siddiqui, S. Singh, Photovoltaic−thermal (PV/T) technology: a comprehensive review on applications and its advancement, International Journal of Energy and Environmental Engineering (2019).

[3] W. Weiss, M. Spörk-Dür, Solar heat worldwide 2018. Global market development and trends in 2017. Detailed market figures 2016, IEA Solar Heating and Cooling Programme (2018) 94.

[4] Global Energy Review 2020, Global Energy Review 2020 (2020).

[5] W. Fuqiang, C. Ziming, T. Jianyu, Y. Yuan, S. Yong, L. Linhua, Progress in concentrated solar power technology with parabolic trough collector system: a comprehensive review, Renewable and Sustainable Energy Reviews 79 (2017) 1314−1328.

[6] L.F. Cabeza, et al., Thermochemical energy storage by consecutive reactions for higher efficient concentrated solar power plants (CSP): proof of concept, Applied Energy 185 (2017) 836−845.

[7] A. Herez, H. El Hage, T. Lemenand, M. Ramadan, M. Khaled, Review on photovoltaic/thermal hybrid solar collectors: classifications, applications and new systems, Solar Energy 207 (2020) 1321–1347.

[8] A.H.A.A.H.A. Kazem, Photovoltaic/Thermal (PV/T) systems.

[9] E. Zambolin, D. Del Col, Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions, Solar Energy 84 (8) (2010) 1382–1396.

[10] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, I. Kirpichnikova, Advanced cooling techniques of P.V. modules: a state of art, Case Studies in Thermal Engineering 21 (2020) 100674.

[11] G. Shen, D. Chen, One-dimensional nanostructures for electronic and optoelectronic devices, Frontiers of Optoelectronics in China 3 (2) (2010) 125–138.

[12] A.B. de Sá, V.C. Pigozzo Filho, L. Tadrist, J.C. Passos, Direct steam generation in linear solar concentration: experimental and modeling investigation – a review, Renewable and Sustainable Energy Reviews 90 (2018) 910–936.

[13] D. Li, Z. Li, Y. Zheng, C. Liu, A.K. Hussein, X. Liu, Thermal performance of a PCM-filled double-glazing unit with different thermophysical parameters of PCM, Solar Energy 133 (2016) 207–220.

[14] L. Lakatos, G. Hevessy, J. Kovács, Advantages and disadvantages of solar energy and wind-power utilization, World Futures The Journal of General Evolution 67 (6) (2011) 395–408.

[15] P. Wray, Solar power, American Ceramic Society Bulletin 87 (7) (2008) 31–33.

[16] S. Tiwari, G.N. Tiwari, I.M. Al-Helal, Performance analysis of photovoltaic-thermal (PVT) mixed mode greenhouse solar dryer, Solar Energy 133 (2016) 421–428.

[17] G.N. Tiwari, A. Tiwari, Shyam, Solar water-heating systems á natural circulation á forced circulation á heat, no. i. (2016).

[18] W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy 80 (1) (2006) 78–88.

[19] K. Hudon, T. Merrigan, J. Burch, J. Maguire, Low-cost solar water heating research and development roadmap, Contract (N. York, N.Y.: 1960) 303 (2012) 275–3000.

[20] S.A. Kalogirou, S. Karellas, K. Braimakis, C. Stanciu, V. Badescu, Exergy analysis of solar thermal collectors and processes, Progress in Energy and Combustion Science 56 (2016) 106–137.

[21] S.E. Division, Review of sputter deposited mid- to high- temperature solar selective coatings for flat plate/evacuated tube collectors and solar thermal power generation applications (2010) 1–86.

[22] K. Hudon, Solar energy - water heating, Future Energy: Improved, Sustainable and Clean Options (2013) 433–451.

[23] K. Balaji, A. Idrish Khan, P. Ganesh Kumar, S. Iniyan, R. Goic, Experimental analysis on free convection effect using two different thermal performance enhancers in absorber tube of a forced circulation flat plate solar water heater, Solar Energy 185 (2019) 445–454.

[24] A. Nokhosteen, S. Sobhansarbandi, Novel method of thermal behavior prediction of evacuated tube solar collector, Solar Energy 204 (2020) 761–768.

[25] L. Yanhua, H. Wengang, Y. Hongwen, L. Mingxin, ScienceDirect ScienceDirect ScienceDirect and Cooling performance and economic evaluation of heating evacuated tube solar collector with auxiliary electric heater for rural heating collector with auxiliary electric heater for rural heating Assessing the f, Energy Procedia 158 (2019) 186–191.

[26] L. Xu, Z. Liu, S. Li, Z. Shao, N. Xia, Performance of solar mid-temperature evacuated tube collector for steam generation, Solar Energy 183 (2019) 162−172.
[27] A. Shafieian, M. Khiadani, A. Nosrati, Thermal performance of an evacuated tube heat pipe solar water heating system in cold season, Applied Thermal Engineering 149 (2019) 644−657.
[28] G. Sadeghi, M. Najafzadeh, H. Safarzadeh, Utilizing gene-expression programming in modelling the thermal performance of evacuated tube solar collectors, Journal of Energy Storage 30 (2020) 101546.
[29] M.J. Blanco, S. Miller, Introduction to Concentrating Solar Thermal (CST) Technologies, Elsevier Ltd., 2017.
[30] K. Lovegrove, R. Bader, D. Fernandez, K. Urkalan, Concentrating solar thermal technology status: informing a CSP roadmap for Australia, ITP Report (2018).
[31] J. Sun, Z. Zhang, L. Wang, Z. Zhang, J. Wei, Comprehensive review of line-focus concentrating solar thermal technologies: parabolic trough collector (PTC) versus linear fresnel reflector (LFR), Journal of Thermal Science 29 (2020).
[32] G. Zhu, T. Wendelin, M.J. Wagner, C. Kutscher, History, current state, and future of linear Fresnel concentrating solar collectors, Solar Energy 103 (2014) 639−652.
[33] C. Silvi, The pioneering work on linear fresnel reflector concentrators (LFCs) in Italy, SolarPACES Conference (2009) 1−8.
[34] N.B. Desai, S. Bandyopadhyay, Line-focusing concentrating solar collector-based power plants: a review, Clean Technologies and Environmental Policy 19 (1) (2017) 9−35.
[35] S. Abouali, et al., Co_3O_4/porous electrospun carbon nanofibers as anodes for high performance Li-ion batteries, Journal of Materials Chemistry A 2 (40) (2014) 16939−16944.
[36] M. Sharma, P. Thakur, V.K. Thakur, S.S. Rahatekar, A review on exergy analysis of solar parabolic collectors, Solar Energy 197 (2020) 411−432.
[37] B. Sandnes, J. Rekstad, A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model, Solar Energy 72 (1) (2002) 63−73.
[38] H. Nazir, et al., Recent developments in phase change materials for energy storage applications: a review, International Journal of Heat and Mass Transfer 129 (2019) 491−523.
[39] R. Reji Kumar, M. Samykano, A.K. Pandey, K. Kadirgama, V.V. Tyagi, Phase change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: a futuristic approach and its technical challenges, Renewable and Sustainable Energy Reviews 133 (2020) 110341.
[40] V.V. Tyagi, A.K. Pandey, R. Kothari, S.K. Tyagi, Thermodynamics and performance evaluation of encapsulated PCM-based energy storage systems for heating application in building, Journal of Thermal Analysis and Calorimetry 115 (1) (2014) 915−924.
[41] A.H.A. Al-Waeli, K. Sopian, H.A. Kazem, M.T. Chaichan, Photovoltaic/thermal (PV/T) systems: status and future prospects, Renewable and Sustainable Energy Reviews 77 (2017) 109−130.
[42] T.M. Sathe, A.S. Dhoble, A review on recent advancements in photovoltaic thermal techniques, Renewable and Sustainable Energy Reviews 76 (2017) 645−672.
[43] M.M. Islam, A.K. Pandey, M. Hasanuzzaman, N.A. Rahim, Recent progresses and achievements in photovoltaic-phase change material technology: a review with special treatment on photovoltaic thermal-phase change material systems, Energy Conversion and Management 126 (2016) 177−204.

[44] S.S. Joshi, A.S. Dhoble, Photovoltaic -thermal systems (PVT): technology review and future trends, Renewable and Sustainable Energy Reviews 92 (2018) 848–882.

[45] D. Su, Y. Jia, X. Huang, G. Alva, Y. Tang, G. Fang, Dynamic performance analysis of photovoltaic-thermal solar collector with dual channels for different fluids, Energy Conversion and Management 120 (2016) 13–24.

[46] M.Y. Othman, S.A. Hamid, M.A.S. Tabook, K. Sopian, M.H. Roslan, Z. Ibarahim, Performance analysis of PV/T Combi with water and air heating system: an experimental study, Renewable Energy 86 (2016) 716–722.

[47] H. Jarimi, M.N. Abu Bakar, M. Othman, M.H. Din, Bi-fluid photovoltaic/thermal (PV/T) solar collector: experimental validation of a 2-D theoretical model, Renewable Energy 85 (2016) 1052–1067.

[48] A. Hameed Jaaz, H.A. Hasan, K. Sopian, A.A.H. Kadhum, T.S. Gaaz, A.A. Al-Amiery, Outdoor performance analysis of a photovoltaic thermal (PVT) collector with jet impingement and compound parabolic concentrator (CPC), Materials (Basel) 10 (8) (2017).

[49] M. Belusko, W. Saman, F. Bruno, Performance of jet impingement in unglazed air collectors, Solar Energy 82 (5) (2008) 389–398.

[50] H.A. Hasan, K. Sopian, A.H. Jaaz, A.N. Al-Shamani, Experimental investigation of jet array nanofluids impingement in photovoltaic/thermal collector, Solar Energy 144 (2017) 321–334.

[51] W. He, J. Zhou, C. Chen, J. Ji, Experimental study and performance analysis of a thermoelectric cooling and heating system driven by a photovoltaic/thermal system in summer and winter operation modes, Energy Conversion and Management 84 (2014) 41–49.

[52] A. Makki, S. Omer, Y. Su, H. Sabir, Numerical investigation of heat pipe-based photovoltaic-thermoelectric generator (HP-PV/TEG) hybrid system, Energy Conversion and Management 112 (2016) 274–287.

[53] S. Lu, R. Liang, J. Zhang, C. Zhou, Performance improvement of solar photovoltaic/thermal heat pump system in winter by employing vapor injection cycle, Applied Thermal Engineering 155 (2019) 135–146.

[54] M. Hu, R. Zheng, G. Pei, Y. Wang, J. Li, J. Ji, Experimental study of the effect of inclination angle on the thermal performance of heat pipe photovoltaic/thermal (PV/T) systems with wickless heat pipe and wire-meshed heat pipe, Applied Thermal Engineering 106 (2016) 651–660.

[55] T.M.O. Diallo, et al., Energy performance analysis of a novel solar PVT loop heat pipe employing a microchannel heat pipe evaporator and a PCM triple heat exchanger, Energy 167 (2019) 866–888.

[56] A.N. Al-Shamani, et al., Nanofluids for improved efficiency in cooling solar collectors - a review, Renewable and Sustainable Energy Reviews 38 (2014) 348–367.

[57] N. Bozorgan, M. Shafahi, Performance evaluation of nanofluids in solar energy: a review of the recent literature, Micro and Nano Systems Letters 3 (1) (2015) 1–15.

[58] S.K. Verma, A.K. Tiwari, Progress of nanofluid application in solar collectors: a review, Energy Conversion and Management 100 (2015) 324–346.

[59] O. Mahian, A. Kianifar, S.A. Kalogirou, I. Pop, S. Wongwises, A review of the applications of nanofluids in solar energy, International Journal of Heat and Mass Transfer 57 (2) (2013) 582–594.