Solar power technology for electricity generation: A critical review

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Abstract
Negative environmental impact of fossil fuel consumption highlight the role of renewable energy sources and give them a unique opportunity to grow and improve. Among renewable energy sources solar energy attract more attention and many studies have focused on using solar energy for electricity generation. Here, in this study, solar energy technologies are reviewed to find out the best option for electricity generation. Using solar energy to generate electricity can be done either directly and indirectly. In the direct method, PV modules are utilized to convert solar irradiation into electricity. In the indirect method, thermal energy is harnessed employing concentrated solar power (CSP) plants such as Linear Fresnel collectors and parabolic trough collectors. In this paper, solar thermal technologies including solar trough collectors, linear Fresnel collectors, central tower systems, and solar parabolic dishes are comprehensively reviewed and barriers and opportunities are discussed. In addition, a comparison is made between solar thermal power plants and PV power generation plants. Based on published studies, PV-based systems are more suitable for small-scale power generation. They are also capable of generating more electricity in a specific area in comparison with CSP-based systems. However, based on economic considerations, CSP plants are better in economic return.

KEYWORDS
central receiver tower, concentrated solar power, linear fresnel reflector, parabolic trough collector, photovoltaic
1 | INTRODUCTION

Due to the increase in world population, development in industrial activities, and enhancement in living standards, the human demand for electricity will grow in the future years.\(^\text{1}\) Traditional fossil fuels such as oil and coal cause carbon dioxide emissions and global warming.\(^\text{2}\)

Thus, it is necessary to explore appropriate alternatives sources for electricity generation which are environmentally benign and sustainable. Solar energy is one of the most attractive sources of energy for electricity generation. Typically, solar energy harnessed in the daytime needs to be stored (thermally or electrically) for utilization in the night. Utilizing energy storage units typically result in increased investment and maintenance costs and hence an increase in the levelized cost of generated electricity. Recent advances in solar energy research and development have helped make solar energy systems more affordable for commercial utilization.\(^\text{3}\) Research continues in order to decrease the constraints (which are mainly technical) and cost of those systems which are typically employed in solar power plants.

Based on a recent International Energy Agency (IEA) report,\(^\text{4}\) the share of fossil fuels in the global energy consumption is equal to 82%, however, it is anticipated that this share will be reduced down to 75% by 2035 by developing new renewable energy sources or adding improvements to the present renewable energy systems.

The energy received by the earth from the sun in 1 day can provide the whole world’s energy requirement for more than 20 years since this the rate of the solar energy which fell to the earth’s surface is 120 × 10⁵ watts.\(^\text{5}\) Development in solar energy infrastructures can enhance the level of energy security since it is an import-independent energy source. In addition, using solar energy results in minimal environmental impacts.\(^\text{6,7}\) The potential of solar energy makes it favorable in several ways such as:

- Since the tropical and subtropical regions receive huge amounts of solar irradiation, solar energy is very suitable to generate electricity in these regions.
- Social acceptance of solar energy increased in recent years.
- Electricity generation using solar energy is relatively affordable and it is appropriate for rural and urban regions.

In the present paper, a comprehensive literature review is conducted on solar thermal power plants that use concentrators such as parabolic troughs, central towers, parabolic dishes, and linear Fresnel reflector systems. The paper will attempt to provide summaries of the studies conducted on solar thermal power generation systems. Besides, a brief explanation of photovoltaic systems and a comparison among solar thermal power plants are presented. In addition, an attempt will be made to evaluate and compare the energetic and exergetic performances of these systems.

Kabir et al\(^\text{8}\) investigated solar technologies and discussed the present and future opportunities and barriers. Islam et al\(^\text{9}\) analyzed solar thermal technologies current status and research trends and concluded that direct steam generation by employing solar energy in solar concentrated schemes is the most promising approach. Rovira et al\(^\text{10}\) compared different technologies for integration is solar combined cycles. Hansen and Van Mathiesen\(^\text{11}\) presented a novel approach to evaluate the potential of utilizing solar thermal technologies in the Europe and assessed four countries (Germany, Austria, Italy, and Denmark) statuses of employing renewable energies, specifically solar thermal energy, to achieve European defined targets. The selected countries are assessed under several criteria including substantial heat savings, expansion of district heating networks and with high-renewable electricity and heating sectors. It was concluded that solar energy in the studied countries have this potential to provide 3%-12% of total heat supply. It was demonstrated that solar thermal technologies cannot compete with other renewable technologies in high-capacity systems due to energy prices and -system flexibilities.

2 | SOLAR THERMAL POWER GENERATION SYSTEMS WITH VARIOUS SOLAR CONCENTRATORS

2.1 | Concentrated solar power

Concentrated solar power (CSP) utilize lenses and mirrors in order to focus solar irradiation on a small area. The concentrated radiation can be applied to generate electricity indirectly. The absorbed heat from solar irradiation is used in thermodynamic cycles in order to produce electricity.\(^\text{12}\) These systems are able to generate electricity even in the absence of sun which can be enumerated as their main advantage compared to solar power technologies. This possibility can be happened by integrating energy storage systems such as thermal storage tank to save the extra amount of thermal energy in the daylight for being used in the periods which sunlight is not available. The most important issues pertaining to solar power plants using CSP technology are\(^\text{13}\):

- High efficiency is obtainable since the thermodynamic cycles are fed by high-temperature input.
- CSP technology uses only the direct component of incoming solar radiation, but it implies the loss of the diffused and reflected components.
- CSP systems’ performance will boost up in locations with higher amounts of Direct Normal Irradiation (DNI).
- CSP systems are not appropriate for small-scale power generation since they require high capital cost.
Among the various types of CSP systems, parabolic-trough collectors have the highest market share which is approximately 90%.14

2.1.1 | Solar thermal power generation systems with parabolic trough concentrators

A parabolic trough concentrator (PTC) utilizes the line focus technology for the CSP. This technology attracts intentions in 1980s due to oil crises.15 PTC consists of collector with long parabolic trough and a pedestal as support of the collector. This technology focuses solar irradiations on its focal line. A receiver is located there which absorb the heat. High absorbance material is utilized to coat the receiver. It is surrounded by a tube which is made of glass. In order to decrease heat losses, vacuum status is created between the tube and receiver as shown in (Figures 1 and 2). Vacuum plays key role in receiver insulation and loss of vacuum can cause four times higher heat loss.16 Using lesser components and leakage-free glass cover, vacuum leakage can be prevented.17

The working temperature of PTC is wide, in range of 100 to 400°C, which makes it applicable for several applications. PTCs are categorized based on their working temperature. PTCs work in temperature range between 300 and 400°C are mainly applied for power generation while the ones operate in the range of 100-250°C are used for heating purposes.18

The achieved energy by the heat transfer fluid (HTF) equals to the collected energy by a trough collector in a hour, which can be concluded as follows19:

\[
E_c = \frac{m}{2} \left[ c_p (T_o - T_i)_{j+1} + c_p (T_o - T_i)_{j} \right]
\]  (1)

In Equation (1), the 1st parenthesis, \((T_o - T_i)_{j+1}\) indicates the measured temperature difference at any time of \(j\) between the inlet and outlet of the collector. \((T_o - T_i)_{j+1}\) represents the temperature difference after passing a 1 hour interval from the \(j\)th time.

Direct production of steam can lead to changes in heat transfer to the steam and the pressure.20 Equation (2). Is applied in order to obtain the efficiency of transferring concentrated heat to HTF:

\[
\eta = \frac{E_c}{A(I_f - I_i) \times 3600}
\]  (2)

For the sake of providing preheat water or reheating the superheated steam, PTCs can be used in thermal power plants which utilize coal as fuel. The effect of utilizing PTC is the reduction in coal consumption, as the result, the reduction in carbon dioxide emission. The effect of using this technology in saving the fuel and carbon dioxide is presented in Table 1.21

Mathematical modeling

In order to provide mathematical modeling for evaluation of the thermal performance of a parabolic trough power plant, Mohammad et al22 consider a typical power plant with trough collectors, Figure 3, and modeled the thermal analysis as follows:

The amount of gained energy in the trough collector is calculated as follows:

| TABLE 1 Fuel saving for hybrid parabolic trough collector21 |
|-------------------------------------------------------------|
| Total field area (m²) | Fuel consumption (kg/h) | CO₂ emission (kg/h) |
|-----------------------|------------------------|---------------------|
| 3000                  | 615291.53              | 703893.51           |
| 6000                  | 589792.76              | 674722.84           |
| 9000                  | 539566.43              | 617264.00           |
| 120 000               | 448437.20              | 513012.16           |
where $m_{cl}$ indicates the mass flow rate of the passing working fluid through the trough collector, $I$ represents the Direct Normal Irradiance, $A_p$ denotes the aperture area of the collector, $T_m$ is the average temperature between inlet and outlet of the collector ($T_m = (T_6 + T_7)/2$), $T_a$ indicates the ambient temperature, and $U_L$ denotes the loss coefficient.

By ignoring all the internal losses and required work in the Pumps, then the delivered heat to the steam generation unit is calculated as follows:

$$Q_{gain} = m_{cl}(h_7 - h_6)$$

$$\eta = \eta_p U_L \left( \frac{\Delta T}{T} \right)$$

$$\Delta T = T_m - T_a$$

where $m_{cl}$ indicates the mass flow rate of the passing working fluid through the trough collector, $I$ represents the Direct Normal Irradiance, $A_p$ denotes the aperture area of the collector, $T_m$ is the average temperature between inlet and outlet of the collector ($T_m = (T_6 + T_7)/2$), $T_a$ indicates the ambient temperature, and $U_L$ denotes the loss coefficient.

By ignoring all the internal losses and required work in the Pumps, then the delivered heat to the steam generation unit is calculated as follows:

$$Q_{gain} = m_{cl}(h_7 - h_6) = m_{cl}(h_1 - h_3)$$

Combining equations 3 and 4:

$$m_{cl}(h_1 - h_3) = \eta_p A_p$$

where $m_{cl}$ indicates the mass flow rate of the passing working fluid through the trough collector, $I$ represents the Direct Normal Irradiance, $A_p$ denotes the aperture area of the collector, $T_m$ is the average temperature between inlet and outlet of the collector ($T_m = (T_6 + T_7)/2$), $T_a$ indicates the ambient temperature, and $U_L$ denotes the loss coefficient.

In order to obtain $U_L$ from above equation, $h_{c,ca}$ and $h_{r,ca}$ must be calculated:

$$h_{r,ca} = \varepsilon_r \sigma (T_c + T_a)(T_2^2 + T_a^2)$$

$$h_{r,cr} = \frac{\sigma(T_c + T_a)(T_2^2 + T_a^2)}{\rho_c \gamma + \frac{1}{\rho_c} + \frac{1}{\rho_c} + \frac{1}{\rho_c} + \frac{1}{\rho_c}}$$

where $\varepsilon_r$ and $\sigma$ are the emittance of the receiver and Steffane-Boltzmann constant, respectively. $\varepsilon_r$ is the emittance of the receiver and $Nu$ represents the Nusselt number. $K_{air}$ indicates the air thermal conductivity.

The input amount of energy from solar to the trough system, the steam turbine work, the total work of the cycle, and the total efficiency of the introduced power plant is calculated as:

$$Q_{solar} = m_{cl}(h_7 - h_6) + m(h_1 - h_9)$$

$$W_{st} = \dot{m}(h_1 - h_2)$$

$$W_{cycle} = W_{st} - \Sigma W_{pumps}$$

$$\eta_{tot} = \frac{W_{cycle}}{Q_{solar}}$$

Appearance of parabolic trough collector

The first applicable PTCs was designed and manufactured with a collector which had 3.25 m² area. The designed PTC was utilized to derive an engine with 373 W capacity. Other similar systems were designed and manufactured during 1872-1875, which utilize air as the working fluid. In another research, Ericsson constructed a system known as

\[\text{FIGURE 3} \quad \text{A typical solar thermal power plant with trough collector}^{22}\]
“sun motor” which consisted of a PTC with 3.35-m-long, 4.88-m-wide. This system was applied to focus solar radiation on a boiler tube. A manual system was applied to track the sun. The absolute operating pressure of the piston was 0.24 MPa and its rotational speed was equal to 120 rpm during summer.23,24 Moreover, in 1907, Maier and Remshardt patented a PTC with DSG (Direct Steam Generation).25 In addition, Shuman designed several solar engine during 1906 and 1911. He used diverse types of both none and low-concentrating solar collectors. Shuman planned and established a large irrigation pumping plant in Mead in 1912 with the help of obtaining the information of the previous experiences. Afterward, Shuman and Charles Vernon Boys differed the construction of the collector. Boiler tubes which were covered by glass were installed along the focal axis of a PTC. The pressure of the saturated steam generated by the collector was equal to 0.1 MPa. The length and width of the PTC rows were 62.17 m and 4.1 m, respectively. Therefore, the total area was 1250 m². Absorber tube diameter was equal to 8.9 cm. The concentration ratio of the system was 4.6 which resulted in the maximum efficiency of 40.7%,18,21 The real output power of Meadi plant expressed to be 14 kW to a maximum of 54 kW, although it was announced to be 75 kW.23 It was suggested that using appropriate steam engine, it is possible to achieve power output equal to 41 kW.22,23 Moreover, the solar radiation was converted into mechanical energy using a PTC and a steam engine by C.G which had 0.37 kW power capacity. For reducing heat loss, a single-tube flash boiler encased in a double-walled evacuated glass sleeve was installed along the focal axis. The system can produce saturated steam at 374°C on the condition of being in the exposure of the sun’s rays within 5 min.23 In addition, Abbot used an identical boiler to power a steam engine with 0.15 kW. It was concluded the theoretical and actual efficiencies of the system which used the boiler were equal to 15.5% and 11.7%, respectively.28

Parabolic trough power plants
Based on the obtained results on http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations, the number of active parabolic power plants in the world is equal to 20, 11 of them are installed in Spain, 2 of them exist in Iran, 5 of them are located in USA and one system is installed in Italy and Morocco. The number of constructed parabolic trough power plants is equal to 27 all over the world. The capacity of the systems installed in Spain are: 150 MW installed in Solnova, Andasol Solar Power Station with 100 MW capacity, Extresol Solar Power Station with 100 MW capacity, Ibersol Ciudad Real with 50 MW capacity, La Florida with 50 MW capacity, Alvarado I of 50 MW, La Dehesa of 50 MW, Majadas de Tietar of 50 MW, Palma del Rio 2 of 50 MW, Palma del Rio 1 of 50 MW and Manchasol-1 of 50 MW. The plants and their capacity which are installed in the USA are Solar Energy Generating Systems with 354 MW capacity, Martin Next Generation Solar Energy Center with 75 MW capacity, Nevada Solar One with 64 MW capacity, Keahole Solar Power with 2 MW capacity and Saguro Solar Power Station with 1 MW capacity. The capacities of the plants installed in Iran are 17 MW and 0.25 MW which are located in Yazd and Shiraz, respectively. In addition, there is one active plant in Morocco with 20 MW capacity. The capacity of the plant in Italy is equal to 5 MW (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations).

Parabolic trough concentrator analysis
Most financially and effectively applied solar collector in the thermal power plants which have intermediate operating temperature range, is the line focusing parabolic collector which also named as parabolic trough collectors.25-27 Some procedures are conducted to increase the performance of the system including the receiver or absorber tube is located at the reflector focal point, a black treated metal tube which is surrounded by a tube made of glass and is utilized as the receiver, for the sake of reducing convective heat losses, the space between the pipe and glass cover is evacuated and for collecting the maximum solar radiation, a tracking mechanism is utilized (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations).28-30 Currently, the parabolic trough concentrator’s tracking systems are founded on “virtual”

| Collector     | Structure       | Aperture width (m) | Focal length (m) | Length per collector (m) | Mirror area per drive (m²) | Receiver diameter (m) | Peak optical efficiency (%) |
|---------------|-----------------|--------------------|------------------|--------------------------|---------------------------|------------------------|-----------------------------|
| LS-1          | Torque tube     | 2.55               | 0.94             | 50.2                     | 128                       | 0.04                   | 71                          |
| LS-2          | Torque tube     | 5                  | 1.94             | 49                       | 235                       | 0.07                   | 76                          |
| LS-3          | V-truss frame   | 5.76               | 1.71             | 99                       | 545                       | 0.07                   | 80                          |
| New IST       | Space frame     | 2.3                | 0.76             | 49                       | 424                       | 0.04                   | 78                          |
| EURO Trough   | Square truss torque box | 5.76               | 1.71             | 150                      | 817                       | 0.07                   | 80                          |
| Duke Solar    | Aluminum space frame | 5                  | 1.49             | 49-65                    | 235-313                   | 0.07                   | 80                          |
tracking. At present, the conventional tracking systems which distinguish the sun position with its sensors have been substituted by a system founded on determining the position of the sun utilizing a mathematical algorithm.

The most efficient parabolic trough concentrator is a new concentrator from the Euro Trough in which an advanced light-weight structure is utilized to obtain cost-efficient solar power generation. Table 2 indicates the new development of parabolic concentrator system.

Expected revenue of parabolic concentrator
The CSP plants’ revenues are split into government tax subsidies and power generation incomes; the former can be obtained by VAT (value added tax) deduction. The latter equals to LCOE multiplied by annual electricity production Ei. So:

Revenuei = power generation incomes + government tax subsidies = (LCOEi) × Ei + β × VAT

In which, β represents the proportion of VAT refunds.

The taxes preferences may involve the production taxes (business tax, VAT and additional taxes) and income tax. The breaks associated with additional taxes, business tax, and income tax ought to be conducted as expenses reductions. VAT concessions should be treated as nonbusiness income. Thus, the government tax subsidies contributed to CSP projects are VAT deductions. For CSP systems, the degradation rate (DR), performance factor (η), TF (tacking factor), and DNI (direct normal irradiation) are used for determining the annual generation capacity, Ei.

\[ E_i = \text{DNI} \times \text{TF} \times \eta \times (1 - \text{DR})^\beta \]  

More equations regarding CSP systems can be obtained by.

Yilmaz and Mwesigye performed a review study on performance, modeling procedure, and simulation of solar trough collectors. The solar power plants with parabolic trough concentrator gather up to 60%-70% of the incident solar radiation and their highest efficiency in electrical conversion is 20%-25%. The single-axis tracking parabolic trough solar collectors’ performance founded on the ordinary meteorological year input data of 11 sites has been presented by Treadwell et al. Based on the obtained data, north-south horizontal axis parabolic trough collectors have been suggested. In parabolic troughs, specialists provided a mathematical derivation of concentration ratio and rim angle and a logical procedure to multi-objective optimization and design for various design environments to assess the optimal utilization of accessible solar energy. A transient simulation model to assess the performance of water heating systems by utilizing parabolic trough solar collectors has been developed by Odeh et al. Also, the principle of operation and design for a novel trough solar concentrator has been provided by Tao et al. The effect of characteristic parameters and crucial design has been evaluated and optimized. Additionally, a three-dimensional numerical examination of heat transfer in a parabolic trough receiver with longitudinal fins using different kinds of nanofluid has been provided by Amina et al.

Additionally, Bellos et al. investigated the optimal locations and numbers of internal fins to increase the thermal efficiency of parabolic trough collectors. As indicated in the results, three fins in the lower part can be considered as the optimal approach. A three-dimensional model of a parabolic trough collector has been provided by Chang et al. for improving the heat transfer in the system by utilizing molten salt as the working fluid and inserting rods. Patil et al. presented novel designs associated with parabolic trough collectors with smaller rim angles. Also, Azzouzi et al. experimentally investigated a solar parabolic trough collector with large rim angle.

Moreover, Coccia et al. investigated the annual product of a PTC, which was low-enthalpy type, with tube receiver. In order to enhance the thermal efficiency of the system, six types of nanofluids were used with different concentrations. Aichouba et al. examined the effect of varying the position of the absorber tube in the solar trough collectors.

2.1.2 Linear fresnel reflector (LFR)

Arrangements of the reflective glass strips at the bottom of the system which rotates around in dependent parallel axis can be enumerated as characteristic of Linear Fresnel reflector (Figure 4). These strips focus on an elevated linear receiver, which further transfers the heat to the HTF.

At the first step, it was introduced as a substitution for central receiver tower; however, it was as efficient as expected because of heat losses which were due to one axis tracking mechanism. Due to its some advantages like low capital cost and no revolute joints, and close exergy efficiency to parabolic trough collector for direct steam generation (DSG), it can be used instead of the parabolic collector.
Table 3 expresses the collected data of NREL contributed to CSP power plant with distinct technologies. According to Table 3, the potential of generating power related to LFR is relatively higher with respect to smaller catchment.57 Some components of the reflector are unused due to the blocking and inter row shading. The levelized cost of energy of LFR increases because of some reasons such as reflectivity, cosine effect, tube absorptivity, heat losses and etc.61 Some novel designs are proposed for semi parabolic LFR solar concentrator in order to eliminate the losses occur due to shading and blocking between two adjacent layers.62 In addition, LFR has the capability of thermal storage (based on molten salts) since the working temperature can achieve up to 550°C with molten nitrate (molten salts contained molten nitrate) as HTF.61

Challenges of LFR
An innovative technology with extensive opportunity for advancement is Fresnel lens-based concentrator solar power.63 The challenges related to LFR are mostly techno-commercial as follows:

- The exceptional reasonable method for large-scale manufacturing of Fresnel lens is casting, however, high viscosity and less fluidity of molten material limits sharp edges generation.
- Advance materials are needed to be investigated for the sake of avoiding ultraviolet degradation.
- In order to prevent dust trapping in grooves, repeated cleaning is needed.
- Excessive expenditure and maintenance concern are added due to requirement of tracking system contributed to CSP.
- In order to have favorable performance, appropriate HTF, such as molten salt, is required since the working temperature of the system is relatively high.
- This technology needs high amount of solar irradiation (DNI), while it is not adequate everywhere.

Advantages of LFR
There are several advantages for Fresnel-CSP systems which result in attention attraction of researchers. The most important ones are listed as follows:

- Fresnel systems produce excessive high temperature which is favorable for various thermal energy applications.
- It is not required to use HTF or heat exchanger in DSG type power plants which use Fresnel-CSP.
- High thermal efficiency, decrease in investment cost and reduction in payback time are other advantages of these systems (http://en.wikipedia.org/wiki/Solar_thermal_energy).
- High efficiency is achievable since its working temperature is high.
- By utilizing CSP technology, it is possible to produce clean solar fuels such as hydrogen.

Mathematical modeling
Bellos et al64 presented a mathematical model to evaluate the thermal performance of a Linear Fresnel reflector as follows:

In order to calculate the total aperture area of the Fresnel collector, \( A_a \), an assumption is made that collectors are in the horizontal location. Then the aperture area is calculated as follows:

\[
A_a = N_{rf} W_o L
\]

where \( N_{rf} \), \( W_o \), and \( L \) are number of reflectors, primary reflector width, and collector length, respectively.

The available solar energy at the reflector surface is obtained as follows:

\[
Q_s = IA_a
\]

The useful heat production that is transferred from the sun to the working fluid is calculated as follows:

\[
Q_u = mC_p(T_{out} - T_{in})
\]

The following ratio is defined to calculate the thermal efficiency of the linear Fresnel reflector:

\[
\eta_{th} = \frac{Q_u}{Q_s}
\]

Power plants with Fresnel reflectors
Based on obtained data, currently there are three active power plants using Fresnel reflectors which are located in Spain, USA, and Australia (http://en.wikipedia.org/wiki/
The active concentrator solar power plant, in Spain is Puerto Errado 1, in USA is Kimberlina, and in Australia is Liddell power plant which produce 5 MW, 1.4 MW and 2 MW, respectively. As the data indicates, in Spain, an extra Fresnel power plant is being constructed.

**Kimberlina (USA)**
Kimberlina is the first Compact Linear Fresnel Reflectors (CLFR) project in North America, located in California, which has 5 MW capacity. Table 4 presents the technical characteristics of Kimberlina power plant. In this power plant, 13 flat narrow Fresnel reflectors make up one group. Each single reflector is able to track and concentrate the sun radiation on the tubes which is installed above the reflectors. The focused sun irradiations transfer heat to water and results in its evaporation. Using the steam, which is overheated at the temperature of 400°C, the turbine generates the electricity (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations).

**Puerto Errado 1 (Spain)**
Puerto Errado 1 which produces 1.4 MW is located in Calasparra in Spain. The plant technical specifications are presented in Table 5. This CSP plant has been active since April, 2009. Also two rows of Fresnel reflectors have been installed there in which the length of each row is 806 m, and the procedure of producing steam is that a direct sun irradiation is concentrated toward the linear receiver which is located at the height of 7.40 m from the ground (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations; http://en.wikipedia.org/wiki/Solar_thermal_energy; http://www.nrel.gov/csp/solarpaces/).

**Liddell power station (Australia)**

**Table 4** Technical characteristics of Kimberlina power plant

| Name                        | Kimberlina Solar thermal power plant |
|-----------------------------|-------------------------------------|
| Location                    | Bakersfield/CA                      |
| Lat/long location           | 35°34′0.0″N, 119°11′39.1″W            |
| Capacity                    | 5 MW                                |
| Land area                   | 12 acres                            |
| No of line                  | 3                                   |
| Line length                 | 385 m                               |
| Mirrors width in line       | 2 m                                 |
| No of mirrors across line   | 10                                  |
| Collector manufacture       | Ausra                               |
| Receiver type               | Non-Evacuated                       |
| Receiver length             | 385 m                               |
| Heat Transfer fluid type    | Water                               |
| Power cycle pressure        | 40 bar                              |

| Name                        | Puerto Errado 1 Thermosolar Power plant |
|-----------------------------|----------------------------------------|
| Location                    | Calasparra, Spain                      |
| Lat/long location           | 38°16′42.28″N, 1°36′1.01″W              |
| Capacity                    | 1.4 MW                                |
| Land area                   | 7 ha                                  |
| No of line                  | 2                                     |
| Line length                 | 806 m                                 |
| Mirrors width in line       | 16 m                                  |
| Collector manufacture       | Novatec Solar Espana S.L (Nova-1)     |
| Heat Transfer fluid type    | Water                                 |
| Solar field inlet temperature | 140°C                              |
| Solar field outlet temperature | 270°C                            |
| Power cycle pressure        | 55 bar                                |
model for evacuated tube absorber which was heated by linear Fresnel lens presented by Zhai et al. Additionally, the four similar trapezoidal cavity absorbers’ thermal performance for LFR have been investigated and compared by Singh et al. In addition, the total heat loss coefficients of the trapezoidal cavity absorber with respect to regular black cover have been examined.

Furthermore, Bellos et al. experimentally and numerically studied the performance of a LFR. The characteristic of the system is a flat plate receiver with 36 m² aperture area which is integrated with a storage tank of 1 m³. Based on the results, the optimum heat production is 8.4 kW. In another work, they analyzed a LFR with two different configurations such as flat mirrors and a parabolic shape reflector. As stated in the results, the maximum exergy performance is on the condition of 700 K. Also, a parametric study for identifying the thermal performance of a LFR has been carried out by A. Barbon et al. The considered parameters are mirror length and width, and receiver height. Cagnoli et al. numerically analyzed the performance of utilizing encapsulated tubes or evacuated tubes in the linear Fresnel collectors.

### 2.1.3 Central receiver tower

Central receiver tower technology can be illustrated as a point focus kind of solar thermal electricity generation system. It has several heliostats which consist of dual axis control and an arrangement in order to focus radiation on stationary receiver (Figure 5). The stationary receiver is utilized in order to absorb the radiation which are concentrated by the heliostats. In addition, receivers are used to transfer heat to the heat transfer fluid (HTF). Afterward, HTF transfers the heat to the fluid used in power cycle.

Power cycle is commonly founded on Rankine cycle for thermal power plants. Additionally, the heat transfer fluid could be utilized as a working fluid in some cases. It can be distinct for the high capacity and storage-based system.

The variation in receiver design can be mentioned as full cavity type to fully external type, which the latter utilizes tubes for absorbing the concentrated solar energy. Afterwards, the heat is transferred to the heat transfer fluid which exists in the tubes. The installed capacity of Spain (2300 MW) leads to be the world head in the CSP technology utilizing solar tower system.

The ratio of the area of receiver to the total area of concentrating heliostats is equal to Concentration ratio (CR), as shown in Equation (14).

\[
CR = \frac{\text{Area of Receiver} (m^2)}{\text{Total Area of Heliostats} (m^2)}
\]

The factors, which mainly influence on the reliability of these systems are temperature, the molten salt, corrosion, and the variation in solar flux. Changes in the mentioned factors lead to thermal stresses in the receiver. It is necessary to keep thermal stresses lower than d 50% of the ultimate tensile strength (UTS). The thermal stresses are obtained by applying Equation (15).

\[
\sigma_{th,max} = \frac{\Delta T \cdot aE}{2(1-\xi)} \ln \left( \frac{d_0}{d_i} \right) \left( 1 - \frac{2d_i^2}{d_0^2 - d_i^2} \right) \ln \left( \frac{d_0}{d_i} \right) \frac{aE}{2(1-\xi)} k_i q_i \rho_i
\]

The losses in the central receiver due to the radiation and convection depend upon shape, temperature of receiver, wind velocity, and direction of the wind. Mostly, radiation losses are the major loss, except the case when the temperature is low and the wind velocity is high. The input from concentrated radiation varies with weather condition and it turns out that excess radiation received in summer, needs to be diverted to the other tower, which can also be utilized by other solar thermal application, thereby reducing the load on power grid.

### Power plants with central receiver tower

In 1981, the first central receiver tower power plant (SSPS) with capacity of 0.5 MW was built in Spain. Table 7 presents various CRT projects which have been carried out in the 20th century.
pioneer in applying CRT can be enumerated as Spain, USA, France, Italy, Japan, and Russia.87

In the past few years, some projects have been performed which are illustrated in Table 8. As the table indicates, the projects of PS10 and PS20 were established in Sevilla, Spain with the power of 11 MW and 20 MW, respectively. Also, these projects have been followed by Sierra Sun Tower in USA, Jülich power plant in Germany, and Gemosolar power in Spain with the power of 5 MW, 1.5 MW, and 20 MW, respectively.88 After the pioneer countries in CRT plants, China has come in the market in 2010 by installing Beijing Yanqing solar power plant. The most significant central receiver power plants in operation around the world are presented in Table 8.

### Central receiver tower analysis

Recently, plentiful researchers have worked on central receiver tower-based solar thermal power.89-98 As an example, Riaz et al.99 modeled large area solar concentrator for central receiver power plants. In this study, two major factors like steering constraints on mirror orientations and the effect of impeding the incident/reflected solar radiation and shadow have been regarded. Additionally, Due to the various orientations, calculation of solar flux density for the CRT has been carried out by Walzel et al.100 Ali 101 determined the tower’s height, the power plant’s staring time, the distance between the tower and the heliostat mirror, and the power plant’s location with the help of computational model in Iraq. Furthermore, an innovative concentrator with enhanced efficiency for solar hybrid power plants has been introduced by Buck et al.102 For the sake of calculating costs and performance, plentiful frameworks of solar-hybrid gas turbine cycles in low-to- medium power capacity have been examined. Moreover, for achieving optimal efficiencies in CRTs, six kinds of heliostat field layouts have been investigated by Schmitz et al.103

Also, Wu et al.104 theoretically illustrated the design of an improved water/steam receiver for a commercial CRT. The power plant splits into four separate cavities in a single receiver unit. Carotenuto et al.105 presented a numerical model of heat transfer performance associated with a multi-cavity volumetric solar receiver. In addition to the previous study, Carotenuto et al.106 investigated a multi-cavity external flow air receiver. As the results revealed, the calculated and anticipated results were exceptionally coincident. Additionally, for the sake of enhancing the performance associated with the central receiver to the steam cycle in a solar thermal power plant, a dual receiver concept was provided by Eck et al.107

### Mathematical modeling

Jadhav et al.111 presented a model to evaluate thermal performance of a cavity receiver of a central tower solar power plant. In the modeling process, it is supposed that a uniform distribution is established on the absorber tube of the cavity receiver. In order to calculate the thermal efficiency of the central tower receiver, radiation thermal losses must be calculated. Other possible thermal losses are neglected, since the temperature is very high and radiation loss is dominant. Hence, the thermal efficiency of the central tower receiver is obtained as follows:

\[
P_{\text{in,solar}} = ICA_R \\

P_{\text{loss,radiation}} = \frac{\varepsilon R T_R^4}{\pi R^2} \\
\eta_{\text{th}} = \frac{P_{\text{in}} - P_{\text{loss,radiation}}}{P_{\text{in}}} = 1 - \frac{\varepsilon R T_R^4}{\pi R^2} \\
\]

In above equations, \(\varepsilon\) is equal to one and \(\sigma\) is the Stefan-Boltzmann constant. It is concluded from the above equation that maximum achievable temperature in the central tower receiver is:

\[
T_R,\text{max} = \left(\frac{\pi R^2}{\sigma}\right)^{0.25} \\
\]

### 2.1.4 Parabolic dish

Parabolic dish concentrators can be named as point focus type devices, which have two main parts: a solar thermal receiver located at the focal point and parabolic reflector (dish) (Figure 6). The characteristic of parabolic dish can be mentioned as having high temperature application, which is possibly appropriate for solar thermal power and solar thermal steam generation.101,102 The range of temperature for PDC fluctuates from 400°C to 750°C with

| Project acronym | Capacity (MW) | Country | Starting year |
|-----------------|--------------|---------|---------------|
| SPS 0.5         | Spain        | 1981    |
| EURELIOS 1      | Italy        | 1981    |
| SUNSHINE 1      | Japan        | 1981    |
| Solar One 10    | USA          | 1982    |
| CESA-1 1        | Spain        | 1983    |
| MSEE/CAT B 1    | USA          | 1984    |
| THEMIS 2.5      | France       | 1984    |
| SPP-5 5         | Russia       | 1986    |
| TSA 1           | Spain        | 1993    |
| Solar Two 10    | USA          | 1996    |
**TABLE 8**  Central receiver solar thermal power plants in operation

| Name          | Country, location | Owners               | Capacity (MW) | Break ground date | Starting year | Heliostat field area (m²) | Receiver Type | Power cycle | Storage | Type          |
|---------------|-------------------|----------------------|---------------|-------------------|---------------|---------------------------|---------------|-------------|---------|---------------|
| Beijing Badaling | China, Beijing    | Academy of Sciences | 1.5           | July 2009         | August 2012   | 10,000                    | Cavity        | Rankine     | 1 h     | Fossil-Solar  |
| Gemasolar     | Spain, Andalucía (Sevilla) | Torresol Energy     | 19.9          | February 2009     | April 2011    | 304 750                   | Cavity        | Rankine     | 15 h    | Fossil-Solar  |
| Juelich       | Germany, Juelich  | DLR                  | 1.5           | July 31, 2007     | December 2008 | 17 650                    | Volumetric    | Rankine     | 1.5 h   | Fossil-Solar  |
| Planta Solar 10 | Spain, San lúcár la mayor (Sevilla) | Abengoa Solar       | 11.0          | 2005              | June 25, 2007 | 75 000                    | Cavity        | Rankine     | 1 h     | Fossil-Solar  |
| Planta Solar 20 | Spain, San lúcár la mayor (Sevilla) | Abengoa Solar       | 20.0          | 2006              | April 22, 2009 | 150 000                   | Cavity        | Rankine     | 1 h     | Fossil-Solar  |
| Sierra        | United States     | eSolar               | 5.0           | July 2008         | July 2009     | 27 670                    | Cavity        | Rankine     | -       | Solar Only    |
| Yanqing       | China, Yanqing county | Academy of Sciences | 1.0           | 2006              | July 2011     | 10 000                    | Cavity        | Rankine     | Two-stage heat storage | - |
concentration ratio more than 3000 and thermal efficiency 23%. 103, 104

A favorable innovation for small-scale power generation is PDC, and it can be used as replacement of DG sets. 116 Parabolic dish technology is also a part of distributed solar power generation, which can reduce the load on centralized power plants. 97, 98

Also, for generating electricity utilizing dish Stirling engine technology, parabolic dish concentrator can be operated 113. The proven efficiency of dish Stirling engine is relatively 30%. 117 A kind of linear alternator for generating electricity from the reciprocating motion directly is called advanced Stirling converter 118. So, it can exclude mechanical transmission losses in the Stirling engine specifically on the condition of free piston Stirling engine. 119 By considering novel technologies, it can be concluded that the combination of the dish-free piston Stirling engine (FPSE) and biofuel is a perfect replacement for DG sets and is capable of being independent from grid power supply. 120

Parabolic dish power plant
As data indicate, presently a parabolic dish power plant called Maricopa Solar with the capacity of 1.5 MW is located in USA (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations). Furthermore, the only power plant which is being constructed is in Spain.

Maricopa Solar (USA)
As mentioned, the capacity of Maricopa solar is 1.5 MW which is located next to the town of Peoria in Arizona. It is included 60 solar dishes each composed of Stirling engine, and electrical energy power’s generator of 25 kW. Additionally, in this power plant, hydrogen is used as a working fluid, and four cylinders Stirling engine and mirrors with silver-plated glass and solar reflectance 94% are applied as well. 121 Table 9 provides the specifications of Maricopa Solar. Also, hydrogen is heated by sun irradiation to 750°C and Stirling engine cools down by air. The generation’s probabilities of the electrical energy and commercial production of electricity have been demonstrated by Maricopa Solar. 121

Mathematical modeling
Loni et al 122 presented an energy analysis for a solar parabolic dish power plant. The modeling is based on finding the thermal losses from the input solar energy. Thermal energy can be wasted through three heat transfer mechanisms including conduction, convection, and radiation. Here, since the thickness of the absorber tube is very small and it has high thermal conductivity, so the conduction heat transfer is neglected. Hence, the useful heat at the absorber tube of a solar dish collector is calculated as follows:

\[
\dot{Q}_{\text{useful}} = \dot{Q}_{\text{solar}} - \dot{Q}_{\text{loss, external conv.}} - \dot{Q}_{\text{loss, internal conv.}} - \dot{Q}_{\text{loss, rad.}} \tag{18}
\]

The amount of useful gained heat can be obtained by writing an energy balance for the flowing working fluid in the solar dish collector as follows:

\[
\dot{Q}_{\text{useful}} = \dot{m}C_v(T_{\text{out}} - T_{\text{in}}) \tag{19}
\]

The term related to amount of loss associated to the external convection and internal convection are calculated as follows:

\[
\dot{Q}_{\text{loss, external conv.}} = h_{\text{outer}}A_{\text{outer}}(T_{\text{surr}} - T_{\text{fluid}}) \tag{20}
\]

\[
\dot{Q}_{\text{loss, internal conv.}} = h_{\text{inner}}A_{\text{inner}}(T_{\text{surface}} - T_{\text{fluid}}) \tag{21}
\]

The amount of wasted thermal energy through radiation loss is obtained as follows:

\[
\dot{Q}_{\text{loss, radiation}} = \varepsilon\sigma A_{\text{aperture}}(T_{\text{surface}}^4 - T_{\text{surr.}}^4) \tag{22}
\]

In overall, the total thermal efficiency of a solar dish power plant after subtracting the losses from useful gained thermal energy is calculated as follows:

\[
\eta_{th} = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{solar}}} \tag{23}
\]

Parabolic dish analysis
Numerous studies have been worked on parabolic dish and its performance. 102, 103, 111, 112 The comprehensive energy and exergy analyses of Stirling engine system and concentrator are illustrated in this section. 104–108 For the sake of evaluating
the convective heat losses from cavity receivers, an analytical model has been presented by Clausing. As indicated in the results based on experimental and theoretical investigations, significant convective loss by cavity receivers has been reported.

Furthermore, the investigation of optimizing the radius of boiler tubes in a radiation-dominated environment like the parabolic dish solar thermal collector receiver has been performed by Bannister. Also, the system’s performance founded on the linearized heat loss model of the solar collector and the irreversible cycle model of the Stirling engine has been examined by Chen et al. In the study, the solar collector’s optimal operation temperature associated with the system’s maximum efficiency has been measured.

Moreover, a low cost solar steam generating system and its performance, design and development have been presented by Kaushika and Reddy. Also, the novel design and innovative materials of parabolic dish have been provided. Additionally, for studying the natural convective heat loss related to three kinds of receiver (cavity receiver, semi-cavity receiver, and modified cavity receiver) for a fuzzy focal solar dish concentrator, a computational model has been presented by Kumar and Reddy. Also, a computational model of combined surface radiation heat transfer and laminar natural convection in a adapted cavity receiver of solar parabolic dish collector has been provided by Reddy and Kumar. In this study, the effects of four major parameters on the total heat loss of the receiver were evaluated, which are emissivity of the surface, operating temperature, the geometry, and orientation. Moreover, according to Reddy and Kumar, by comparing of 3-D model and renowned models, it was concluded that the former model could be utilized to obtain precise anticipation of heat loss from solar dish collector. Also, an innovative design of a 500 m² concentrator with 13.4 m focal length and altitude–azimuth tracking paraboloidal dish concentrator has been introduced by Lovegrove et al. Pakhare et al. experimentally examined the influence of applying nanofluid on the performance of solar dish collectors. It was monitored that using nanofluid can increase the water temperature in the storage tank up to 90°C. Loni et al. compared solar dish collectors with various cavity receiver and working fluids.

### 3 | PHOTOVOLTAIC (PV) TECHNOLOGY

Photovoltaic (PV) technology is applied in order to directly convert solar irradiations into electricity. It utilizes diffused elements of incoming solar irradiations. Hence, PV technology is appropriate in regions with either high or low solar radiation. There are several types of photovoltaic materials which can be used for power generation. Mono and polycrystalline silicon, Cadmium telluride (CdTe), Gallium arsenide (GaAs), triple-junction solar cells composed of Indium gallium phosphide (InGaP) are among the most common materials used for PV cells. In order to generate electricity at a larger scale, solar cells are combined to form a module of multiple cells; these modules are then assembled into a (photovoltaic) PV array containing the length up to several meters. Based on NREL report, there are several solar modules which are inter-connected utilized to generate electricity in utility-scale.

The technology of PV is sustainable especially for small-scale applications. These systems can be used both grid-connected and off-grid. The PV modules can be installed as fixed systems or can be assembled with a tracking system to obtain higher electricity; however, tracking system requires more area for installation.

PV technology firstly was used to provide electricity in satellites and aircrafts. However, PV technology is utilized for both off-grid and grid-connected electricity generation nowadays. This technology can be applied for other purposes including transportation, telecommunication, rural electrifications etc.

#### 3.1 | Generations of photovoltaic technology

PV technology is categorized 1st Generation PV, 2nd Generation PV, and 3rd Generation PV. Since the used semiconductors in these generations differ, the efficiency and performance of these types are different. The first and second generations of PV modules are more commercially mature yield large-scale generation, while the third generations are still in R&D phase. Various types of PV systems are shown in Figure 7. Comparison between various types of PV systems is represented in Table 3.

Kumar and Kumar presented two parametric models in order to assess the performance of PVs. 5 and 7 parameters are selected in two different models to provide an exact
model for forecasting the PVs performance. The Authors employed both numerical and analytical approaches on the basis of minimum required data from the datasheet of the manufacturers. Open circuit and short circuit condition were applied on both models for further mathematical calculations. The obtained results from both predicting model were compared to the manufactures datasheet under different surrounding conditions. In overall, it is concluded that model with 7 parameters is more efficient and provide more accurate responses.

Kumar and Kumar performed a review on different PV technologies and also analyze the mathematical models broadly. Several standard parameters such as performance ratio, yield energy, reference energy, and capacity utilization factor were considered and different presented PV technologies were compared. In addition, energy efficiency and exergy efficiency were also discussed. Finally, it is found out that under different ambient conditions degradation and failure modes is important for exact forecasting of PV systems’ performance (Table 10).

According to Fraunhofer ISE, Si-wafer based technology had a share of about 90% of the total production in 2013 and the share of multi-crystalline PV technology was about 55% of the total production. It has also been emphasized by Fraunhofer ISE and Energy Informative that among the thin-film technologies, CdTe leads with an annual production of 2GWp and currently has the largest market share. Above Table 11 also implies that a-Si is now commercially mature technology and being used for small-scale applications only. CPV systems have gained much popularity and yield higher efficiencies.

3.2 | Mathematical modeling

The generated power from a PV device can be calculated as follows:

\[ W_{PV} = A_{PV}FFV_{oc}I_{sc} \]  \hspace{1cm} (23)

where \( A_{PV}, FF, V_{oc}, \) and \( I_{sc} \) indicate the total surface area of the PV arrays, the fill factor, open circuit voltage, and short circuit current, respectively.

4 | COMPARISON OF CSP AND PV TECHNOLOGY

Various factors including efficiency, economic aspects, social acceptance, and environmental effects are important criteria in selecting sustainable power generation system.

4.1 | System efficiency

CSP technology has higher capacity in electricity production in comparison with PV modules for small-scale power generation. Although the overall efficiency of PV plants is lower in comparison CSP plants, PV systems require smaller land for installation. In the same area, PV power plants generate more electricity compared with CSP plants. Since PV systems have small size, higher number of PV systems can be installed in the same area in comparison with CSP plants. Several studies have proven this fact. For instance, Desideri...
TABLE 10  Worldwide projects related to solar concentrators

| Name and location | Concentrator type | Focus (point/linear) | Output (kW) | Sun concentration (X)² | Tracking (yes/no) | Efficiency of the system |
|-------------------|-------------------|----------------------|-------------|------------------------|-------------------|-------------------------|
| Alpha Salarco, Pahrump, Nevada, USA | Fresnel lens | Point | 15 | n/a | Yes | n/a |
| AMONIX and Arizona Public service Arizona, USA | Fresnel lens | Point | 300 | 250 | Yes | 24.0% |
| Australian National University Spring Valley, Australia | Parabolic trough | Linear | n/a | 30 | Yes | 15% |
| Petal Sede Boqer, Israel | Parabolic dishes | Point | 154,000 | 400 | Yes | 16.5% |
| BP Solar and Polytechnical University of Madrid Tenerife, Canary Island, USA | Parabolic trough | Linear | 480 | 38 | Yes | 13.0% |
| Entech Inc, Fl, Davis, Texas, USA | Fresnel lenses | Linear | 100 | 20 | Yes | 15.0% |
| Fraunhofer- Institute for Solar Energy Systems Freiburg, Germany | Parabolic trough and CPC3 | Linear and Point | n/a | 214 | Yes | 77.5% |
| Polytechnical University of Madrid, Spain | Flat concentration devise (RXI) | Point | n/a | 1000 | No | n/a |
| Photovoltaics International, LLC Sacramento California, USA | Fresnel lens | Point | 30 | 10 | Yes | 12.7% |
| Solar Research Corporation, Pvt, Ltd, Australia | Parabolic dish | Linear | 0.2 | 239 | Yes | 22.0% |
| SulFucus Ben Gurien University, Israel | Paraboloid and hyperboloid | Point and Point | 0.25 | 500 | Yes | 81.0% |
| SunPower corporation USA | Fresnel lens | Point | n/a | 250-400 | n/a | 27.0% |
TABLE 11  Overview and comparison of photovoltaic technologies. Source^{120-123}

| 1st Generation PV (Si-wafer Technology) | 2nd Generation PV (Thin-film Technology) | 3rd Generation PV (Multi-junction Technology) |
|----------------------------------------|----------------------------------------|----------------------------------------|
| Technology                             |                                        |                                        |
| Single Crystalline Silicon (c-Si)      | Polycrystalline Silicon (p-Si)         | Amorphous Silicon (a-Si)               |
|                                        |                                        | Copper Indium Gallium Di-selenide (CIS/CIGS) |
|                                        |                                        | Cadmium Telluride Cells (CdTe)         |
|                                        |                                        | Concentrated Photo-voltaic (CPV)       |
|                                        |                                        | Dye-sensitized (DSSC)                 |
|                                        |                                        | Organic or Polymer (OPV)               |
| Commercial PV module efficiency at air mass 1.5 (in %) | 15-19 | 13-15 | 5-8 | 7-11 | 8-11 | 25-30 | 1-5 | 1 |
| Commercial mature or not?              | Commercially mature with large-scale production | Commercially mature with large-scale production | Commercially mature with small-scale production | Commercially mature with medium-scale production | Commercially mature with large-scale production | R&D phase | R&D phase |
| Maximum PV module efficiency (in %)    | 25 | 20.4 | 12.2 | 19.8 | 19.6 | 40 | - | - |
| Current PV module cost (in US$/W)      | 0.7 | 0.7 | 0.8 | 0.9 | 0.9 | - | - | - |
| Market share (in 2014) in %             | 90 | 55 | 32 | 25 | 43 | - | - | - |
| Maximum PV module output power (in watts) | 320 | - | 300 | 120 | 120 | 120 | - | - |
| PV module size (in m²)                  | 2.0 | 1.4-2.5 | 1.4 | 0.6-1.0 | 0.72 | - | - | - |
| Area needed per kilo Watt (kW) in m²    | 7 | 8 | 15 | 10 | 11 | - | - | - |
et al.\textsuperscript{120} showed that despite some advantages of CSP plants such as capability of electricity production in the absence of solar radiation, power generation of PV systems are higher than CSP plants for the same occupied land. Schultz et al.\textsuperscript{121} obtained that the conversion efficiency of conventional available PV modules are in the range of 14\% to 22\%.

4.2 System sustainability

Several studies have focused on the relationship between sustainable development and environmental issues. Fossil fuels and carbon dioxide emission due to their combustion is the main source of greenhouse gases emission. Environmental aspects, social acceptability and cost-effectiveness of power plants have high importance. These factors are considered for sustainability analysis as shown in Figure 8.

4.2.1 Environmental effects

In order to investigate the long-term sustainability of power generation systems, environmental effects must be considered. The main environmental issues which are related to solar power plants are in assembling and decommissioning. Almost no harmful effect exists after solar power plant commissioning and also during their operation.

Desideri et al.\textsuperscript{122} concluded that assembly of PV systems have more environmental effects in comparison with CSP plants. In addition, based on comparison of PV and CSP plants with 1 MWh capacity, it was observed that PV power plant had more environmental effects during the life cycle.

In the process of PV cell manufacturing, various hazardous materials are utilized for semiconductor surface cleaning; therefore, the risk of inhaling silicon dusts exist for workers involved in manufacturing. Based on National Renewable Energy Laboratory (NREL) report,\textsuperscript{123} more toxic materials exist in second generation of PV modules in comparison with the conventional existing cells. It is necessary to mention that the land usage during solar power operation have moderate environmental effects. No GHG emission has been proved during operation of solar power plants. However, emissions exist in other phases such as transportation, maintenance, and decommissioning.\textsuperscript{124} Based on published reports by NREL,\textsuperscript{125,126} the harmonized median life cycle GHG emissions of the Tower and Trough based CSP systems vary from 22 to 23 g CO2 eq/kWh, while for c-Si and thin-film (TF) PV-based systems harmonized median GHG emissions are below 50 g CO2 eq/kWh. Therefore, by considering the harmonized life cycle GHG emissions of both solar power plants, CSP technologies are more appropriate in comparison with PV systems in terms of environmental aspect.

4.2.2 Economic aspects

Economic aspects, including investment cost and operation and maintenance costs, play important role for implementation and social acceptability of solar power plants. In order to compare PV and CSP plants, the levelized electricity cost (LEC) is an applicable measure as utilized by Desideri et al.\textsuperscript{120} which can be estimated by the following equations:

\[
LEC = \frac{f_{cr}IC + C_{O&M}}{E_{el}}
\]

\[
f_{cr} = \frac{k_d(1+k_d)^n}{(1+k_d)^n - 1} + k_{ins}
\]

In the equations, \(f_{cr}\), IC, and \(C_{O&M}\) are annuity factor, investment cost, and \(C_{O&M}\) annual operation and maintenance cost, respectively. \(E_{el}\) is the annual net electricity output, \(k_d\) is the real debt interest rate, \(k_{ins}\) is the annual insurance rate, and \(n\) is the depreciation period in years.

Initial investment cost is an important factor in solar power plant installation. Several studies have been conducted in order to analyze PV and CSP plants financially. Vergura et al.\textsuperscript{115} obtained initial investment cost for both PV and CSP power plants with the same output power in Italy as presented in Tables 4 and 5.

Based on IEA reports,\textsuperscript{127,128} specific ICs for CSP and PV plants installation are in the range of 4200-8400 US$/kW and 2000-5200 US$/kW, respectively. Obtained results from the literature are represented in Table 4.

Based on the cost analysis conducted for PV and CSP power plants, it can be concluded that initial investment cost of CSP power plants is higher compared with PV plants. However, economic returns of CSP plants are better in comparison with PV power plants. Moreover, as shown in
Table 6, it is concluded that the maintenance costs of CSP and PV power plants are 1% and 2% of IC, respectively. Higher maintenance cost of CSP plants is due to its more complicated mechanism.

4.2.3 | Social acceptance

In order to develop a system, it is necessary to consider social acceptance. The necessity of social acceptance of solar power systems are reported in several studies. Results from reviewed articles showed that social acceptance play a key role in development of various technologies. Development of small-scale and large-scale solar power plants demonstrates their acceptance as sustainable and environmentally benign source of energy. In 2013, more than 800 MW of power plants based on CSP technology are planned to be installed in the USA, South Africa, Spain, and India. Solar energy are used for other purposes such as desalination or heating systems which shows its acceptability. CSP technologies are more applicable for large-scale purposes, while PV modules can be used for both small and large-scale purposes.

5 | CONCLUSION

Several studies related to solar energy are reviewed and their results are represented. First, various solar thermal power plants are compared. It is concluded that parabolic trough concentrator are more efficient in comparison with linear Fresnel reflectors; however, they require more investment cost. Other methods are introduced in order to obtain higher energy from the sun such as applying parabolic dish concentrator which are point focused devices and utilized for high temperature application. In addition to solar thermal power plants, solar energy can be directly converted to electricity by utilizing PV modules. There are various type of PV modules and they are categorized based on their semi-conductor materials. First generation of PV modules have higher share in market and efficiency. In next steps, PV systems and CSP plants are compared. Based on the cost analysis conducted for PV and CSP power plants, it can be concluded that initial investment cost of CSP power plants is higher compared with PV plants. However, economic returns of CSP plants are better in comparison with PV power plants. Moreover, as shown in Table 6, it is concluded that the maintenance costs of CSP and PV power plants are 1% and 2% of IC, respectively. Higher maintenance cost of CSP plants is due to its more complicated mechanism. Regarding the reviewed studies, PV systems are more applicable for small-scale power generation and have higher output electricity compared with CSP plants in the same area of installation. However, CSP plants have some advantages such as better economic return and lower CO₂ emission.

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CONFLICTS OF INTEREST

The author declares that they have no conflict of interests regarding the publication of this paper.

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