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A thorough review of the existing concentrated solar power technologies and various performance enhancing techniques

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Abstract

Solar thermal power plants today are the most viable alternative to replace conventional thermal power plants to successfully combat climate change and global warming. In this paper, the reasons behind this imminent and inevitable transition and the advantages of solar thermal energy over other renewable sources including solar PV have been discussed. The current literature on different types of solar thermal power plants and their performance optimisation techniques is quite scattered. Efforts have been made in this paper to bring the scattered information together in one thorough review so that it helps researchers across the spectrum undertaking studies on concentrated solar power technologies. This paper has established a brief background of these technologies. Furthermore, it has put forth a comprehensive review of different concentrated solar power technologies implemented throughout the world. The review in its latter part has highlighted the current trends of various hybrid, performance enhancing techniques being employed with these technologies. A brief review of the importance of economic analysis of these technologies has also been done. The future scope and course of action adopted to keep this technology growing are also discussed.

Keywords Solar concentrated · Thermal · Renewable · Parabolic

Abbreviations

IEA	International energy agency
OPEC	Organisation for the Petroleum Exporting Countries
CSP	Concentrated solar power
PV	Photovoltaic
SEGS	Solar energy generating systems
PTC	Parabolic trough concentrator
HTF	Heat transfer fluid
SDS	Sustainable development scenario
LCOE	Levelised cost of electricity
GHG	Greenhouse gases
LFR	Linear Fresnel reflector
DSG	Direct steam generation
TES	Thermal energy storage
PCM	Phase change material
LHS	Latent heat storage
PV/T	Photovoltaic/thermal
ζ-NTU	Effectiveness—number of transfer units
DNI	Direct normal radiation

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Introduction

The energy crisis and renewables as the alternative energy source

The rapidly exhausting fossil fuel resources will gain enormous importance quite soon. Conventional energy resources such as crude oil, coal, and natural gas have been accumulating under the earth's surface for more than 500 million years. Going by the current rates of demand for electrical and mechanical power, it is estimated that crude oil will be depleted in less than a hundred years and coal in the next few hundred years. However, the energy consumption of the world since the 1950s has increased rapidly, and it is expected that it will continue this growth until the 2070s. There were two causes for this humungous increase in global energy consumption in the past: the relatively low cost of fossil fuel and rapid industrialisation in North America, Europe, and Japan. The additional complicating factors currently include China's and

India's rapid increase in energy consumption as they represent approximately one-third of the world's population, the expected depletion of oil resources before long, and the effect of human activities (industrial, municipal, etc.) on global climate change [1].

Renewable energy sources such as solar, hydro, wind, and biomass are finally showing technological maturity and cost competitiveness. The oil price shocks of the early and late 1970s, climate change, and other complicating factors mentioned before developed a new interest in renewable energy. According to the IEA, renewable resources account for roughly 13% of the primary energy supply of the world [2]. India made the largest contribution to the growth of demand for the primary energy supply of almost 30%. India's share of global energy use is expected to rise to 11% by 2040 [3]. Hence, rapid adoption of renewable energy systems in India is absolutely necessary not only for the country, but for the world.

Also, conventional thermal power plants (the most common source of electrical power throughout the world) have been susceptible to various energy crises throughout history (especially in the 1970s and 1990s). The price of fossil fuel can be influenced by frequent changes in the political stability or geopolitics of the OPEC countries. Large-scale deployment of renewable energy power plants, especially CSPs, would increase the energy security of different countries, which would help accelerate government action through policy formulation and implementation on climate change and global warming. Also, the recent trend of high fossil fuel prices and the energy emergencies in China and India in 2021 due to low coal supply are an urgent reminder for an alternative to conventional thermal power plants (Fig. 1).

Need for solar energy, especially Concentrated Solar Power

"The only energy earnings or income we have is the direct radiative energy from the sun." The sun radiates solar energy uniformly in all directions [1]. This solar energy is essential to sustain life on our planet. It is a clean, inexhaustible, abundant, and universally available energy source. It is obvious that mass deployment of solar power is the backbone of a successful transition to a renewable-heavy economy. While other renewable energy sources (e.g. wind, biomass, hydroelectricity, etc.) are derivatives of solar energy, tapping directly into solar radiation presents the opportunity to increase solar-to-electricity efficiency by a higher order of magnitude [4]. Solar irradiation at a location varies daily, and the daily irradiation varies throughout the year. Yet, solar energy is still more predictable than wind energy. It is important to note that peak insolation almost always coincides with peak energy demand during the day, so it can be efficiently utilised to match commercial power needs. The sun has an energy output of 2.8 10^{23} kW, out of which 1.5 10^{18} kWh of energy reaches the earth per year [5]. Hence, our yearly energy demand is more than met by the daily insolation of the earth.

Solar energy can be converted to electricity by two methods: photovoltaic conversion (PV) and concentrated solar power (CSP). Solar power provides the following socio-economic benefits: environmental protection; economic growth; job creation; diversification of energy sources; rapid deployment; and potential for technology transfer and innovation throughout the world.

Solar thermal power plants had been hardly considered as a viable alternative to conventional thermal power plants (oil-fired, gas-fired, or coal-fired) by the wider public or the scientific and engineering community until a few years ago.

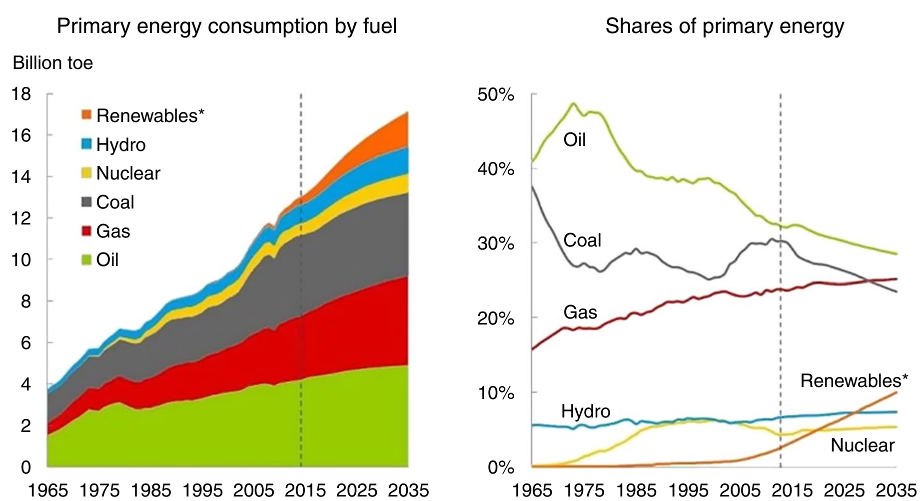


Fig. 1 Primary energy consumption of the world for 70 years, *2017 Energy Outlook* [3]

This was quite unfortunate and very surprising, as solar thermal power has several distinct advantages over other large-scale energy technologies, detailed as follows [5]:

1. They offer relatively low power costs for mass production.
2. They have a simple structure consisting of conventional and straightforward components such as mirrors and pipes. These components can be produced fairly quickly and in a very short time.
3. Available industrial facilities and technologies can manufacture the individual components, unlike wind, tidal, and other sources of renewable energy.
4. They are the quickest way to replace today's coal-fired and gas-fired thermal power plants for the base load power supply.
5. Production of carbon neutral hydrogen and carbon neutral synthetic fuels using various cycles.

By 2032, the primary energy requirement in the country would be 3–4 times the present level. Hence, CSP is crucial for the rapid and sustainable development of a nation.

Current installed capacity of concentrated solar power

The graph shown in Fig. 2 indicates the cumulative growth in installed capacity of CSPs in the past ten years. It has been observed that the installed capacity has grown four times in the last decade because of the push by climate conservation organisations and positive investment in large parts of the developing world. Unfortunately, as it has been highlighted later in this study, that most of these installations have taken place in the G7 countries. China is the only country in the developing world seriously accelerating the installation of CSP plants.

Introduction to Concentrated Solar Power

Solar thermal power plants are not an innovation of the last few years. Records of their use date as far back as 1878, when a small solar power plant made up of a parabolic dish concentrator connected to an engine was exhibited at the World's Fair in Paris [7]. In 1913, the first parabolic trough solar thermal power plant was implemented in Egypt. After the energy crisis of the 1970s, nine parabolic trough power plants were installed during 1984–1991.

The SEGS PTC plant in the USA became the first commercially deployed CSP in 1984. All stages of the plant were completed in 1990. Unfortunately, from 1991 to 2005, no commercial CSPs were deployed throughout the world. However, from 2005 to this day, the world has rapidly embraced CSP technology for multiple reasons [8].

Concentrated solar power (CSP) harvests solar energy by concentrating the insolation onto a small receiver area by means of mirrors, lenses, and other optical devices. The heat from the concentrated solar radiation is transferred to a

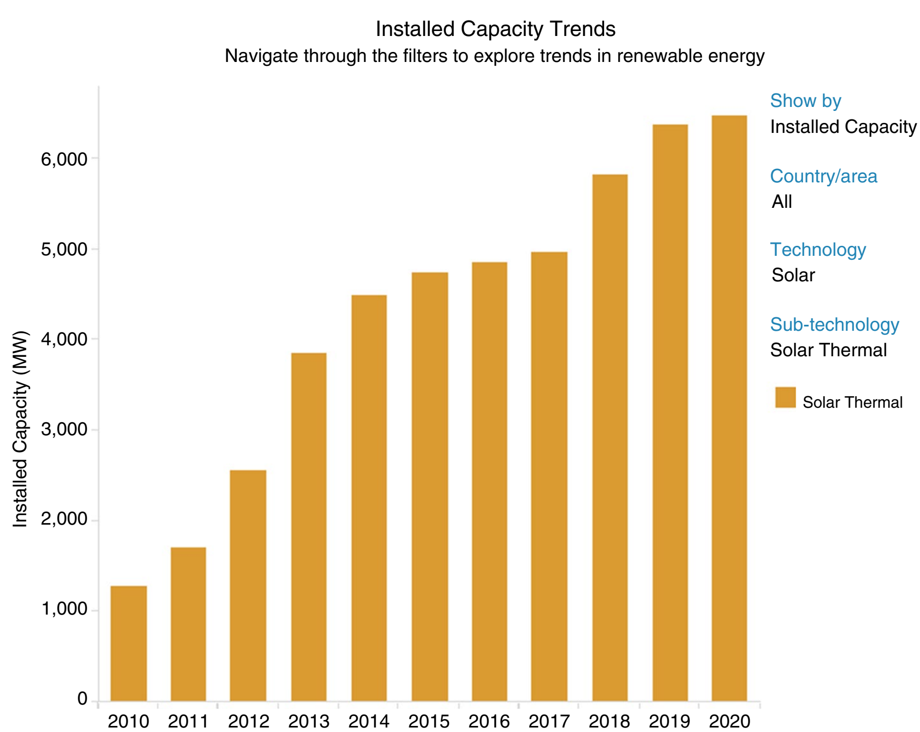


Fig. 2 solar thermal installed capacity from 2010 to 20, IRENA [6]

heat transfer fluid (HTF) through an absorber, which operates a thermodynamic system based on a thermodynamic cycle to generate electrical power. Concentrated solar thermal power is a global-scale technology that has the capacity to satisfy the energy and development needs of the world without destroying it. The desert regions of India are one of the few places in the world with a high amount of 'Direct solar radiation', perfect for solar thermal power plants [9].

CSP generation is expected to increase by 34% in 2019. Though this figure is exceptionally high, it (CSP) still does not agree with the sustainable development scenario (SDS) [10] (Fig. 3).

A CSP plant can be roughly divided into three major units:

1. Solar energy collection: this consists of the concentrators, the receiver, tracking mechanism, piping systems, etc.,
2. Thermal energy storage,
3. Thermal power generation unit: this includes the generator, the turbine/heat engine, controls of the cycle, etc.

The capacity of a CSP plant is dependent upon the capacity of the generator unit. The capacity is determined by the designers considering the energy demand of the demand source (which can be an industrial facility, residential area, factory, etc.) and factors that influence the energy demand (such as energy fluctuation, peak load magnitude, and duration). The decision to determine the capacity considers the following factors relating to the amount of solar energy available (such as daily insolation, peak insolation, and duration of sunlight) and other environmental and meteorological conditions secondary. For this reason, different CSP plants of the same type and capacity have varying sizes and configurations of solar fields. A CSP plant can be complemented by coal, natural gas, and oil-fired plants as sources of auxiliary power [9] (Fig. 4).

Classification of concentrated solar power based on type of concentrators

Central Solar tower receiver

From the early 1980s to late 1990s, many research activities in the field of solar tower technology took place in North America and Europe. In 1982 in Southern California,

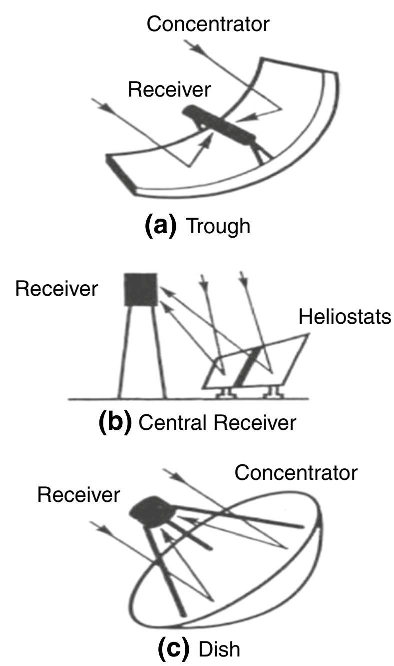


Fig. 4 Thermal energy collection techniques of solar thermal plants, wind and solar power systems design, analysis, and operation [12]

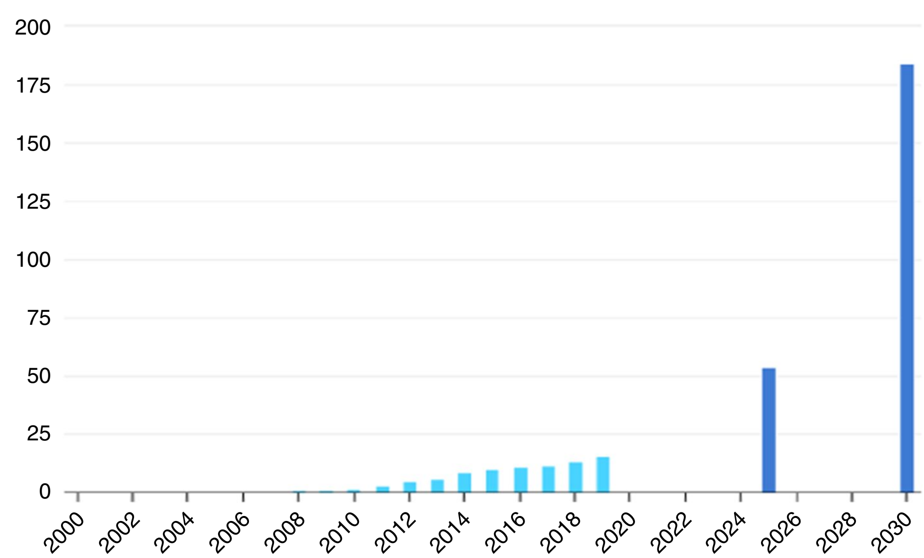


Fig. 3 IEA, *Concentrating solar power generation in the Sustainable Development Scenario, 2000–2030*, IEA, Paris [11]

world's first CSP tower plant 'Solar One' was established. It had a capacity of 10 MW and was functional from 1982 to 1986 [13]. Since then, a lot of solar power towers have been built throughout the world for research as well as for commercial purposes. Spiros et al. [14] believe that this was a result of the experience gained from the research activities conducted initially. Germany and Spain in Europe are the pioneers of this technology.

Solar tower power generation is a type of CSP that concentrates insolation onto a receiver mounted at a certain height on a tower (also called as the solar tower). The solar irradiation is concentrated by means of a heliostat field that surrounds it. The receiver heats up a heat transfer fluid/working fluid, which operates a turbine/heat engine to generate electrical power. The solar tower CSP mainly includes the following:

a. Heliostat field: Several small mirror panels are integrated to form a single concave surface, supported on a steel structure. The focal length of the heliostats is equal to the distance between each of them and the receiver. The heliostats in the concentrator field reflect the insolation onto the receiver mounted on the solar tower, through double-axis tracking [1].
b. Receiver tower: The receivers are designed to absorb the heat from the reflected solar flux and transfer that heat to an HTF at a very high temperature. The HTF can be heated directly or indirectly. Receivers can be classified as directly (external and cavity receivers) and indirectly irradiated (volumetric) receivers [1].
c. Thermal energy storage.
d. Generator unit: They generate power directly or indirectly through a thermal cycle.

The higher temperatures attainable in solar towers can help push for solar hydrogen generation to manufacture 'solar fuels', a green alternative to transportation fuels [4]. In fact, the Hydrosol plant project in Germany has succeeded in direct hydrogen production from solar radiation. The multi-channelled honeycombed monolithic solar reactors have been installed on the solar tower facility of Plataforma Solar de Almeria (PSA) in Spain, showing that hydrogen production is possible on a solar tower under realistic conditions and demonstrating the high potential of the particular thermochemical cycle technology for further scale-up. Currently, solar towers are a commercial-scale technology with multiple projects of over 100 MW capacity being undertaken. Also, the LCOE of solar towers is rapidly reaching the levels of fossil fuel plants. All operational commercial solar thermal power plants are based on the use of Rankine cycles, which are limited in the efficiencies they can achieve by the relatively low temperatures at the receiver. However, recent developments in the field of high-temperature receivers [15] along with rock-based packed-bed storage systems [16] have opened up an interesting possibility. High-temperature receivers allow the use of higher-efficiency combined-cycle setups, whereas packed-bed units offer the possibility of cheap storage which permits the consideration of solar-only operation.

Initially, solar power towers used water as the working fluid. However, solar power towers in USA nowadays use nitrate salts as the working fluid. These salts are non-flammable and non-toxic and have better thermal storage capabilities than water. Pavlovic (2012) et al. [13] further state that European solar power towers use air as the working fluid. The authors also make the point that solar power towers are quite profitable in the 50–100 MW range. Likewise, the authors also make the case that of all the CSPs, solar power towers require the largest land area and quantity of water per unit electricity generated.

Currently, there are 10 active commercial solar power towers in the world: five in China, two in the USA, and one each in Israel, Chile, and South Africa (Fig. 5).

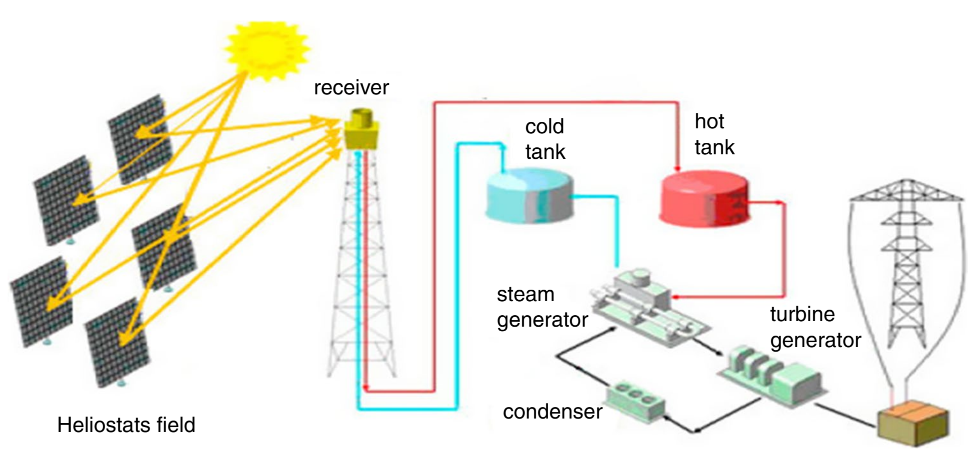


Fig. 5 A schematic for a typical solar tower power plant with molten salt storage [17]

Parabolic trough concentrators

In PTC solar power technology, solar irradiation is focused on the focal line of the paraboloid mirrors. A metal tube housed in an evacuated glass tube runs along the length of the focal line of the paraboloid mirrors. This metal tube is coated with an absorber material so that the maximum amount of heat reflected onto it is absorbed by the HTF flowing within. Problems with PTC are as follows: low concentration ratio (70–80), complex piping arrangement and high frictional losses, difficulty in raising the temperature of HTF, and restrained system efficiency.

Even with all of these problems, PTC-based plants are the readiest for commercial use of all the solar thermal power systems [1, 9, 12]. According to Pavlovic et al. [13], PTC systems provide the best land use factor among all CSP systems. It makes it easier to research and commercialise co-generation, hydrogen production, desalination, and other technologies. Bamisile et al. [18] conducted a performance analysis of a multi-generation PTC system which is capable of electricity generation, cold or hot water, and hydrogen production. The study involved analysing two Rankine cycles with regeneration and reheating. The system used a double-effect and a single-effect absorption cycle for cooling. Also, a proton exchange membrane was employed to produce hydrogen. The results of the study showed reduced energy and energy efficiencies and a reduction in GHG emissions. This study gave direction for further research in the allied applications of CSP plants to improve their overall efficiency. Such a commercial plant would be quite economical for the developing and underdeveloped worlds as it might solve the issues of load-shedding, freshwater shortages, and less electricity coverage. The hydrogen that is made could be used, especially in the developed world, to charge EV batteries or make electricity [18].

Many researchers have carried out studies in the past decade that have led to several advancements being reported and implemented for various components and sub-systems of PTC plants. These advancements have resulted in improved performance of the PTC plant, reduced operating and maintenance costs, or both. These advancements include desalination, improved parabolic troughs, different and efficient HTFs, hydrogen production, etc. One such experimentation is done by Alguacil et al. [19], where direct steam generation has been satisfactorily attempted in the trough absorber tubes. This experiment would help solve the toxicity problem of conventional HTFs and also reduce energy losses in pipes and heat exchangers. Certain conscious attempts have also been made to increase the aperture area of the troughs to improve their thermal and optical performance. Wang et al. [20], in their thermo-economic assessment of PTCs, have introduced a radiation shield to reduce the operation temperatures in order to improve the solar to thermal conversion efficiencies of PTCs. In their study, Aseri et al. [21] looked at how well two PTC systems worked in a city in India to figure out how much money they could save. In the first case, a larger aperture area parabolic trough was used with an advanced HTF to reach higher temperatures. In the second case, the same parabolic trough was used with molten salt as an HTF and storage medium. The results showed a 12.3% capital cost reduction in case one and a 29.9% reduction in case two. According to El Gharbi et al. [22], an important cost factor in PTC plants is the manufacturing of the glass in parabolic form. These studies will help to reduce the cost of initial investment, an issue hindering the progress of not just CSP but most renewable energy power generation techniques. The developing world will most benefit from these cheaper plants, as they account for a majority of the pollution caused by conventional thermal power plants. Table 7 explains similar studies done by Linrui Ma et al. [23], Wang et al. [20], Ceckici et al. [24], and Moharram et al. [25] (Fig. 6).

Solar dish concentrators

A solar parabolic dish is a point-focusing type of CSP. These systems employ double-axis tracking to concentrate insolation onto a thermal receiver mounted at the focal point of the parabolic dish. The parabolic dish has several small mirror panels that concentrate the solar energy.

The receiver has thin tubes within, which circulate the working fluid (helium, hydrogen, or air). This working fluid absorbs heat from the concentrated beam, heats up, and expands. This expansion drives a piston operating on a thermodynamic cycle (a Stirling cycle in almost all cases) producing work. The rotary motion obtained drives a generator, producing electricity. While designing the parabolic dish, one needs to keep in mind that the dish has to point directly at the sun to prevent the formation of shadows on the collector surface. This ensures optimum heat collection [5] (Fig. 7).

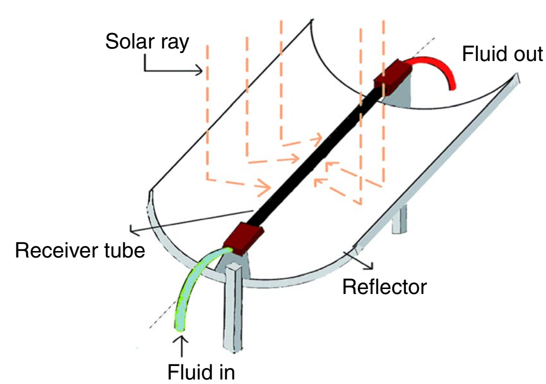


Fig. 6 A schematic for solar parabolic trough concentrator [26]

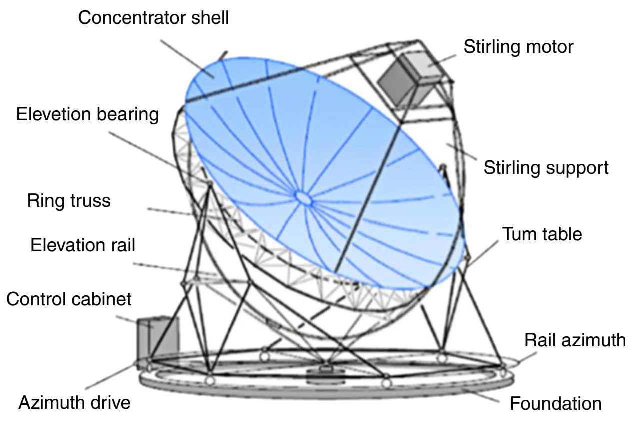


Fig. 7 A solar dish concentrator power generation system [26]

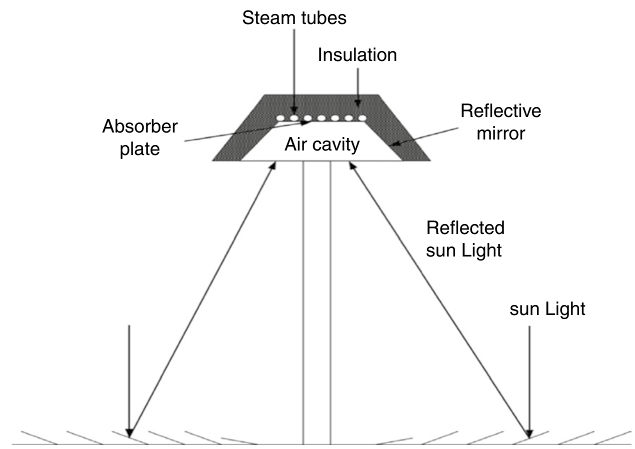


Fig. 8 A schematic of a Fresnel lens concentrator used in concentrated solar power systems [28]

For this system, the concentration ratio ranges from 600 to 3000, the operational temperature is up to 800 C, and the solar dish-Stirling net efficiency is 30%. The dish-Stirling system can generate power within a range of 10–100 kW. These systems are best suited for modular, off-grid, and low-power applications [5, 9].

The heat engine of this system can employ both Rankine and Stirling power cycles. However, Stirling cycles are the most effective and widely used. Since the Stirling engine is more compact than a Rankine power system, the latter is favoured. However, Stirling engines are not a completely mature technology yet, so microturbines (for Rankine) are being considered. Also, for systems generating more than 50 kW, Stirling systems are difficult to build as the heat sink of the cold side becomes unwieldy. These systems are an excellent renewable energy alternative to diesel engines [1, 27].

Linear Fresnel Lens-type concentrators

The Fresnel lens was invented in 1822 by Augustine Jean Fresnel, a French mathematician and physicist.

The LFR CSP plant is similar to a PTC plant, where the linear Fresnel reflectors replace the cylindrical parabolic troughs. The reflectors focus the incoming solar irradiation onto the focal line of the Fresnel mirrors. An absorber tube, with the HTF flowing within, runs along the focal line of the mirrors. This absorber tube is located at a fixed height. The mirrors track the sun by rotating about their axes to reflect the insolation onto the absorber tube. High temperatures are reached in the HTF, which runs a thermodynamic engine to make power [9] (Fig. 8).

The need to manufacture the glass of PTC CSP reflectors in parabolic form inflates the initial investment. To reduce this cost, El Gharbi et al. [22] make the point that many researchers are working on Fresnel reflectors. They argue that the parabolic shape is roughly approximated by a succession of flat mirrors whose slopes are regulated according to the position of the sun. While they may reduce investment costs, they also, unfortunately, reduce efficiency. Hence, engineers might have to make a trade-off between cost and efficiency depending on the requirements.

The Linear Fresnel plant is the 'youngest' of all the CSP technologies and quite nascent; hence, further research must be done for this technology to mature more [5]. Vinod Kumar et al. [29] argue that Fresnel plants have the ability to attain higher temperatures, compact size, higher thermal efficiency, and lower investment costs. This makes them suitable for hybridisation applications, combined industrial steam power generation, hydrogen production, space power applications, and DSG-type thermal power generation. The authors conclude by saying that development of techno-economic viability of supply chain management of Fresnel CSP components can help commercialise the technology, which will lower the LCOE for CSP plants.

El Gharbi et al. [22] conducted a comparative study of PTC and Fresnel CSP, using data from a site in the Hassi Rmel region of Algeria. A numerical analysis was performed to compare their performance and efficiencies. The study found that Fresnel CSP is optically analogous to PTCs. The optical quality and thermal efficiency of Fresnel CSP were found to be lower than those of PTC. This, they reasoned, was due to the higher influence of the angle of incidence and the cosine factor.

Common accessories and technologies used in concentrated solar power

Layout of the solar field for a typical concentrated solar power plant

There are three types of layouts of a solar field for a CSP plant: direct return layout, inverse return layout, and central feed and return layout. The first two types are used for small industrial processes and heat applications, while the latter is used for large applications.

The central feed and return layout are classified into two types:

1. H-field layout: In this type of layout, the field is divided into two header pairs, two on each side of the power block. These four header pairs are arranged in the East–West direction.
2. I-field layout: In this type of layout, the field is again divided into two header pairs. The power block is situated at the centre of the field. The headers are arranged in an east–west direction. [1]

The optimisation of solar field is a rather complex problem. Besides the complications of working the energy on an annual basis, the non-exhaustive list of variables to optimise requires multiple software tools to improve the performance to obtain maximum efficiency. Yiyi Zhou et al. [30] and Anass Zaaoumi et al. [31] have in their respective studies applied different optimisation techniques to improve the performance of the solar field. Reflector or mirrors used in CSPs account for 50% of the installation's costs. Vinod Kumar et al. [29] mention that due to difficult operating conditions and environmental impacts, they degrade easily leading to a substantial drop in efficiency and reduced life cycle. Hence, they also account for high maintenance costs.

Therefore, current studies focus on optimising the design of the solar field to trap maximum amount of insolation in the cheapest way possible. This reduces both the size and cost of the solar field and consequently the CSP plant.

The solar tower technology can be used for desalination of water in co-generation systems. The heliostat field can be exploited in multiple ways for this purpose. Likewise, Spiros et al. [14] make the case that out of the large number of desalination technologies available, only few have reached a semi-commercial state that can be effectively combined with CSP operation. Currently, multi-effect desalination and reverse osmosis systems are used. The former needs electricity and heat, whereas the latter needs only electricity (Fig. 9).

Importance of thermal storage systems for concentrated solar power systems and the review of recent technological trends

A solar thermal power plant can operate only when there is a sufficient amount of direct solar radiation available. Solar thermal power is not dispatchable, which means that it is unable to produce and supply power on demand at the behest of power grid operators or market demands. However, solar thermal power can be made dispatchable by employing thermal storage. This way, the plant can operate independent of the solar resource, producing power even at night or during cloudy days. The extraction of heat from solar energy for generating power has the added advantage that thermal storage is possible. Solar PV plants have to employ chemical storage through batteries or fuel cells. Here, thermal storage in a solar thermal power plant is relatively cheaper than chemical storage employed in solar PV due to high investment costs and a high loss rate of 20–50%. Due to the intermittent supply of renewable energy sources, energy storage is a necessary precondition for them to seriously compete with conventional energy sources like fossil fuels [5]. The future of CSP technologies depends on coming up with a cost-effective way to store heat [32].

For TES analysis and review, Ulgo Pelay et al. [32] surveyed CSP plants and divided them into five groups depending on their time of commissioning. They have then performed a statistical analysis of the purpose of the plant (research, commercial power generation, both, etc.), the type of CSP technology, hybridisation (co-generation, gas-fired, etc.), and the type of thermal storage system incorporated. The authors have found that 47% of the current CSP plants are integrated with TES, 74% of the under construction CSP plants, and 77% of the planned CSP plants are to be integrated with TES. However, the majority of TES use sensible heat storage technology due to its dependability, low cost, and ease of implementation.

The authors have thus concluded that to make future CSP plants more economically competitive and dispatchable, TES system integration plays a crucial role. Also, latent heat and thermochemical storage systems, because of their high energy density, are more suitable for large-scale CSP plants than the current sensible heat storage systems. For this to be possible, some technological barriers such as high thermal conductivity of PCMs and thermochemical materials and removal of solid deposits from heat exchanger surfaces are necessary [32].

Alnaimat et al. [33] make a valid point as to why thermal energy storage or energy storage is almost inevitable for the sustenance of CSP technologies. According to them, conventional systems are used to supply excess power during over-demand, which causes an increase in carbon footprint. Due to the temporal intermittency of

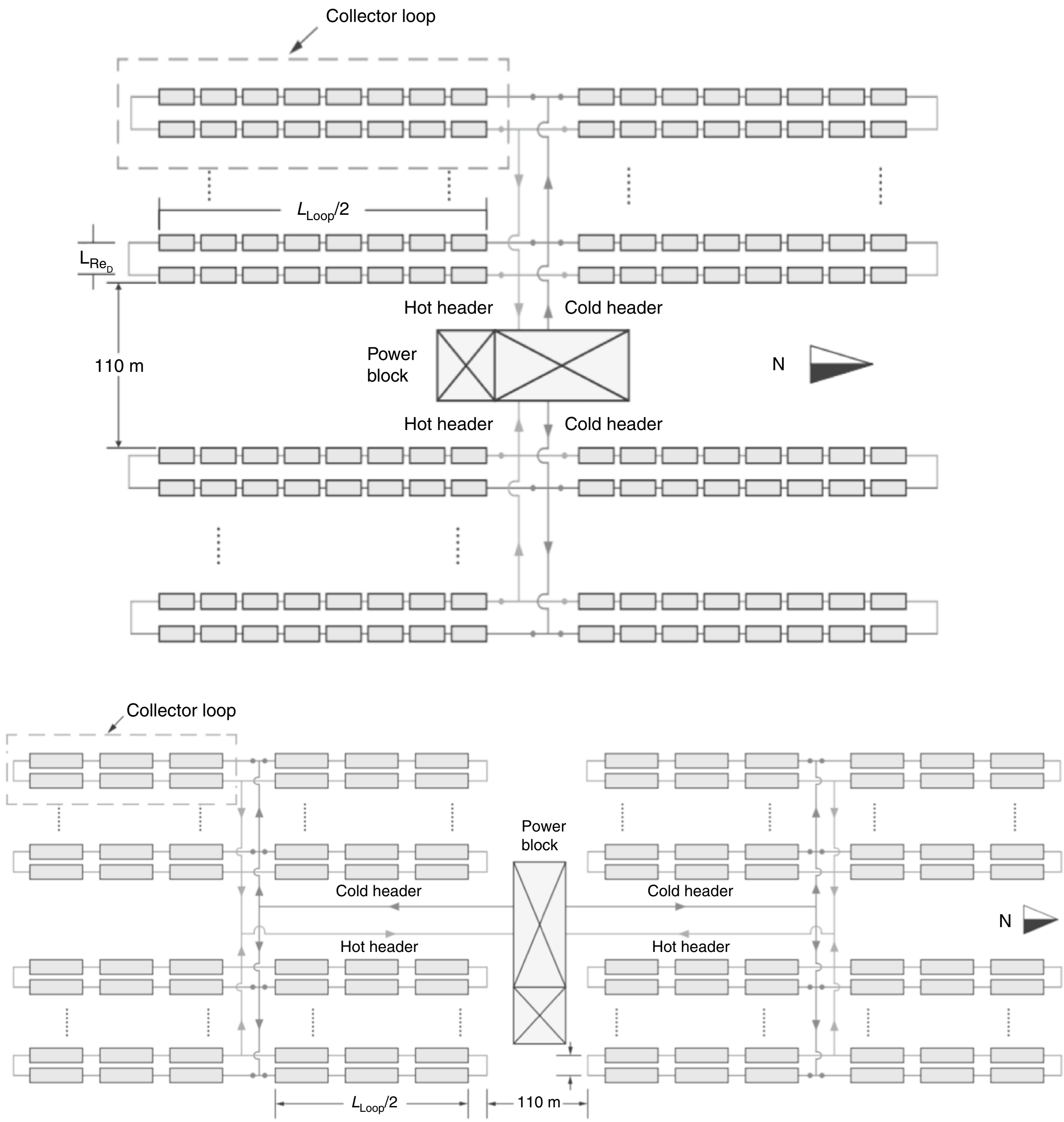


Fig. 9 I-field (above) and H-field layout (below) of solar field [1]

solar energy, the production side is highly non-deterministic. Similarly, the utility patterns too are non-uniform, with peaks and troughs in energy consumption by the users. The argument put forth, which is quite valid, is that an energy storage system will effectively dampen this mismatch by storing surplus energy during off-peak hours. The stored energy can then be released during the non-availability of solar energy. For CSPs, energy stored in the form of heat is the most economical and environmentally friendly.

Gil et al. [34] have summarised the following major requirements of thermal energy storage systems for CSP: energy capacity, charge and discharge heat rates, safety and environmental impact, max and min temperatures, thermal and chemical stability for thousands of cycles in contact with different materials, heat losses, and costs. Here, one can argue that small-scale CSP plants are not economically compatible with a TES. Hence, the above-mentioned requirements need to be fulfilled for a CSP to have a TES system (Table 1).

Therminol VP-1 is the most common HTF for PTC plants. The oil, Therminol 11 VP-1, is a eutectic mixture that is capable of being sufficiently stable up to 400. However, large-scale storage of the oil in oil tanks is not economically feasible as it is quite expensive. A major problem with heat storage with PTC and oil circuit is the limited temperature range between the oil input and output temperatures (the maximum being 100 K). For molten salt-solar tower heat storage, the temperature difference is nearly 300 K. To store the same amount of heat, a molten salt-PTC system would require nearly three times the quantity of salt. Hence, an interest in low-cost heat storage systems for PTC plants is understandable. Heat storage with concrete for PTC is also being researched. Potassium nitrate, sodium nitrate, and calcium nitrate are the salts used for molten salt heat storage [5].

The use of phase change materials (PCM) in the form of latent heat storage (LHS) is a very promising technology for thermal energy storage in CSP systems. They have the capability to absorb and release large amounts of heat. Unfortunately, LHS has found restricted commercial applications due to the thermal stability of the storage material and the limited size of storage containers. Lebedev et al. [35] describe how the study of the influence of thermal cycling on the physical properties of PCMs is important for their commercialisation. Lukas Heller's report [36] mentions that high energy density and constant temperature heat transfer are the advantages of LHS systems. The PCMs can be implemented favourably into a saturated or superheated steam power cycle, in which large amounts of heat are required at a constant temperature for evaporation of the working fluid. Hence, solar towers and PTC plants seem quite favourable for the application of PCMs.

Recent developments in receiver designs to optimise concentrated solar power plant performance

The receivers are also called 'heat-collecting elements'. They absorb the heat of the concentrated solar radiation focused on them by the concentrators. The heat is then transferred to the HTF that flows within the receivers. The physical orientation of the receivers varies depending upon the type of concentrators used. Line-focusing collectors like the parabolic trough and the LFR make use of metal tubes (usually stainless steel) that run along the length of the collectors. Point-focusing collectors used in solar towers and parabolic dishes make use of receiver panels that cover the entire receiver area. The receiver tubes and panels are coated with an absorber material that absorbs the solar irradiation. The PTC and LFR receivers are present in an evacuated glass tube to prevent heat losses. In a solar tower, a heat loss caused by convection is stopped by an internal cavity receiver [10].

Many researchers are conducting studies to improve the performance of the receivers and absorbers in order to improve the performance of CSP systems. In one such study, Gonzalez-Portillo et al. [37] have done techno-economic optimisation of CSP systems with free-falling particle receivers. Their model provides upgrades to previous similar models, which help in the improvement in their fidelity, accuracy, and representativeness of actual systems. The results of the study conducted on a 250-m-high solar tower

Table 1 A summary of advantages and disadvantages of different sensible heat storage thermal energy storage systems

Sr. no.	Thermal energy storage fluid	Advantages	Disadvantages
1	**Solar salt (active sensible heat storage)**	Meets requirements for todays' superheated cycles sufficient volumetric heat capacity Low specific cost [36]	low high temperature for supercritical high-efficiency cycles Freeze protection necessary
2	**Sodium (active sensible heat storage)**	Suitable for higher-temperature operation	High cost and large storage volume
3	**Steam/water (active sensible heat storage)**	Not toxic	Large storage volume No other storage technology than accumulator available
4	**Packed beds storage (active sensible heat storage)**	Moderate mechanical stresses Cost-effective Environmentally safe [61]	Not mature technology
5	**Ceramics (passive sensible heat storage)**	commercial deployment Seems promising [61]	Improved design to reduce risks from thermally induced mechanical loads
6	**Graphite (passive sensible heat storage)**	Low cost High heat capacity High thermal conductivity	amateur technology, not commercialised

with 16 h of thermal storage showed a reduction of LCOE to 0.056 USD/kWh. This is a positive development as it brings researchers closer to the goal of reducing the LCOE to 0.05 USD/kWh. Conroy et al. [38] compiled literature that engaged in steady-state thermal and mathematical modelling of tubular receivers. In their study, the authors adopted contrasting approaches and indicated a general trend towards semi-empirical techniques over simplified analytical models. The semi-empirical techniques were found to be more flexible and accurate with fewer computations, allowing testing and simulation of various geometries, configurations, HTFs, materials, and operational conditions at the design stage of the receiver.

Mahdi et al. [39] in their review have summarised the analysis and findings of different research in the field of central receiver tower design in CSPs to enhance the amount of insolation absorbed. Among many studies, most dealt with solar power tower life extension, material selection, heat loss reduction, maximising thermal and optical efficiencies, and study of the effects of different variables. The summary indicated that most authors focused on the high capacity of hot HTF production to be sufficient for power conversion cycles (Figs. 10 and 11).

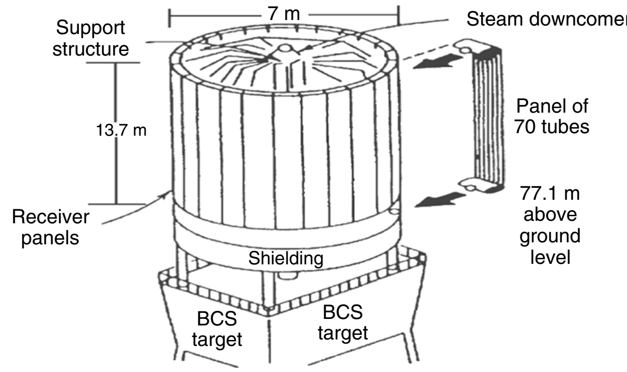
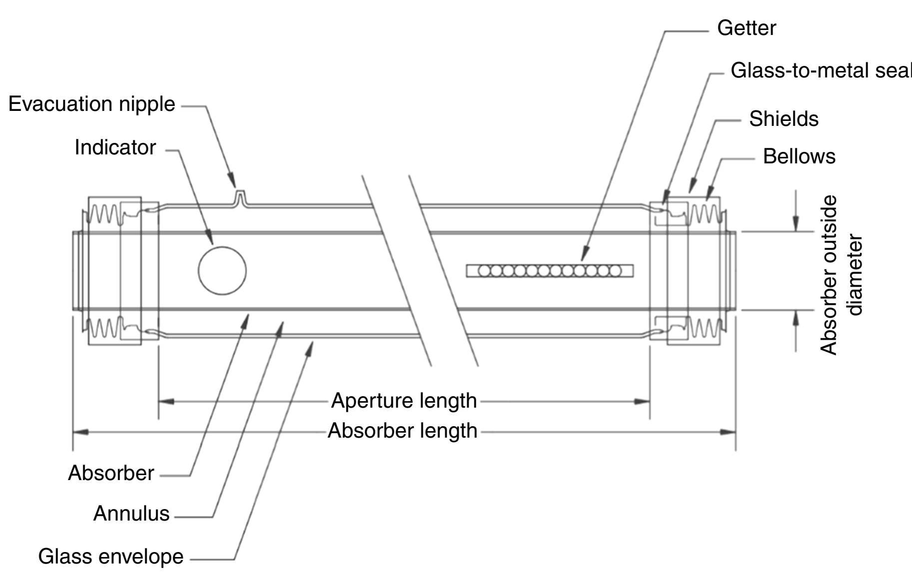


Fig. 11 The receiver of the Solar One central receiver facility at Barstow, California. This is an external type receiver. [1]

Brief overview of heat transfer fluids and their applications in concentrated solar power technology

The heat transfer fluids are used in line-focusing CSP plants. They absorb heat from the solar field and transfer it to the power generation unit and the thermal storage system. Following are the probable HTFs for CSPs: air, water, molten salts, glycol-based, glycerol-based, and synthetic oils. The use of air and water as HTF in CSP is impractical. Air has very low thermal conductivity, and on top of that, it has a high specific volume. This means air will expand a lot at high temperatures, which would require large absorber tubes, consequently increasing the cost of the equipment. Water, despite its availability, non-toxicity, and impressive thermal conductivity, will react with the equipment material, leading to corrosion. Molten salts have a tendency to solidify at higher temperatures, so they are limited to use in thermal storage systems. Although many researchers, including Juan Ignacio et al. [41], have experimented with molten salt HTFs and have observed positive results. Hence, the viable options left are glycols, alcohols, and synthetic oils. Glycols and alcohols oxidise at high temperatures, leading to the formation of acids. These acids are corrosive in nature. Various corrosion inhibitors can be added to them to avoid the corrosive effect. Glycols and alcohols are slightly toxic, and alcohols are highly flammable. These disadvantages are combated while designing CSP plants [42].

Fig. 10 A typical Absorber tube for a Parabolic trough concentrator [40]



Glycols are limited to CSP applications up to 175 and synthetic oils up to 450. The following are important points that highlight the selection criteria for the HTF (Tables 2 and 3):

a. High operating temperatures,
b. Stability at high temperatures,
c. Low maintenance costs,
d. Non-corrosive,
e. low freezing point and low vapour pressure,
f. Low viscosity.

A review of various studies conducted on CSP technology and a discussion of various enhancements, system modification strategies adopted for better performance

Design review for CSP, PV-T plants

Table 4.

Review of studies on performance improvement strategies for solar tower power plant

Table 5.

Review of studies on performance improvement strategies for Fresnel lens concentrator power plants

Table 6.

Review of studies on performance improvement strategies for parabolic trough concentrator power plants

Table 7.

Review of studies on performance improvement strategies for PV/T systems

Table 8.

Gaps and objectives of the study:

Objectives of the study

1. To explain with factful reasoning the need for imminent energy transition to renewable energy resources.

Table 2 Physical properties of various HTFs

HTF	T_{MAX}/K	Specific heat (C_p)/kJ kg^{-1} K^{-1}	Density (ρ)/ kg m^{-3}	Thermal conductivity (k)/W m^{-1} K^{-1}	Dynamic viscosity (μ)/ mPa s
Biphenyl	500	2.03	853	0.123	0.32
Phenyl-naphthalene	600	2.6	832	0.077	0.11
Therminol 12	510	(1.66–3.08)	562	0.066	0.135
Nitrate salts	865	1.495	1899	–	3.26
Hitec	720	2.213	1992	–	6.37

Table 3 Summary and short comparison of the different types of concentrated solar power systems

Parameter	Solar tower	Parabolic trough concentrator	Linear Fresnel	Solar dish concentrator
Type	Point focusing	Line focusing	Line focusing	Point focusing
Concentration ratio	300–1000	70–80	70–80	600–3000
Operational temperature (◦C)	800–1200	400–450	Same as PTC	800–1000
Maximum efficiency (%)	Up to 25%	Upton 20%	Same as PTC, has ability to be highest	up to 30%
Installed capacity	10–600 (MW)	50–600 (MW)	50–150 (MW)	10–100(kW)
Commercial experience	High	Very high	Low	Very low
Possibility of thermal storage	Yes	Yes	Yes	No

Table 4 Literature review of PTC systems

Sr. no.	Author	Publication year	Design parameters for the CSP/PV-T plant	Performance analysis and results /experimental methodology/conclusions drawn
1	Aysar et al. [43]	2016	Cylindrical parabolic trough collector, max temperature = 500 °C Optical concentration ratio = 82:1, I = 730 W/m^2 Therminol VP-1, Specific heat = 2.436 kJ/kg°C Liquid phase = 12°C—400°C Vapour phase = 260 °C–400 °C	In this paper, the authors have discussed the sizing and design characteristics of a 10-MW solar PTC plant in Jericho. The plant is going to employ 20 collector loops having four PTCs per loop to collect the solar thermal energy needed to produce the required power The LCOE (levelised cost of electricity) calculated for the proposed solar PTC is 0.16 USD per kWh
2	Spiru et al. [44]	2010	Design-point method was adopted to design the solar field The increase in temperature of the fluid determined the no. of thermal collector loops, whereas the thermal power to be supplied determined the no. of collectors per loop The length of the pipes in the solar filed determined the pumping power required The number of collector loops influences the pressure and temperature conditions of the HTF in the solar field HTF—Therminol VP-1 Parabolic trough collectors used	In this study, the authors have performed the sizing of a solar field for a PTC CSP plant, operating on a Rankine cycle, generating 50 MW of energy Though the design-point method adopted was simple and effective, the design characteristics could be further optimised to reduce the initial investment cost The authors have employed a conventional source to supply auxiliary power The installation and operation of more such plants can help reduce cost of electricity in the future and conservation of fossil fuels for emergency use
3	Aditya et al. [45]	2018	Reflector specifications: Solar dish concentrator Reflective surface—aluminium Aluminium foil thickness—0–03 mm Width—100 mm Reflectivity—75% I = 1353 W/m^2 HTF—air	The authors in this study have made an attempt to design and develop a solar Stirling engine with a dish reflector for power generation An aluminium foil coating has been used as reflectivity of aluminium is more than that of gold and silver. It is an apt choice as not only it has higher reflectivity but also is quite cheap in comparison The experimentation reveals that the engine has difficulty operating in the morning and evening runs due to low-intensity solar radiation. However, the system operates smoothly during afternoon hours due to high intensity of direct solar radiation The study seems promising, although it highlights the fact that solar dish concentrator systems, though portable, need auxiliary power backup or any form of energy storage for deployment in practical applications
4	Ali et al. [46]	2018	A mathematical model was formulated based on certain governing equations for the Photovoltaic -Thermal module. An energy balance was considered for the heat exchange between the solar irradiation and the heat transfer fluid The heat transfer and fluid flow were modelled based on Navier–Stokes and other energy equations. The boundary conditions were set for the for-incident radiation, fluid flow and heat transfer Governing equations to study the effect of thermophysical properties of the nanofluid and shape of the SiO_2 nano-particles were also incorporated into the model The finite volume method was employed to solve the governing equations and the boundary condition to obtain the results of the numerical analysis	The authors in this study have performed a numerical analysis of photovoltaic–thermal solar collector. The collector uses a water SiO_2 nanofluid to collect the thermal energy The effect of adding the nanofluid to the thermal and PV efficiency of the collector was investigated. Artificial neural networks were used to obtain the correlation between the PV-thermal performances of the collector The results revealed that the cylindrical-shaped particles gave the best performance. They gave the highest efficiency enhancement of 7.39% The correlation study found that higher nano-particle concentration, higher insolation, lower heat transfer coefficient, and inlet temperature of the heat transfer fluid will provide highest total and thermal efficiency

Table 4 (continued)

Sr. no.	Author	Publication year	Design parameters for the CSP/PV-T plant	Performance analysis and results /experimental methodology/conclusions drawn
5	Fatih et al. [47]	2019	75 W polycrystalline panels were used in the study Aluminium fins of uniform cross-section were studied with the PV panels in ten different configurations. The different configurations involved various fin lengths, shapes and sequences The aluminium fans were attached to the back surface of the PV panel to study its effect on the panel's temperature and efficiency Heat transfer and uncertainty analysis was performed on the system model	Depending on the efficiency of the photovoltaic panel, some of the incident solar radiation is converted to heat, causing rise in temperature of the panel. Increase in solar radiation intensity increases power and heat generation. However, higher temperature of the panel due to high heat generation can cause reduction in its efficiency Hence, in order to regulate the temperature of the panel during high solar intensity hours, the authors have used different configuration of aluminium fins for cooling The analysis revealed non-homogenous distribution of temperature on the PV panel. Fins of 7 cm×20 cm dimensions and staggered array configuration were found to provide the best results Highest energy and exergy efficiency values of 11.55% and 10.91% were achieved. The aluminium fins acted as efficient heat sink to absorb excess solar heat from the panel

2. To use reliable data to help understand why concentrated solar power is the best alternative to replace conventional thermal power plants.
3. To provide a brief overview and short comparison of the types of CSP along with the description of the basic accessories used in a CSP.
4. To conduct a thorough literature review of the different studies undertaken in the field of CSP till date.

Gaps in the study

1. A further detailed study of literature on co-generation systems involving CSP in combination with different renewable sources such as wind, ocean thermal, and biogas can also be done.

Economic overview of concentrated solar power technologies

Economics is the discipline that helps individuals and organisations make rational decisions about the allocation of scarce resources. This is done by reducing the parameters of design and the options available in monetary terms. Then, certain economic tools are employed to compare and select the best option.

While designing a powerplant, in addition to technical (capacity, peak load, etc.) and meteorological factors (seismic activity, wind speed, solar DNI, etc.), many economic factors are also considered. In the context of CSP, the initial and operating cost of the four different types of plants, the different types of receivers, layouts, etc., are the economic factors that are involved in the decision-making. In the world of renewable power generation technologies, solar thermal power generation faces stiff competition from solar PV and wind energy systems. The latter two systems are not just more technologically mature, but also cheaper than the former. Hence, economic analysis of various power generation technologies is done to determine the most economically rewarding technology for given conditions. The risk assessment and cost analysis help determine the places where cost reduction can be done to make a certain technology cheaper, hence more economically competitive [14]. CSP will grow only if it becomes accessible to the developing and underdeveloped world. For this to happen, it has to be cheaper than its conventional and renewable peer technologies. Determining the LCOE of a plant is the best way to compare different technologies to find the most economically viable alternative.

According to the US Energy Information Administration (EIA), LCOE 'represents the average revenue per unit of electricity generated that would be needed to cover the costs

Table 5 Literature review of solar tower systems

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/ Enhancement/ modification strategy adopted
1	Juan et al. [41]	2008	120-m^2 large-area glass-metal heliostats, Number = 2480 HTF and storage fluid—nitrate The plant has 647 MWh thermal storage capacity, capable of supplying power for 15 h High-temperature storage at 565 °C Low-temperature storage at 285 °C Storage time is 10 to 20 h High pressure reheats turbine (10 to 20 MW)	In this paper, the authors have designed a demonstrative central solar tower receiver project, where they have aimed to capitalise on its abilities to reach highest temperatures and efficiencies in electricity production A unique factor of this project is that nitrate salt is chosen to function both as the HTF and as the fluid for thermal storage. This has ensured higher efficiency, low system complexity and low-risk and efficient electric power supply Also, large-area heliostats have been used to reduce the cost and complexity of designing the collector field To facilitate the dual function of the nitrate salts, a forced recirculation evaporator has been included in the shell side of the heat exchangers to prevent nitrate freezing
2	Fatih et al. [48]	2019	The system consists of a central solar tower receiver surrounded by a field of heliostats. The receiver absorbs the concentrated solar energy and transfers it to the molten salt HTF Hot and cold storage tanks store thermal energy. A heat exchanger is used to transfer heat to the steam turbine circuit that consists. The steam turbine circuit generates commercial electricity and freshwater The entire system is mathematically modelled based on the following design parameters: ambient wind velocity, pressure and temperature, heliostat area and its efficiency, the efficiency of the steam turbine, pump and condenser, the inlet temperature of molten salt for the hot and cold storage and the solar irradiation	The authors in this study have designed and analysed a solar tower power plant integrated with a desalination system The plant has also been provided with a thermal energy storage option The steam generated by the solar field is used drive a steam turbine to produce electrical power. Under sunny conditions, the system is found to generate 24.46 MW of power, which reduces to 20.17 MW under cloudy conditions or at night The steam at the end of the turbine stage, possessing low-grade thermal energy is then utilised by a multi-effect desalinator to produce fresh water The electricity generated by the system serves two purposes: residential use and freshwater production through a reverse osmosis unit This study is another great example where co-generation systems can be quite effectively used with CSP systems. This integrated system has succeeded in producing 240.2 kg/s of fresh water
3	Vinayak et al. [4]	2017	The aperture areas of tripod heliostats studied were 62 m^2 and 100 m^2 The heliostat support frame was first designed, and four variations were selected. The variations of the heliostat structure were then simulated under extreme wind load and operational wind load conditions. The simulation began with the structure with lowest cost, and the variation was eliminated if the member failed Optimising the performance of the tripod heliostats to reduce costs is at the crux of this paper as both heliostat cost and performance play a critical role in determining the plant LCOE	The heliostats in a solar power tower project account for half of the capital cost. This high cost is due to the expensive support structure of the heliostats. This cost is further supplanted by the complex and heavy drive mechanisms and their maintenance Hence, it is very important to optimise the structural design and functioning of individual heliostats to reduce the cost, without affecting the performance The authors of this study sought to resolve this issue by developing and analysing a tripod heliostat. From the simulations and the study, the authors concluded that a triangle size of 3000 mm and a yoke height of 500 mm are optimum for heliostats. Also, the authors were successful in bringing down the structural cost to about 40% of conventional heliostat cost The tripod heliostats are cheaper and less bulky and have low maintenance, giving them an edge over conventional heliostat

Table 5 (continued)

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/ Enhancement/ modification strategy adopted
4	Mohammad et al. [49]	2020	A 50-MW DSG solar tower plant is designed operating on a regenerative steam Rankine cycle The tower has two external cylindrical receivers mounted on top, one each for the evaporator and the superheater. The plant also has a natural gas-fired auxiliary boiler for continuous operation A heliostat field with a solar multiple of 1 is designed in a radial-staggered configuration. The field has been dividing into two sections: the one closer to the tower reflects the insolation on to the superheater, while the one farther away from the tower reflects the insolation on to the evaporator	In this paper, the authors have carried out a thermo-economic assessment of a DSG dual-receiver solar tower plant operating on a regenerative Rankine cycle The authors have also incorporated a flexible operation strategy for the heliostat field. In this strategy, the section of the heliostat field can either be defocused, or focused between the evaporator and the superheater based on the transient conditions The developed operational strategy allowed for flexible operation of the direct steam generation plant. The LCOE achieved was low and quite competitive. A huge reduction in CO_2 emissions added to the economic benefits of this plant An improvement to this already efficient system would be the incorporation of an energy storage (mostly thermal) system, as during large DNI hours, the potential of the defocused heliostat field is wasted
5	Yiyi et al. [30]	2014	The optical efficiency of the solar field can be calculated by calculating the product of the mirror reflectivity of the reflector/heliostat, the cosine efficiency, the shadowing and blocking efficiency, the spillage efficiency and the atmospheric attenuation efficiency The hourly performance of thousands of heliostats on certain days of the year has to be observed and the four efficiencies at hundreds of solar positions have to be simulated to calculate the annual optical efficiency Details of the cornfield layout: Annual optical efficiency = 86.3% Ground coverage = 38.3% Details of the radial stagger layout: Annual optical efficiency = 82.5% Ground coverage = 33.6%	The heliostat field is the most important and expensive component of the solar tower power plant. Hence, the arrangement or layout of the heliostat field around the solar tower plays quite an important role as it not influence the performance through optical parameters but also the cost as larger area for layout would incur higher cost This study investigates an innovative method to design the heliostat field layout by optimising the land use, maximising annual optical efficiency, while considering the specific ground area required by individual heliostats to prevent their mechanical collision Two field layouts: Cornfield and Radial staggered, are simulated by Monte Carlo ray tracing method based on graphic processing unit computation method to determine their annual optical efficiency for comparison It was found that the overall optical efficiency of both the optimal layouts is 10% more than the general field layout. The ground coverage too is 4–8% more. The authors have also found out through the design process that the ground coverage has no direct relation with the field layout

Table 6 Literature review of LFR systems

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/enhancement/modification strategy adopted
1	Al-Dohani et al. [50]	2018	Maximum insolation: 700 W/m^2 (the design point) Working fluid: water HTF and thermal storage fluid: 100% KNO_3 60% KNO_3 + 40% $NaNO_3$ Solar spot intensity, assumed distance between the receiver and the lens, and magnification power of lens used to design the solar field The heat exchanger dimensions were obtained by a simple energy balance of the heat to be supplied by the solar salt to the water	The authors in this paper have designed a solar power system with Fresnel lens concentrators They have done experimental comparisons with different configurations of the solar salt and heat exchanger design to obtain the best performing system The system was found to perform better with KNO_3 + $NaNO_3$ solar salt mixture than with 100% KNO_3. The mixture lengthens the duration of thermal storage, improves heat transfer (improving efficiency) and minimises salt volume (reducing cost) The solar salt mixture was later experimented with different dimensions and materials of the heat exchanger For a given power output, brass on the shell side and copper on the tube side provided the best performance
2	Adam et al. [51]	2022	No. of collectors: 144 double-axis Fresnel lens collectors. Each collector has eight square Fresnel lenses placed side by side A square receiver is positioned at the focus of each Fresnel lens The plant consists of one 2 MW biomass boiler, a 3.7-MW backup boiler and a 400-m^3 storage tank	Fresnel lens is line-focusing type of concentrators like parabolic troughs. However, in this study the authors have investigated the performance of a point-focusing type-Fresnel lens collector field The annual performance testing of the collector field revealed heavy heat losses from the collector and piping. This was validated by a simulation of the collector field A sensitivity analysis of the model found that soiling of the lenses was largely responsible for the reduction in heat generation The analysis also revealed that the performance of these lenses is less likely to be influenced by operating conditions than other flat plate collectors making them more suitable for high-temperature operations

of building and running a generating plant over an assumed financial life and duty cycle'.

This includes factors such as:

a. Upfront costs,
b. Maintenance,
c. Degradation over time,
d. Financing,
e. Market shifts.

For large-scale energy developers, LCOE also acts as an effective way to compare competing sources of energy. They use it to compare solar power with wind, coal, and other energy sources.

$$\mathrm{LCOE} = \frac{I - \sum_{t=1}^{n} \frac{\mathrm{Dep}\times\mathrm{TR}}{(1+r)^t} + \sum_{t=1}^{n} \frac{\mathrm{LP}}{(1+r)^t} - \sum_{t=1}^{n} \frac{\mathrm{Int}\times\mathrm{TR}}{(1+r)^t} + \sum_{t=1}^{n} \frac{\mathrm{AO}}{(1+r)^t} - \frac{\mathrm{SV}}{(1+r)^n}}{\sum_{t=1}^{n} \frac{\text{Initial kWh}\times(1-\text{system degradation})}{(1+r)^t}} \tag{1}$$

where I = initial investment, Dep = depreciation, TR = tax rate, LP = loan payment, Int = interest on loan payment, AO = annual operations cost, SV = salvage value, and r = discount rate.

Thermal energy storage makes CSP dispatchable and eases its integration with the power grid.

Other metrics for economic analysis of power plants are as follows:

a. Energy return on investment in energy (EROEI),
b. Payback period,
c. Return on investment,
d. Net present value (NPV),
e. Internal rate of return (IRR).

Table 7 Literature review of PTC systems

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/Enhancement/modification strategy adopted
1	Alguacil et al. [19]	2014	Plant capacity: 8MWh Solar field: parabolic trough collectors with three loops of evaporators and two loops of superheaters Solar field supply steam at 8 bar and 450 °C for first stage and at 550 °C for second stage	Direct generation of steam inside the receivers of a parabolic trough concentrators has been studied in this paper A theoretical model was developed consisting of an innovative strategy to ensure stability of plant under transient conditions, achieving receiver temperatures of 450 °C and 550 °C and different configurations of ball joints and flexible rotation joints This model was validated by the experimental results obtained from the 8-MWh demonstration plant Such type of configuration can ensure low thermal losses, high cycle efficiency, lower land area for solar field, and better performance
2	Sorour et al. [52]	2020	Steam power plant capacity: 300 MW Concentrators: parabolic trough HTF: Therminol VP-1 Steam is extracted from the low-pressure turbine (LP) and is supplied to the solar field where it is heated by the PTC for regeneration The extracted steam is also operating desalting units	This study investigates the integration of a conventional steam power plant with CSP The system analysis results show that this retrofitting has improved the performance of the steam power plant by 9.8 MW The LCOE of the solar-assisted system when compared with an equivalent PV plant showed 44% reduction When the results of the techno-economic analysis were compared with an equivalent conventional steam plant showed 56% cost reduction over a lifecycle of 25 years This type of configuration, where CSP is used for reheating and regenerating purposes in a conventional power plant helps reduce emissions and fuel costs
3	Manar et al. [27]	2020	Solar pond basin dimensions: Cylindrical basin (dia = 1.6 m and height = 2 m) The three layers: Bottom layer: 40 cm thick, 11.76 kg/m^3 of salt-water concentration Middle layer: 30 cm thick, 4.9 kg/cm^3 of salt-water concentration Top layer: 10 cm of freshwater Thermal collectors = 4 (1.90 m × 0.90 m), Emissivity: 0.88 PV module: 150 W, 22.32 V_{oc} (Multicrystalline), no.: 2 Water is the HTF for both the thermal collector and the heat exchanger	In this paper, an innovative idea was tested where the heat generated during the operation of the PV modules was collected and stored in a solar pond. Heating coils are placed at the bottom of the solar pond. The ends of the coil are connected to the heat exchanger installed behind the PV cell This system of PV module-thermal collector improved the thermal efficiency of the solar pond reaching a maximum value of 42% in the month of September The hourly efficiency of the PV module for all months was also recorded. The solar PV system reached a highest value of 15% in January The solar pond achieved a high temperature of 35 ˚C. This heat could be used for process heating and other applications. This technology if employed for large-scale PV plants can also run a small-scale solar parabolic dish plant, enough to operate the tracking and cleaning mechanism of the PV arrays

Table 7 (continued)

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/Enhancement/modification strategy adopted
4	Nour et al. [25]	2014	The solar field was modelled based on the parabolic trough characteristics and the solar irradiance The storage system was modelled based on the thermal load demand, the operating hours and the molten salt/HTF fluid characteristics Mathematical models were developed for the heat exchanger, the turbine unit and the multi-stage flash desalinator	In this study, the authors have designed a CSP co-generation plant producing water and electricity. The entire mathematical model has been sub-divided into six models These models were simulated in parallel for a time period of over a year Climate data and design input parameters, such as PTC collector characteristics, storage system characteristics, and turbine unit specifications, were used as constraints to obtain the results The results confirmed the practical viability of using CSP in co-generation systems to produce electricity and freshwater, low-grade heat for industrial process, etc.
5	Duygu et al. [24]	2017	ORC working fluid: R134a Single pass shell and tube heat exchanger Type of concentrators: Parabolic trough HTF in concentrators: Therminol VP1 Solar radiation: 900 W/m^2 The heat exchanger group for PTC and geothermal fluid were modelled using E-NTU method with iterative solution method being applied to find the entry and exit temperature of geothermal fluid The PTC filed too is modelled mathematically whereas the turbine, regenerators, pump, and condensers are designed by applying thermodynamic balances	In this study, a hybrid power generation system has been studied. A geothermal Organic Rankine cycle system has been used in conjunction with a parabolic trough CSP system The working fluid of the cycle has been heated to a higher temperature by an array of parabolic trough concentrators. This has resulted in an increase in the net power output of the system However, there has been a decrease in the energy and exergetic efficiency of the integrated system due to the irreversibilities of the PTC and the condensers The study supplants the idea that CSP can be used as an auxiliary source of thermal energy in many conventional and renewable plants to increase the net output of the system
6	Qiliang et al. [20]	2021	Parabolic trough concentrators of aperture area = 5.76 m. Eight SCAs oriented in north–south direction with single-axis east–west tracking HTF and thermal storage fluid: 60% $NaNO_3$ and 40% KNO_3 by mass Thermal storage specifications: Hot tank temperature: 550 °C Cold tank temperature: 290 °C Installed capacity: 100 MW with thermal storage for six hours	The study mentions that parabolic trough concentrators face the problem of decrease in solar to thermal conversion efficiency at high temperatures. This the authors argue, happen due to severe heat loss from the absorber tube at high temperatures Hence, in this paper the authors have performed the thermos-economic assessment of an enhanced parabolic trough receiver that employs a radiation shield to address the heat loss issue. The radiation shield is made of highly polished aluminium that reflects back maximum heat lost from the absorber tube The assessment has revealed that the enhanced receiver has led to an increase in loop thermal efficiency of the parabolic trough collectors The net electrical energy output was reported to increase by 9.77% and the LCOE reportedly reduced by 8.67%

Table 7 (continued)

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/Enhancement/modification strategy adopted
7	Linrui et al. [23]	2021	North-west China is decided as the location for the power plant study because of the abundant solar irradiation there Each loop in the solar field consists of four EUROTROUGH-150 SCAs SCHOTT PTR70 is assumed as the absorber tube and Therminol VP-1 is assumed to be the HTF A thermal–hydraulic model is developed for a two-stage regenerative Rankine cycle to which is validated on a 1-MW pilot plant	The performance of a PTC power plant is governed by an appropriate operation strategy of the solar field. This operation strategy involves controlling thermal parameters such as the outlet temperature, flow rate, flow distribution by regulating hydraulic devices such as pump and valves The authors argue that majority of the literature investigating different operation strategies for the solar field assume uniform and perfect performance of the parabolic trough concentrators. However, they argue, for a more practical and accurate model to study the PTC loops it is inevitable to develop a better operation strategy Hence, an innovative operation strategy for the solar field based on non-uniform performance of the PTC loops targeting their degrading optical parameters is developed The developed operation strategy was found to increase the net electrical output by 3.4% with low costs and better feasibility
8	Wang et al. [53]	2020	The SEGS VI 30-MW parabolic trough solar thermal power plant in California, USA, is used for research. The plant has a solar field with 50 loops in total using the LS-2collector The improved plant design has the solar field divided into three sections: high-temperature section, middle-temperature section, and low-temperature section supplying heat to the superheater, evaporator, and the preheater, respectively The authors have compared the design values of water and thermal oil inlet–outlet temperatures, the turbine inlet and exhaust temperatures, pressures and flow rates and the properties of intermediate stage steam extraction for regeneration with the simulated values and then compiled the errors in tables	In this paper, the authors have tried to enhance the performance of a 30-MW parabolic trough plant by improving the heat exchange system between the solar field and the power block To do this, they have used the idea of energy cascade utilisation by employing sectional heating for the preheater, evaporator and superheater In the original plant, there was large exergy loss due to the presence of a large terminal temperature difference in the heat exchange process. Therefore, by optimising the oil flow in these three sections this temperature difference has been reduced The results have shown that there is an increase in the solar field efficiency and the overall plant efficiency of the improved 30 MW plant. Also, there has been a significant reduction in the no. of collectors required which has consequently reduced the capital cost and the LCOE
9	Anass et al. [31]	2021	The study is conducted on a combined-cycle parabolic trough solar thermal power plant located in Eastern Morocco. The location has a DNI of 5.2 kWh/m^2 The hot HTF from the collectors generates steam in a heat exchanger that feeds the heat recovery steam generator connected to a steam turbine of 172 MW capacity In this paper, three models are used to accurately estimate the hourly electricity generated by the parabolic trough solar power plant	The parabolic troughs are integrated with two natural gas-fired gas turbines The first two models AM I and AM II are analytical models. AM I is based on the calculations of heat loss in the PTCs, while the AM II is based on the global evaluation of the thermal efficiencies of the collectors. The third one is based on hourly energy generation and meteorological data employing artificial neural network model The ANN model is more sensitive to the fluctuations in meteorological parameters than the analytical models. The authors have argued that the modelling based on steady-state phenomena is the reason behind the less accuracy of analytical models The results of the author's simulation of all three models have shown that the ANN model produces the best performance and hence is better for estimating the energy produced by a solar power plant

Table 7 (continued)

Sr. no.	Authors	Publication year	Design characteristics and features of system under study	Improvement/Enhancement/modification strategy adopted
10	Wasim et al. [54]	2021	Utilising a non-Newtonian Maxwell fluid model, Cattaneo–Christov effects have been used to examine the process of heat transfer. Our theoretical investigation also relies on entropy, solar radiation, and thermal physical characteristics over a stretching surface Partial differential equations have been transformed using the transformation approach into solvable ordinary differential equations with boundary conditions A collection of nonlinear ordinary differential equations has been used to condense partial differential and the boundary conditions	The presented work seeks to observe the heat distribution in a parabolic trough solar collector installed in a solar-powered ship by a stretched sheet and the influence of Maxwell nano-molecules on entropy generation outline Single-walled carbon nanotubes -engine oil (SWCNT-EO) and Multi-walled carbon nanotubes/engine oil (MWCNT-EO) nanofluids have been utilised as working fluid Utilising SWCNT-EO nanofluid increased the thermal efficiency between 1.6 and 14.9% in comparison to MWCNT-EO The thermal boundary-layer thickener grows over time in the presence of nanomaterials, radiative flow, viscidity dissipative flow, and heat generation, which reduces the heat exchange rate
11	Fateh et al. [55]	2014	Parabolic trough collectors are used for the design of solar field. This is done as PTC plants are the most technologically matured The mathematical models adapted in this paper to calculate and design pumps, heat exchangers, efficiency, solar field are straightforward and accurate	The authors of this paper have designed a 1-MW PTC plant to power a local grid in Egypt Therminol VP-1 is selected as the heat transfer fluid for the solar field. It is chosen because it is the most common and successful HTF for the solar fields of PTC plants Also, the lowest ambient temperature is selected as lower ambient temperature would result in higher heat loss, which in turn would bring down the plant capacity However, water is selected as the working fluid for the power block. The power block is going to operate on the Rankine cycle. Hence, water is the best option. Also, it is selected as it has low global warming potential, inexpensive and non-toxic

Table 8 Literature review of PV/T systems

Sr. no.	Authors	Publication Year	Design characteristics and features of system under study	Improvement/Enhancement/modification strategy adopted
1	Fatih et al. [56]	2018	75 W Polycrystalline panels were used for the study Measurement if variables such as ambient air and PV panel back surface temperature, current voltage, solar radiation, and wind velocity were recorded 10-mm-thick aluminium foam fins of different lengths were attached to the back of the PV panels Data from the experimental test rig are gathered for the dynamic modelling with ANN in order to determine the input–output of the network	The temperature of the PV cells play a very important role in controlling the electric conversion efficiency. Hence, temperature regulation becomes very important to prevent overheating of the PV cells In this study, the authors have performed an experimental analysis of a PV/T system that uses aluminium foam fins for temperature regulation The results showed that the addition of fins reduced the surface temperature of the panels resulting in higher power output. Wind velocity too has a positive impact as it cools the fins, preventing them from heating The authors constructed a dynamic neural network using the experimental data to model the system. This dynamic model can be used for performance predictions of such systems
2	Fatih et al. [57]	2020	Polycrystalline panels of various geometric shapes of shading were used in the experiment The experiments were performed on clear sky conditions in July 2018 The experiment was influenced by the weather conditions of the city of Elazig in Turkey Hydrated calcium chloride ($CaCl_2{\cdot}6H_2O$) was used as the phase change material for cooling of the panels Thermoelectric modules and aluminium fins were also used	In this study, the authors have investigated different cooling methods to improve the performance of the PV panels The PV/T system has been studied with different configurations of cooling systems like only PCM and PCM + thermoelectric modules with aluminium fins. The aluminium fins too have been used in various numbers and layouts The results have shown that the output power increased for all configurations of the cooling systems. However, aluminium fins cooling systems are found to be the cheapest solutions with maximum power output and efficiency

The DEWA project in Dubai holds the record for the lowest LCOE at USD 73/MWh in 2017. It is a combined PTC-Tower project, with 600 MW PTC and 100 MW tower CSPs. According to a survey conducted by an independent media site, the LCOE for coal power plants in the same year ranged from USD 60 to 143/MWh. This project is a great example that, with technological innovation, CSPs are more than capable of replacing conventional thermal power plants.

Ismael et al. [7] performed an exergetic analysis and life cycle assessment on 50 MW PTC plants. The study used the eco-indicator 99 method, the cumulative energy demand method, and the specific exergy costing (SPECO) method in order to conduct a thermo-economic analysis of the systems. It was found that the solar field contributed 79% to environmental impact, the most. Steel, molten salt, and synthetic oil had the most impact of all the construction materials. The LCA reports showed that the human health damage category had the most impact with 69%, followed by the resource category with 24% and the ecosystem quality damage category with 7%.

The results also showed that the CSP technology trumped the oil-fired and natural gas-fired technologies in all the categories. The analysis also showed that within the 50 MW PTC plants, the solar field followed by the storage system had the greatest contribution impact because of the high amount of steel, molten salt, and synthetic oil used in these components. Also, the high-cost rate due to the huge initial investment in the solar field can be overcome by increasing the operation time of the CSP plant. Hence, in order to economise CSPs, optimisation for cost reduction of the solar field is of utmost importance.

Future prospects in concentrated solar power technology

Combining technological solutions with investment profitability is a critical aspect in designing both traditional and innovative renewable power plants. Often, the introduction of new advanced-design solutions, although technically interesting, does not generate adequate revenue to justify their utilisation [56].

Solar energy is an easily replenishable power source that has the ability to provide energy security and energy independence to everyone and everything. Such a proclivity is tremendously important for the socio-economic prosperity of all individuals, companies, and industries and for the conservation of the planet. In CSP, direct solar radiation is the primary source of energy. Hence, solar thermal plants would flourish at locations within the sunbelt of the Earth. The major markets are areas with a DNI of greater than 2000 kWh/m^2. Among the most promising areas of the world are: the South-Western USA; Central and South America; Africa; the Middle East; the Mediterranean countries of Europe; Iran, Pakistan, and the desert regions of India; the former Soviet Union; China; and Australia. The solar DNI has a direct impact on the LCOE.

In order to make CSP economically competitive, a lot of research has been undertaken to create new trends. Every aspect of the CSP plants has been thoroughly researched to devise new techniques, which have been listed below:

1. The improvement in solar energy collection capacity and efficiency has been the aim of many researchers. For a given solar DNI, higher collector efficiency not only increases the capacity but also reduces the solar field area. For this, anti-soil coatings (to remove dust from the concentrator surface), high reflectivity coatings (e.g. silver polymers), and stainless steel parabolic troughs are being tested.
2. The performance of absorber tubes and receivers is also being investigated by the researchers with the motive of increasing the absorptivity and decreasing convection losses. Borosilicate glass covers and AR coatings are employed to reduce reflection and convection losses. Hydrogen in the vacuum annulus makes a huge difference in how much heat is lost.
3. The use of HTF also has a huge impact on the plant. Therminol VP-1 is the most commonly used HTF. However, direct steam generation, use of molten salts and other synthetic oils are also being investigated. Molten salts are not suitable for PTC and LFR plants. DSG is ideal for solar tower and parabolic dish collectors.
4. Thermal storage is vital for CSP plants to make them economic. Recently, high-temperature latent heat storage has gained popularity. However, the low thermal conductivity and thermal stability of the phase change materials is a big challenge.
5. Various thermodynamic cycles are being experimented with to suit different operating conditions, HTFs, applications, etc. The thermodynamic cycles that can be employed are:

a. The Brayton cycle (air and helium),
b. Supercritical $CO_{2,}$
c. The organic Rankine cycles,
d. Kalina cycle.

Alfredo et al. [57] have studied the application performance by summarising and analysing the main degradation mechanisms in a CSP plant. Detection, prevention, and mitigation of degradation mechanisms such as absorber tube deformations and cracks; corrosion in the absorber tubes and the TES tanks; mirror soiling and dust accumulation; and mirror erosion and ageing are discussed by qualitative and quantitative analysis of literature in this field. The authors concluded by summarising the above-mentioned degradation mechanisms and ending by discussing the current trends in their prevention and mitigation. This study shows that CSP is getting more mature and that current industries are able to adapt to it.

Conclusions

Solar thermal power plants have the ability to increase the pace of the energy transition from conventional sources to renewables. They can quickly replace the conventional thermal power plants of the developing world, reducing carbon emissions and consequently avoiding climate change. CSP has gained prominence in recent years. However, a lot of research and policy amendments need to be done to familiarise it with the world. This is evident from the current scenario where PTC (which is less efficient than its point-focusing counterparts) dominates the market and almost 22 out of the 58 operational CSPs in the world are in Spain alone. The conclusions of this study are summarised as follows:

From the reviews, it is clear that power generation is not the only purpose of CSP. CSP can be used in co-generation and conventional plants during peak loads. In fact, its use in co-generation plants can help reduce the carbon footprint of conventional thermal power plants. CSP can also be utilised for reheating and regeneration, reducing fuel consumption and carbon emissions while also increasing the plant capacity and thermal efficiency.

The current study also shows that molten salts are the best way for CSPs to store energy for use both during the day and at night.

The concentrator field accounts for almost 40–50% of the plant's cost. Hence, its optimisation to collect as much thermal energy as possible has been the research objective of a lot of papers. This can be achieved by optimising the layout of concentrators, enhancing the performance of absorber tubes, etc.

CSP technologies that can attain higher temperatures like PTC and solar tower can be very effectively used for power generation and desalination simultaneously. This technology can help combat the water shortage crisis and conserve groundwater levels in many drought-hit areas throughout the world.

CSP can also be used with PV-T technology to extract the excess heat from the PV module for heating purposes.

This paper has tried to cover all topics relating to CSP technologies, from technical to economic. It has also conducted a comparative study of the current scenario to throw light on the probable future trends. Further research can be done in a detailed review of the energy storage technologies for CSPs, especially hydrogen fuel cells and carbon neutral synthetic fuels. All the papers reviewed in the literature survey and the review have focused on individual topics in the context of CSP technology. Those aspects could be the progress, the economics, the design, the optimisation of individual components to improve performance, etc. Keeping this in mind, an effort has been made in this paper to bring all these topics together to present a concise review of concentrated solar power technology.

Declarations

Conflict of interest The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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