Progress in Research and Technological Advancements of Commercial Concentrated Solar Thermal Power Plants

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Abstract

A global transition towards more sustainable production and consumption systems is underway. This transition process is particularly visible in energy systems, where modern renewables, majorly solar PV and wind power, accounted for around 10% of global power production in 2020. It is widely believed that the transition to a low carbon economy would inevitably increase energy storage requirement to a significant extent in the near future. In this context, concentrated solar power (CSP) technologies are seen to be one of the most promising ways to generate electric power in coming decades. To reduce the cost of power generation from CSP technologies, over 1000 articles have been published in the last five years, and it is necessary to observe the overall research and technological advancements in this sector which is missing in the current literature. To bridge this gap, this work presents a comprehensive review on the actual state of all major components of cutting-edge CSP technologies and condenses all the available information and categorizes them considering the main functional parts and remarking the current research progress in each part as well as the future challenging issues. It intends to understand and explain the foundations of the innovative concepts, future research directions and strategies developed over the past 10 years to tune the engineering and thermal sciences of concentrated solar power. It is evident that the cost has come down, however to make the cost of CSP technology at par with other renewable power sources, there are multiple challenges especially in water consumption, materials design, and receiver subsystems. Each of these challenges is discussed in detail and suggestions are presented for addressing the challenges. The information and insights presented in this detailed review study is expected to serve as a good resource for practicing engineers and researchers intending to undertake their research on this subject.
1. Introduction

The world's energy system is undergoing major changes as we move towards a net-zero carbon economy. Indeed, the undeniable impact of greenhouse gas (GHG) emissions on the climate encourages countries around the world to progressively promote renewable energy technologies. However, due to intrinsic intermittency of renewable energies such as wind and solar photovoltaic, their large-scale introduction will pose a challenge for the stability of the power grid, as unexpected changes in local meteorology can significantly alter the production wind and solar PV power. Therefore introducing more variable renewable energy sources (VRES), namely wind and solar PV generation into the energy mix puts pressure on the power system. Concentrated solar power (CSP) is a technology offering a solution to this problem, because unlike conventional solar PV plants, CSP plants can incorporate thermal energy storage (TES) systems such as molten salt energy storage to allow them to generate electric power whenever it is needed – day and night, regardless of the weather conditions. This makes CSP a far more promising solution for large scale power generation from solar and therefore the most suitable technology to promote a massive penetration of solar energy in the power generation industry.

CSP technologies are among the most viable and promising renewable energy technologies that can be scaled up for a rapid transition towards high renewable energy utilization scenario (Calvet et al., 2021; Fang and Zhao, 2020; Giaconia et al., 2020; Laporte-Azcué et al., 2020; Liu et al., 2022; Martínez et al., 2020; Powell et al., 2017; W. Wang et al., 2021; Wang, 2019). While the bulk of CSP electricity will come from large, on-grid power plants, these technologies also show significant potential for supplying specialized demands such as process heat for industry, cogeneration of heating, cooling and power, and water desalination. CSP also holds potential for applications such as household cooking and small-scale manufacturing that are important for the developing world. The possibility of using CSP technologies to produce solar fuels (e.g. hydrogen and jet fuels), is another important aspect of CSP which strengthen its role in the low carbon economy. Moreover to mitigate the climate change, the IEA says that by the end of the century, CO\textsubscript{2} will need to be removed to keep temperature rise to under 2 degrees. So, along with switching to renewable energy, we will need to remove carbon dioxide from the air. Heat is required to perform the thermochemistry involved in CO\textsubscript{2} air capture. As the heat-based form of solar energy, CSP is well positioned to play a key role in CO\textsubscript{2} removal, to begin to rebalance the earth’s atmospheric chemistry. It is expected that CSP, together with wind and solar photovoltaic, will constitute a stable, high percentage of renewable energy generation system that will be price-competitive with conventional energy sources (Agency, 2021; IRENA, 2014; Zhang et al., 2021).

However, the cost reductions achieved by rival technologies (mainly solar PV) force CSP developers to go further in the search of cost reductions due a highly competitive market and the lack of tariffs that correctly value the dispatchability of CSP. While CSP has been widely criticized for being expensive and often inefficient, the tables are now turning. Technology has improved significantly, costs are falling rapidly, and most importantly, environmental benefits are increasing. In fact, many governments around the world have made decisions to increase the use of solar thermal power over traditional fossil fuels such as coal. For example, this year (2022) four Chinese provinces have announced to build 24 CSP plants with a combined capacity of 2450 MW by 2024 (Kraemer, 2022a, 2022b, 2022c). Each of the planned projects includes at least 6 hours of low cost thermal energy storage (most of them include ≥ 9 hours). The current
TES costs are low compared to storage in chemical batteries, which suggests a role for CSP with TES (i.e., CSP+TES) relative to PV+batteries, due to favorable storage costs for TES despite the disadvantage in generation costs for CSP (Kennedy et al., 2022).

2. Motivation and Objectives

The commercialization of the CSP technologies in recent years has led to a great deal of progress in various topics such as concentrators, receivers, point and line focus technologies, heat transfer fluids, heat storage materials, control, etc. Given the multitude of recent studies as well as ongoing efforts in developing CSP technologies, it is considered timely to offer a comprehensive review by covering an overall perspective in the recent progress in CSP research at commercial level. Moreover, the research progress for CSP application need to be updated, especially those for thermal heat storage system.

Therefore, the purpose of this review is to provide a holistic overview on the most recent advances in CSP technologies available at commercial scale so that the reader can keep up with the rapid development that is happening in this context. This review differentiates from these previous studies by focusing on practical technological challenges related to CSP system and equipment, alongside a comprehensive compilation of data, technological options and open investigations is exposed with the aim to be interesting for expert and also non-expert researchers, professionals, or other readers.

This comprehensive review discusses all major subcomponents of a CSP system in following order: current status of the CSP market (section 3), basic physics of CSP technology (section 4), key requirements for CSP plants (section 5), overview of mainstream CSP technologies (section 6), CSP cooling system (section 7), economic aspects of CSP plants (section 8). Each section covers the characteristics required for high performance, the current state-of-the-art technologies used in the field, the challenges and the current research direction to further improve performance.

3. Current status of the CSP market

As shown in Fig. 1, the historical development of CSP plants is characterized by strong ups and downs in a sequence of boom-bust cycles triggered by changes in national policy support (Lilliestam et al., 2021b). The first wave of CSP development took place in the California, United States during the 1980s, when Federal and State policies and tax incentives led to the construction of nine CSP plants of some 350 MW generation capacity between 1984 and 1991. Falling energy prices, delays in the extension of incentives and reduced incentives hampered further deployment of CSP plants in United States. Between 1995 and 2005, there was a period of commercial inactivity as no solar thermal power plants were built in the world. The second major CSP development saw the introduction of the feed-in tariff (FIT) legislation for CSP projects in Spain in 2007. The FIT allowed 25-year off-take contracts with a high fixed tariff rate or a fixed adder on top of market time-of-delivery pricing (Mehos et al., 2020). This led to the construction of about 50 CSP plants in Spain between 2007 and 2013 with total generating capacity around 2300 MW. In January 2012, the feed-in tariff (FiT) program implemented in 2007 was cancelled by the Government for new applicants, so that it would not be awarded to CSP plants beyond the 2304 MW approved in 2009 to enter into operation before 2014. In June
2013, a new law issued by the Spanish Government replaced the feed-in tariff by a Complementary Payment to be added to the Pool price of the electricity to provide the investors with a “reasonable profitability” of 7.5% over the lifetime of the project, and applicable to plants already in operation. The Spanish government eliminated the FIT and no new projects were built. The FIT was fixed and did not encourage cost reduction or generation during preferred periods. Consequently no new CSP plant has therefore been built since 2013 in Spain. However, the FIT demonstrated that rapid growth in the deployment of CSP technology was possible when an appropriate and stable policy is in place (Price et al., 2021). The next major wave started in 2013 was the international proliferation of CSP projects which is marked by expansion first in the United States (which subsequently halted, following uncertainty about future policy support (Mehos et al., 2016)), and then in emerging countries including South Africa, Morocco, Israel, and Kuwait through competitive bidding processes. Many of these projects have encouraged the use of thermal energy storage to allow solar generation to be dispatched to periods of highest need. Many of these projects have promoted the use of thermal energy storage, which allows solar energy to be used during times of greatest demand (Price et al., 2021). The latest wave in CSP projects came in September 2016, when China adopted FIT approach to support the construction of 20 CSP plants (1.35 GW) by the end of 2018 as a step toward CSP target of 5 GW as part of 13th Five-Year national Plan (Gosens et al., 2020). These examples illustrate that policy instability makes CSP deployment difficult due to the length of time required for CSP project development, financing, and construction (Price et al., 2021).

Fig. 1. Concentrated Solar Power development path from 1982 to 2030 (Palacios et al., 2020)

Although till now considerable growth has been made in the installed capacity of CSP plants, CSP is still a relatively immature technology (del Río et al., 2018). Immature technologies typically rely on policy incentives to reduce private sector risk and encourage developers to
deploy the new technology. CSP deployment in the past has been driven by policy, and CSP policy support and the CSP project pipeline is disappearing. Fig. 2 shows CSP policy support and the capacity of CSP plants under construction. Ongoing CSP projects rely on generous FITs (China, Israel) and access to low-cost financing (the Middle East and Africa). The particular historical development of CSP also offers insights of relevance to the theory of technological learning. Since the CSP has developed under a sequence of different policy regimes, rather than many regimes operating in parallel, and as the CSP industry has been marked by a long period of discontinuity, when the development of new projects came to a complete halt, so CSP can shed light on the link between policy support design, and industry continuity.

As of June 2021, the CSP market has a total capacity of 9162 MW worldwide, among which 6475 MW are operational (IRENA, n.d.) and 2916 MW are under construction. Estimations also consider that there are other 8472 MWe under development, which brings an overview of the growing potential of the CSP sector in the development of new future projects to come. Considerable growth in the CSP sector has been observed over the past decade with global capacity increasing from 1.2 GW in 2010 to roughly 6.2 GW in 2019 (Fig. 3). This growth is likely tied to the feasibility of employing CSP for several applications, especially when thermal energy storage integration and hybrid operation are considered (Mohammadi et al., 2019). Although the US and Spain are recognized as the world leaders in terms of CSP development and capacity, new markets are growing rapidly in places such as China, South Africa, Morocco, Chile and India, and China. Alone China is expecting to add around 2000 MW CSP to their
energy basket (“Project Database,” 2021). As per “Technology Roadmaps Concentrating Solar Power,” released by the International Energy Agency in September 2014 under a proper policy support, it was estimated that by 2050 the cumulative installed capacity of global CSP generation facilities would reach 1089 GW (Agency, 2015). In this sense, the report presented by the European Solar Thermal Electricity Association (Agency, 2015) stated that solar thermal power systems could supply as much as 6% of global electricity demand in 2030, and this figure could easily reach 12% in 2050 (Khandelwal et al., 2022; Neelam et al., 2021). In addition to the current installed CSP capacity of 9.1 GW, around 8.8 GW of CSP projects are under pipeline mainly in China, Chile, South Africa, and the Middle East (see Fig. 4). In addition to the current installed CSP capacity of 9.1 GW, approximately 8.8 GW of CSP projects are underway, mainly in China, Chile, South Africa and the Middle East. In this context world largest CSP project with 700 MW capacity is under construction at Dubai solar park, UAE.

**Fig. 3.** Development of solar thermal power plant capacities from 2009 to 2020
4. Basic Physics of CSP

To use the sun energy, a CSP plant uses mirrors to focus sunlight onto a receiver where a heat transfer fluid (HTF) is heated. The heated HTF can then be stored thermally to be dispatched when required. The energy contained in HTF is ultimately transferred to the steam. Electricity is then generated by a steam turbine with the efficiency limited by the Carnot cycle. Therefore, the coupling of thermal energy storage (TES) and a turbine allows CSP to replace existing power generation such as coal and gas in maintaining system integrity and dispatchable energy. The working principle of a typical CSP plant is illustrated in Fig. 5. Compared with a conventional thermal power plant, the most intuitive difference between the two is that the conventional boiler is replaced with thermal collection and storage facilities in CSP generation, whereas the thermal cycle mode and respective equipment applied for thermal–work-power conversion are basically the same as those used in conventional power plants.

![Diagram of CSP plant components](image-url)

**Fig. 4.** CSP Projects underway in different countries

**Fig. 5.** Schematic representation of the component parts of a solar thermal power system
5. Key Requirements for CSP Plants

CSPs require specific environmental and socioeconomic factors to be commissioned, financed, and built successfully and effectively. These factors are:

5.1. Geographical location with high level direct normal solar radiation:

Although all requirements are essential for CSP projects, arguably the most important is location. If the geographical climate is not suitable for CSP installation, there is no logical reason for it to happen. Areas with low levels of DNI or high levels of diffuse radiation are unsuitable for CSP plants, making ideal locations those which surround the equator. High-intensity, high-exposure solar energy is ideal for any CSP type and will prove the installation to be entirely cost-effective.

5.2. Continuous areas of land

This point is still based on location but is focusing on a different environmental aspect. Even with high DNI, cloudy locations will detrimentally affect the function of the plant; CSPs need direct sunlight to run efficiently, and frequent cloud cover will prevent this. While land needs will vary by technology, a typical CSP plant requires 5 to 10 acres of land per MW of capacity.

5.3. Water consumption per kWh

In power generation via CSP technologies, a significant amount of water is used for number of reasons such as a working fluid in the steam Rankine power cycle, for cooling and especially in the arid and semi-arid conditions, to clean dust off the mirrors (collectors). The challenges associated with the water requirements of CSP plants are discussed in detail in Section 7 of CSP cooling system.

5.4. Proximate and easily available grid access:

The land it is situated on must be suitable for power generation, with easy access to the high-voltage transmission lines of the electrical grid. Areas with outdated access or that are already at full capacity are unsuitable until the grid has been (SEIA, 2021).

5.5. Financing

If an ideal location is found, any projects still have to be financed; whether it is through contractors or a private company, the project must have funding. This, unfortunately, often acts a barrier to the growth of CSPs and STE itself. The 2008 crash was the beginning of this problem; CSP investment was high and government subsidies were offered in many countries prior to the crash, but it ended almost immediately. Continued economic problems have created setbacks for the industry, with the recent Covid-19 pandemic and subsequent economic crash causing further uncertainty.

5.6. Community Acceptance

This factor is not a requirement but does greatly improve the chances of implementing a successful CSP project. Although the responses to CSP plants by local communities is typically positive, there can be friction between the communities and the developers. To encourage not only an easier construction period, but also to use as evidence that CSPs are a positive addition to localities, any opportunity to gain community acceptance should be taken.
5.7. CSP Advantages and Disadvantages

CSP offers many advantages for the low carbon economy including: uncomplicated implementations and operations; supplements other sources of energy; relatively uninterrupted source of electricity; converts solar energy into a transportable form energy.

Some of the key benefits of CSP—which, combined with thermal energy storage, can be used to generate electricity 24 hours a day—are listed below (additional key benefits of CSP are presented in Fig. 6):

- **Environment friendly**: Genuine clean and renewable energy, a perfect substitute for fossil fuel energy, the ultimate solution to energy shortage, air pollution and climate change.
- **Continuity, stability, dispatchability**: Grid-friendly, compared to intermittent energy utilization such as PV and wind power. A high-quality power source of continuity, stability and dispatchability, able to serve as base-load power, peak load regulator, a booster to higher proportion of renewable energy in the grid.
- **Cost-effective**: Huge potential, of cost reduction in the wake of industry expansion, maturity and technological breakthroughs. Possibly be priced in parallel to that of fossil fuel energy in the future.
- **Momentum for related industries**: Able to incorporate overcapacity of cement!, steel: glass, chemical products, machinery, and promote the development of high-end equipment, automation and software
The current prospects of CSP cannot be properly considered without discussing some of the disadvantages of CSP technology:

- The requirement for relatively high consumption of water by CSPs is often criticized, especially for CSPs in the MENA region.
- Installations require a considerable amount of available land (usually, fairly remote land), therefore, availability of suitable locations is a major factor. Moreover, the large area requirement can disturb habitats and threaten any species living in the area. Some animals are attracted to the light of the reflectors and can die from the extreme temperatures if they get too close (Jeal et al., 2019). There have been several reports of birds dying mid-flight at SPT (Ho, 2016a).
- At present, LCOE of CSP is higher than Solar PV, wind, and bio energy.
- Only feasible at large scale: with the exception of CSP parabolic dish systems - a technology that hasn’t seen much adoption yet - CSP systems are only feasible at the utility scale. This is in marked contrast to solar photovoltaic - solar panels - which are easy to apply as well as cost effective even at the level of individual homes.
- Concentrated solar fields are vulnerable to damage and destruction from: high winds, tornadoes, & hurricanes storms and hail sand storms, which scour the mirrors.
- CSP plants use more materials for construction than most non-renewable power plants.
- CSP plants can also be linked to the emission of nitrous oxide due to the decay of nitrous salts, and to the production of other toxic substances, such as biphenyl.
- The molten salt (mixture of sodium nitrate and potassium nitrate) used in modern CSP plants for thermal energy storage releases nitrous oxide, which is a harmful gas, and their releases need ventilation or hazards to workers may result.

Some of these disadvantages are relatively easy to overcome, and others will likely not affect the likelihood of future investment. For example, areas can be thoroughly scouted before development to ensure there are no animals residing there (easy to overcome), and the releasing of nitrous oxide is un-ideal but when offset against the greenhouse gas emissions prevented, it is unlikely to prevent investment of local support. Other disadvantages, such as water shortages and the CSR threat to birds, are usually addressed by developers and a suitable solution found.

6. Overview of Mainstream CSP Technologies

The solar energy system can be categorized into two group’s i.e. active and passive technologies. The passive technology means collecting solar power without converting thermal or light energy, while the active solar system absorbs solar radiation (Herrando and Markides, 2016). The active solar system can be further grouped into photovoltaic (PV) and concentrated solar power (CSP) systems. The concentrated solar system can be grouped in two classes i.e. point focus and line focus (Fig. 7).

![Fig. 7. Classification of concentrated solar systems by their focusing type](image)

At present, there are four available CSP technologies (Fig. 8) including parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR) and parabolic dish collector (PDC). The PTC is a mature CSP technology and almost 80% of currently operating commercial CSP plants is based on this technology. However most of the CSP plants under
construction are based on SPT technology. The LFR and PTC belong to linear focusing CSP systems, while PTC and PDC systems are point focusing. Compared to the linear focusing CSP systems, the point focusing ones can produce solar heat at higher temperatures owing to their higher sunlight concentration ratio. Thus, they can have higher turbine efficiencies. The availability of CSP technologies in diverse range is a drawback to some extent, but it is also an advantage (Abbas and Martínez-Val, 2017).

6.1. Parabolic Trough Collector (PTC)

Parabolic trough collector (PTC) is the most widely used system among the concentrated solar thermal technologies due to its technical maturity and performance stability. Currently PTC occupies more than 77% of the global CSP installations. Fig. 9 illustrate the layout of a large commercial PTC based CSP plant. Major components and their design requirements for a PTC based CSP plant are discussed below.
6.1.1. Reflector (mirror)

The reflector or mirror is the most important and costlier part of the PTC system. The prime function of mirrors is to reflect solar radiation and concentrate it on the receiver. The mirrors of commercial PTC-based CSP plants are made of high-reflective material layers with substrates and superstrates that protect the reflective layer from corrosion or abrasion for increased durability (Tagle-Salazar et al., 2020). Silver-plated glass reflector, anodized sheet aluminum (sometimes coated with a polymer film), aluminized polymers, and silvered polymer films are the most commonly used materials for reflector production. Efforts are being made to find alternative materials having a lower cost.

Typical PTC mirrors for CSP plants are made from float glass of 3 - 4 mm thickness with low iron content to avoid absorption in the glass, with a silvered backside, protected by a multilayer protection coating from the backside (copper, protection paints, and final lacquer) (Fig. 10). Aluminum and polymer coated mirrors typically suffer from lower optical, mechanical, and durability properties. Table 1 represents the main types of reflectors used in CSP applications.

Fig. 10. Typical structure of commercial PTC mirror for CSP application (a) a silvered thick-glass mirror (b) aluminum mirror. (Fernández-García et al., 2017)
Table 1: Types of mirrors with coatings (Tagle-Salazar et al., 2020)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Typical hemispherical reflectance</th>
<th>Cost ($/m²)</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvered glass mirrors</td>
<td>A copper substrate (replaced by a water-insoluble precipitate layer in recent years) protected by paint coatings in the back, with a silvered-based coating and a high-transmittance low-reflective glass as cover (superstrate, usually a low-iron glass)</td>
<td>Up to 0.96</td>
<td>20–30</td>
<td>High resistance to corrosion</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Commercially deployed</td>
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<td></td>
<td></td>
<td>Heavy and fragile</td>
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<tr>
<td>Aluminized reflectors</td>
<td>Polished aluminum sheet with an aluminum-based reflective layer and oxide-enhancing layer</td>
<td>Up to 0.9</td>
<td>&lt;20</td>
<td>Lightweight and flexible</td>
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<td>Low cost</td>
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<td>High variability of durability</td>
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<td>More applicable for low-enthalpy concentrators</td>
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<td>Low durability in polluted locations</td>
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<td>Under development</td>
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<td>Less expensive</td>
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<td></td>
<td>High reflectance and lightweight</td>
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<td></td>
<td>Higher flexibility</td>
</tr>
<tr>
<td>Silvered polymer reflectors</td>
<td>Silvered-reflective layer coated with flexible polymer and a very thin UV-screening film superstrate</td>
<td>0.9–0.95</td>
<td>20–30</td>
<td>Long term performance needs to be proven</td>
</tr>
</tbody>
</table>

The desirable properties of reflectors are:

- High direct (specular) reflectance. Typical benchmark values are >92% of solar-weighted direct reflectance.
- Shape fidelity of the parabolic shape. Deviations produce an inaccurate focus and can lead to “spillage.” Goal is an intercept factor of >95% over the majority of the annual operating conditions.
- Shape stiffness under dead load and wind load. Deformations are allowed for high wind speed, as they occur only in a limited number of operating hours of the collector.
- Durability in terms of surface quality (hard coat, not scratched) and in terms of reflector quality. The preferred reflecting material is silver due to its good optical properties for reflecting the solar spectrum. Aluminum and multilayer coatings are under development. Metallic coatings are sensitive to corrosion and require appropriate long-life protection.

During the manufacturing of commercial PTC reflectors deviations or errors may occur which have remarkable influences on the optical performance of the PTC. The most important errors are shape error, slope error, receiver deviation error, specularity error, tracking error, and frame deformation. The high precision installation methods to avoid those errors are very expensive and complex (Zhao et al., 2016). Shape error estimates the eccentricity of the focal line (where the receiver is) due to deviations and misalignments of the mirrors. Slope error is the angular deviation of the actual surface normal direction from the ideal normal direction. The slope error
significantly degrades the optical performance of the PTC system (Donga and Kumar, 2019). When the receiver is not fully aligned to the focal line of the reflector, then such misalignment is known as deviation error. Specularity error describes the phenomenon that the reflected light accumulates around the specular direction defined by the law of reflection on a mirror surface. As the collector is not always perfectly pointed to the sun, tracking error occurs during operation. Fig. 11 illustrates the aforementioned errors.

![Geometrical errors in PTCs](Tagle-Salazar et al., 2020)

6.1.2. Support structure
The PTC support structure carries the key components of the collector module and is responsible for their accurate alignment in any operating conditions and over an operation period of several decades. The structure is generally made of structural materials such as steel or aluminum. PTC supporting structure consists of four major parts from a structural perspective: concrete foundations, the frame, the main support (columns, struss, piles), and the receiver brackets (Fig. 12). Main criteria beside geometric accuracy and cost effectiveness are thus mechanical stiffness and corrosion resistance. The loads affecting the structure include dead load, weight of the components, loads of the receivers, and wind loads (bending and torque).

![Structural division of a PTC](Brackets Frame Main Support Concrete Foundation)
6.1.3. Receiver (absorber)
Receiver is a dark-coated stainless steel tube to absorb sunlight focused by the mirrors and transfer that thermal energy to a fluid flowing within them. Desirable properties of the receiver tube are:

- Its optical properties are preferably selective, with absorptance of ≥ 95% and more in the solar spectrum range (300 - 2500 nm) and low emittance for the infrared radiation (beyond 2 μm) to reduce the thermal losses in operation. This is achieved with sputtered Cermet coatings consisting of several layers of metallic and ceramic coatings with a thermal emissivity below 11% at 400 °C.
- It must be protected by a glass tube (usually made of borosilicate with transmittance 90%) to reduce convective heat losses and to protect the sensitive absorber surface from soiling and mechanical damage. To reduce the losses through infrared radiation, the glass cover should be treated with an anti-reflective layer on both side surfaces. Generally, silicon dioxide (SiO2) having reflective index of 1.22 and thickness around 150 nm is used as anti-reflective coating.
- To reduce the oxidation degradation of the coating surface and eliminate convective heat losses, the annulus between glass tube and receiver tube should be evacuated to < 10^{-4} mbar.
- To avoid optical losses due to intercept factor, the length of the receiver between supports is limited by the bending of the absorber tube under dead weight of tube and contained fluid. A bending of about 2–5% of the absorber tube diameter can be accepted.
- The diameter of the absorber is small relative to the collecting aperture of the reflector, thereby decreasing the surface area associated with heat loss.
- Typical geometry and optical properties of receiver tube for CSP plant include: diameter (70 - 110 mm), wall thickness (2 - 6 mm), length (4 – 5 m), glass tube outer diameter (120 - 125 mm), absorptance (96%), glass transmittance (96%), and overall optical efficiency (88%).
- It must has service life > 20 years

6.1.4. Tracking System
The concentrating properties of the collector require tracking of the PTC mirrors to the apparent movement of the sun over the sky. Hence to align the collector with the position of sun, tracking is performed through a drive mechanism (usually hydraulic system) which moves though one rotation per day. A hydraulic or mechanical driven tracking mechanism equipped with sensors is employed to track the sun continuously by operating in a closed loop circuit to minimize cosine losses. The accuracy of the solar tracker is a key parameter when compared to the acceptance angle of the concentrator in order to maximize the optical efficiency. To obtain high intercept factor, good accuracy of the tracking system with tolerable tracking deviations less than 1 mrad (0.02°) is required. Usually differential solar sensors are used to enhance the accuracy of the tracking for reaching the tracking accuracy. Two types of solar tracking are used in PTCs namely, north-south and east-west, as shown in Fig. 13. Most parabolic trough collectors adopt north-south axis tracking and only track the solar azimuth angle rather than the solar elevation angle. The north-south tracking method has the advantage of lower tracking energy consumption, but with a higher end- effect. For east-west tracking systems, the opposite is the case (lower end effect and higher energy consumption) (Tagle-Salazar et al., 2020).
For countries located in the Northern Hemisphere, the PTC has a smaller solar elevation angle in winter, which leads to a larger solar incidence angle and high cosine loss, and therefore part of the solar incidence rays are not concentrated and remain unused (Odeh et al., 2003; Qu et al., 2007, 2017). To address this limitation of single axis-tracking system of PTC collector, two-axis tracking is considered as one of the most efficient and primary tracking methods for the PTC technology (Qu et al., 2017), however the additional tracking axis will increase the operational costs imposed by the control process (Yao et al., 2014). This type of tracking maintained a zero incidence angle and then removed the effect of cosine loss on collector performance. Qu et al. (Qu et al., 2017) tested a porotype of 300 kW solar PTC system with rotatable axis tracking as it is depicted in Fig. 14. As mentioned during the winter season, solar incidence angle is large, so rotatable axis tracking permits more irradiation to be harvested while in summer the north–south axis tracking is adopted. Their results demonstrate that the daily cosine loss of this dual axis tracking system can be reduced by 10.3%, resulting in a 5% increase in average collector efficiency compared to the conventional system with single axis tracking. However, it is important to test this idea with a detailed financial analysis for commercial systems of greater nominal power (Bellos and Tzivanidis, 2019). Fathabadi, (Fathabadi, 2020) reported that there is no economic justification for adding a two-axis sun tracker to PTC system.
6.1.5. **Heat Transfer Fluid (HTF)**

The HTF transports the thermal energy from the solar field to the heat-exchanger steam generator systems providing the superheated steam for the turbine of typically 370–380°C. For any type solar field, the outlet temperature is restricted by HTF properties – so HTF with high thermal stability are preferred. For PTC system, typical HTF is a biphenyl/diphenyl oxide fluid (synthetic oil) with temperature stability up to 400°C. The flow rates through the receivers must be high enough to ensure appropriate heat removal from the absorber walls and low enough to keep pumping power for the fluid reasonably low. The loop length of a PTC field depends on HTF properties and preheater outlet temperatures.

6.1.6. **Power Block**

Major components of power block include, a steam turbine, heat exchangers and cooling towers. For optimal use of sun hours daily starts of steam turbine is necessary. The major challenge with steam turbines for CSP plants is the fast starts ups. Therefore, these turbines should be designed with the operational flexibility required by the CSP application e.g. they should endure frequent load variations and numerous startups and shutdown procedures.

6.1.7. **HTF pumps**

Pumps are used to circulate HTF through solar field and power block. Their design should permit wide fluctuations in operating conditions expected in CSP plants

6.1.8. **PTC power plant configuration**

A PTC system is made of a number of individual large parabolic reflectors or focusing mirrors fixed together to move as one solar collector assembly (SCA). The SCA concentrate solar irradiance onto heat transfer fluid tubes that run through the center of the system or through a focal point. Individual collector modules are typically 5 - 6 meter tall and 12 - 13 meter long. About a dozen of individual collector modules make each SCA up to 100 - 150 meter length. These plants use vast areas of linear parabolic collectors to concentrate sunlight onto a receiver positioned at the reflector’s longitudinal focal point. The single-axis tracking collectors are arranged in parallel rows and track the sun either from north to south or from east to west throughout the day. The direction of tracking is paramount to the efficiency of the trough; north-south axis rotation allows troughs to follow the sun each day using tracking motors and is considered the more efficient method. The systems used in 1984 were very similar to today, but there has been considerable progress in improving collector efficiency. As a such promising system, however, the PTC system faces a knotty problem of deteriorating solar-to-thermal conversion efficiency at high operating temperature, which exerts seriously negative impacts on the further development and utilization of the PTC system (Q. Wang et al., 2021).
Solar receiver tubes are the key element in the performance of parabolic trough collector technology. They are responsible to collect solar energy and to transfer the heat collected to the heat transfer fluid. The typical large scale PTC receiver tube is composed of two concentric pipes, an inner stainless steel pipe containing the working fluid and an outer glass tube surrounding the steel pipe. The glass tube is made of low iron borosilicate glass to increase its transmittance for solar radiation. The outer surface of the steel pipe has an optically selective surface with a high solar absorptance and low emittance for thermally generated infrared radiation. To reduce the convective thermal losses and increasing the overall efficiency of the PTC receiver tube, a vacuum ($\sim 10^{-5}$ mbar) is maintained in the annulus between the inner steel tube and outer glass tube. The solar receiver tube is connected to parabolic mirrors through swivel or rotary joints which provide rotational movement to heat transfer fluid collector piping (see Fig. 15). Major components of a solar receiver are shown in Fig. 16. As the receiver tubes expands 2–3 cm when heated from ambient to operating temperature, bellows on the ends of the receiver tube are used to maintain the airtight connection from glass to absorber. Because glass and metallic receiver tube expand at different rates, the most sensitive part of the receiver is the glass-to-metal seal. It is one of major technologic difficulties to achieve good glass-to-metal seal during the manufacturing process of the solar absorber tube. Data from existing commercial parabolic trough power stations show that 29% of the failures were reported to involve loss of vacuum, in most cases due to the failure of glass to metal seals (Lei et al., 2019). The detail on the glass-to-metal seal process can be found in references (Lei et al., 2012, 2008).

Key challenges in parabolic trough receivers to be met in the future are to extend durability and to reduce manufacturing cost and maintenance. Regarding durability, maintaining the vacuum is the major concern because thermal losses and selective absorber stability are directly related to the vacuum level (Morales and San Vicente, 2017). The loss of vacuum in the inner annulus is produced by the diffusion of hydrogen from the decomposition oil-based heat transfer fluid flowing through the wall of the metal pipe. To maintain the required level in the receiver tube, Getter (metallic compounds designed to absorb gas molecules) are installed in the vacuum space to absorb hydrogen and other gases that permeate into the vacuum annulus over time.

![Fig. 15. Schematic of swivel or rotary joints at 160 MW Noor-I parabolic trough CSP plant, Morocco](image-url)
In PTC system a heat transfer fluid (HTF) is circulated through the absorber tubes to collect the solar energy and transfer it to the steam generator or to the heat storage system, if any. The operating temperature of PTC system is around 393 °C while the efficiency of a steam turbine is ranging from 36 - 40%. Modes of heat loss from an evacuated tubular receiver in PTC system are illustrated in Fig. 17. The overall energy losses associated with total solar flux incident on the PTC aperture plane can be categorized into optical losses and thermal losses. The optical or reflectance loss of the modern PTC system is around 23% while the thermal loss in the receiver tube is ≤10% at 400 °C. The thermal loss in the receiver tube is the sum of the radiation loss of the absorbent tube and the loss of conduction of the metal bellows at the receiver end. To reduce convective heat loss from the receiver tube, the annulus between the steel absorber tube and the glass envelope is evacuated. Conduction loss is relatively much small and represents only 3% of the total heat loss when thermally well-insulated at an absorber temperature of 400 °C (Burkholder and Kutscher, 2009). Thus, reducing the radiation heat loss of the receiver is an effective approach to enhancing CSP efficiency. The heat losses from receiver are proportional to the receiver area, so smaller the receiver compared to the aperture area, greater the concentration and thermal efficiency will be achieved. Decreasing the absorber tube diameter minimizes the heat loss with a reduction in the acceptance angle. The heat loss is also affected by the concentration ratio which is ratio of aperture area to the receiver-absorber tube area. The theoretical maximum concentration ratio for a flat receiver PTC is about 107 suns. However, in a real PTC system, the absorber is cylindrical rather than flat, so the theoretical maximum concentration ratio for a standard PTC is limited to approximately 70 suns (Ahmad, 2017; Canavarro et al., 2013; Ceylan and Ergun, 2013; Moya, 2021a; Rodriguez-Sanchez and
Rosengarten, 2015; Shyam et al., 2021). Further considering many other factors which affect the concentration ratio (e.g. angle of radiation incidence), the maximum concentration ratio of the commercial PTC system is limited to 42% of the maximum theoretical possible concentration. As a result, in practice PTC systems are designed to have a concentration value from 25 and 30. The concentration ratio has a significant effect on optical efficiency; the result indicates that the increase in concentration ratio of 2.69% yields 1% improvement in optical efficiency (Mamadou Idrissou et al., 2021).

Fig. 17 Energy flows at a parabolic trough receiver

The technological diversity of the PTC system is relatively low, with most of the technology transfer and know-how being achieved through mergers and acquisitions (Lilliestam et al., 2021b). Initial experience for the trough expansion was gained in the SEGS stations in California, constructed by Luz in the 1984 and mostly still operational today. Most leading companies are, through acquisitions, movement of workers, or co-development of projects, connected to SEGS in various ways (De la Tour, n.d.).

6.1.9. Absorber Coating
As discussed in the preceding section, solar absorber tubes (receiver) are the key complement to CSP technologies. In both PTC and SPT receiver configurations, the absorber tube is made of a metal substrate, such as a stainless steel or nickel-based alloy, over which a solar thermal absorber coating (STAC) is applied. Different STAC formulations are applied in state-of the art commercial PTC and SPT solar field: spectral selective coatings (SSC) are typical for PTC while non-selective, high solar absorptance (HSA) coatings are preferred for the solar central receiver (Caron et al., 2022). A SSC is characterized by a high solar absorptance and a low thermal emittance, while a HSA black coating only exhibits a high solar absorption value (>95%). Several considerations guide the choice of a coating, in addition to its opto-thermal performance:
i) the operating temperature range of the heat transfer fluid ii) the durability of the coating under operating conditions and iii) the cost effectiveness (Caron et al., 2022).

The selective coatings work on the principle that the spectral range of solar radiation is very wide, while energy is mainly concentrated in the range of visible and near infrared spectrum (0.25–2.5 μm). The absorbers are therefore capable of reacting differently to wavelengths above and below 2.5 μm – they are selective. This significantly reduces losses from heat radiation. A commercial solar selective absorber material should be capable of absorbing an abundant amount of the incident solar radiation (λ = 0.25–2.5 μm) and emit very low thermal radiation in the infrared (IR) range (λ = 2.5–30 μm) at the operational temperature (Fig. 18) (Poobalan et al., 2022).

As shown in Fig. 19, absorbers consist of a number of layers, carefully designed to work together. The first layer of a typical selective coating is metallic (made of Al, or Cu, or Mo) and high reflective in the infrared range. The following layer consists of a Cermet material (metallic ceramic composite e.g., Mo-Al₂O₃ or Mo-Si₂O). Finally, the top layer is antireflection ceramic layer consists of oxides like Al₂O₃ or Si₂O which is extremely hard and also scratch-resistant. Current commercial receivers with selective coating achieve absorption values of solar radiation between 0.95 and 0.96 and lower values of 0.09 - 0.10 in emissivity of the thermal radiation at 400 °C (Fredriksson et al., 2021). Moreover, recent coatings can withstand tube temperatures of about 550°C, with significant thermodynamic advantages. A selective coating is more difficult to design once temperatures rise over 600 °C, since there is a larger overlap between the thermal emission spectrum and the solar spectrum (Ambrosini et al., 2015). Based on the absorption mechanisms and design principles, these SACs can be categorized into five different types in Fig. 20, including: a) Intrinsic absorber, b) Semiconductor absorber, c) Multilayer absorber, d) Cermet absorber, e) Textured surface coating.
Fig. 19. Multi-layer coating of the absorber tube (Fredriksson et al., 2021)

Fig. 20. Schematic diagram of various solar absorber coatings. Adapted from: (Poobalan et al., 2022; Salvi et al., 2018; Xu et al., 2020; Zhang et al., 2017)

- **Intrinsic absorbers**: uses a single material with intrinsic selective properties of the material.
- **Semiconductor absorbers**: utilizes the property of semiconductor bandgap to absorb short-wavelength radiation. The bandgap semiconductors absorbers lie in the range of 0.5 - 1.26 eV, and metals to enhance the solar selectivity.
- **Multilayer absorbers**: consist of coatings with several layers of thin metallic/intrinsic absorber and dielectrics layers.
- **Cermet (metal-ceramic composites) absorber**: consist of metal nanoparticles embedded in a ceramic or dielectric material.
- **Textured surface absorber**: involves surface texturing with porous or fine granules of sizes similar to the wavelength of incident radiation.
The thermal efficiency of a receiver tube can also be enhanced by improving the thermal conductivity of the base fluid (HTF) inside the receiver tube. Among the many possible options to enhance the thermal conductivity of HTF, one option is to add small amount (0.1 – 3 wt.% ) of metallic nano-sized particles (with size range 1–100 nm) to the base fluid, and this fluid is then referred to as a nanofluid. This due to the fact that metals have much higher thermal conductivity than any kind of fluids e.g. thermal conductivity of copper is about 700 times greater than any fluids at room temperature (Bejan and Kraus, 2003). The use of nanofluids for solar collectors is becoming a popular area of research (Chavez Panduro et al., 2022). Most common nanoparticles include, CuO, Al₂O₃, Cu, ZnO, Al, SiC, Fe, TiO₂ and SiO₂. Among them, the use of Al₂O₃ nanoparticles is the most usual choice in nanofluid-based PTC (Bellos and Tzivanidis, 2019). In this context, the outcome of the research on Al₂O₃ as a potential nanofluid for PTC application show that thermal efficiency enhancement ranging from 1.2% to 8.5% (Bellos et al., 2016; Bellos and Tzivanidis, 2017; Bretado de los Rios et al., 2018; Mwesigye et al., 2015; Wang et al., 2016).

The use of Al₂O₃ nanoparticle is the most usual choice in nanofluid-based PTC. Subramani et al. (Subramani et al., 2018) found experimentally that the use of water/Al₂O₃ leads to 8.5% thermal efficiency enhancement. Mwesigye et al. (Mwesigye et al., 2015) found that the Syltherm 800/Al₂O₃ nanofluid leads to 7.6% thermal efficiency enhancement with a 40% penalty in pressure drop. Moreover, Bellos et al. (Bellos et al., 2016) found that the use of oil/Al₂O₃ nanofluid is able to enhance the PTC thermal performance close to 4.3%. In another study, Wang et al. (Wang et al., 2016) proved 1.2% thermal efficiency enhancement with Syltherm 800/Al₂O₃ nanofluid.

In recent years, many researchers have attempted to investigate the potential use of the nanofluid for thermal enhancement of receiver tubes in PTC systems. Fig. 21 illustrates the synthesis and application of nanofluid in PTCs system. The details on the progress of nanofluid utilization in solar collectors can be found in the comprehensives review studies (Chavez Panduro et al., 2022; Dandoutiya and Kumar, 2019; Farhana et al., 2019; Gupta and Dixit, 2021; Leong et al., 2016; Minea and El-Maghlany, 2018; Nawsud et al., 2022; Olfian et al., 2020; Tiwari et al., 2021; Wole-Osho et al., 2020). However there many challenges, which prevent the commercialization of nanofluids for enhancing the thermal performance of PTC receiver tubes. Some of the major challenges include:

- Stability of nanofluids over time at high temperatures: Most of the experimental studies did not consider the transient response of the nanofluids operating within solar thermal collector (Leong et al., 2016). Most of the experimental research has focused on the thermal performance of the nanofluid at low temperature applications up to 90°C. However, as the PTC system operates around 400°C, further experimental work is needed to characterize the thermal conductivity of nanofluids at higher temperatures. It is noted that the chemical and physical deterioration of nanofluids at high temperatures is due to the presence of oxygen (Chavez Panduro et al., 2022). Stability of nanofluids affects not only the thermal properties of nanofluids but also its optical properties.
- Increase in nanofluid's viscosity: The addition nanoparticles into the base HTF increases the viscosity of the HTF resulting an increase in pumping power which will in turn
increase the operation cost of the system. Therefore, the monetary value of thermal performance enhancement using nanofluid should be justified with resulting increase in operational cost (Leong et al., 2016).

- Non-homogeneous dispersion of nano-particles: Preparing a nanofluid with a homogeneous suspension of nanoparticle dispersion is often a challenge owing to agglomerating or clustering tendencies of nanofluids.
- High cost of nanofluids: The capital cost of nanofluid is much higher than the conventional HTF (Mahian et al., 2013) primarily because of the high production cost of nano-particles.

Fig. 21. Schematic of nanoparticles and their application in PTCs (Tiwari et al., 2021).

6.1.11. Future Research Direction

To make PTC based solar power generation more cost-effective, many R&D institutes and manufacturing companies have embarked on the development of new PTC designs and technological improvements to meet the growing demand of green power at affordable costs. For example, to protect the PTC mirrors from dust and wind load, GlassPoint proposed a novel
enclosed trough architecture where the PTC solar field is encapsulated by multiple glass canopies (Fig. 22). This allows the PTC collectors to be of low cost and lightweight construction. The side walls of the enclosure still need to be strong enough to withstand the wind, but that requires far less material, than reinforcing every mirror individually, as each wall protects many individual troughs. Overall, enclosed trough systems have less than half the amount of metal, glass and concrete than in an outdoor system of equivalent size. Simultaneously with the R&D efforts to improve the technology, additional cost reductions have been pursued by increasing the size of the solar field to take advantage of the positive effect of a size scale-up (Moya, 2021b). However, it has been reported that that increasing the solar field beyond certain size, instabilities and control problems of HTF flow arise due to the difficulty in achieving a uniform mass flow distribution in the network of receiver tubes. In this context, research is underway on the use of compressed gases (e.g. CO2, air or N2) inside the receiving tubes to transfer solar radiation into thermal energy in the form of sensible heat of the gas because this option would address barriers related to thermal stability and fire hazards of thermal oil (Moya, 2021b). Other key areas are future trends in working fluids (to replace thermal oil, molten salt, pressurized gases, and water/steam) and reduction of the water consumption in PTC CSP plants. In this context, research in the use of compressed gas (e.g. CO2, air, or N2) inside the receiver tubes to transfer the solar irradiation into thermal energy in the form of the sensible heat of the gas is also underway because this option would overcome the barriers associated with the thermal stability and fire hazards of thermal oil.

PTC with a larger aperture concentrator and high-concentration ratio is one of strategies to improve the cost-effectiveness of PTC power plants and has many advantages of saving the area of heat collection field, shorting the loop length to drop voltage drop to save self-power consumption, and reducing the amount of supporting parts such as absorber tube, control valve, driver, tracker, interface hose and balance-of-system components (Gong et al., 2020).

Compared to a standard 5.7 m aperture system, the large aperture PTC solar collector with size greater than 7 m offer the following advantages (Large Aperture Trough (LAT), n.d.):

- Requires over 40% fewer components, resulting in a 20% reduction in bill of materials costs
- The high geometric concentration ratio (103 vs 81 for standard size aperture) results in higher heat flux per unit length, reducing PTC receiver losses
- Average Intercept Factor (98% vs 95% for standard size aperture) enhance the optical efficiency of the PTC system.

Very recently through the support of the World Bank Fund, Northwest Electric Power Design Institute Co., Ltd (NWEPDI) of China has developed the world – (with SCA heat collection area of 1285 m2). Compared with the conventional European parabolic trough collector, its annual average optical efficiency is increased by 5% to 8%, and the cost is reduced by 15% to 25% (“Large-aperature parabolic trough solar collectors developed by NWEPDI will be applied in Dunhuang city - China National Solar Thermal Alliance,” n.d.). This new Large-aperture PTC system will be applied in 100 MW Dunhuang CSP plant in China.

Along with the technological advancements in the PTC system, there is a need to explore the prospects for integrating the PTC into applications, resulting in feasible investments considering the social, economic and environmental impacts. For example, large scale PTC demonstration for multi-generation (e.g. combined power, heating and cooling systems) is something that needs
to be demonstrated at utility scale in the near future. Integrating the PTC system into multi-generation system is an optimal way to produce many useful outputs with high efficiency and using a clean energy source (Kasaeian et al., 2020). Therefore, keeping in view the current high cost (relative to PV) of PTC CSP system, multi-generation systems can become a very attractive power generation path. Future research could include multi-objective optimization by considering multiple variables and operations analysis of the PTC driven multi-generation system to prove the reliability of the integrated system.

![GlassPoint pilot plant, South Oman (Bierman et al., 2014)](image)

6.2. **Solar Power Towers (SPT)**

A solar power tower (SPT) is characterized by the way in which solar energy is collected and concentrated. SPT system utilize dual-axis sun-tracking mirrors called heliostats to focus sunlight onto a single receiver at the top of a tower. A heat transfer fluid (usually molten salt) heated in the receiver up to around 565 °C is used to generate superheated steam for the turbine (Fig. 23).
Although the first SPT pilot plant called Solar One with a capacity of 10 MW was built in California in 1982, it was not until 2011 that the first commercial-scale SPT plant (19.9MW capacity), called Gemasolar CSP plant was commissioned in southern Spain in 2011. Gemasolar uses an external receiver on top of a 140 m tower to heat molten salt from 290 °C to 565 °C for a 20 MW steam-Rankine power plant (Fig. 24). An SPT plant consists of three main systems: heliostat field, solar collector and power-block island. The advances and challenges associated with these three systems are discussed in the Section 6.2.1., 6.2.2. and 6.2.3., respectively. Solar power towers (SPT), also known as central receiver systems (CRS), use large number of mirrors, called heliostats that track the sun individually in two axes. Heliostats are computer controlled to track the position of the sun in a two axis to achieve the ideal angle of incidence. In this way the Heliostats focus direct solar irradiation onto a receiver mounted high on a central tower where the light is captured and converted into heat. To ensure a high optical efficiency, especially in scaled-up CSP plants, a tower of 100 meter above the ground is required (Li et al., 2017). Generally, to maximize the amount of concentrated solar flux received by the receiver, it should be placed as high off the ground as possible. However, this will bring the increase in the maintenance difficulty of the receiver, construction costs; pumping energy to pump the fluid to such a height; and heat loss as the fluid travels the greatest distance (Li et al., 2017). The height of the central tower of a typical utility scale SPT CSP plant ranges from 150 – 260 meter. The world's tallest solar tower reaches is constructed with height of 262.44 meters at 100 MW Noor Energy CSP plant at Dubai (see Fig. 25). The mirrors reflect the sunlight onto the central receiver where a fluid is heated up. Aside from the use of a central tower, the other key difference between SPT and other CSPs is the use of flat mirror reflectors instead of the usual curved. This greatly reduces the overall cost of SPT installation as curved mirrors are considerably more expensive than their flat counterparts. SPT system can achieve higher temperatures than parabolic trough and linear Fresnel systems, because more sunlight can be concentrated on a single receiver and the heat losses at that point can be minimized (IRENA,
There are also clear advantages to the use of SPT; a single receiver reduces installation size and potential energy losses; high concentration ratios (up to 1500) can be attained; and they rarely have a capacity lower than 10 MW (Michael et al., 2016). Although over 77% of the currently in service CSP plants are of PTC type, however it is worth noting 52% of the recently (since 2018) commissioned CSP installations (e.g. 100 MW Shouhang Yumen, China, 110 MW Ashalim Plot B, Israel, 150 MW Noor-III, Morocco, 100 MW Xina Solar One, South Africa) are SPT systems. Moreover SPT share around 62% of the under construction/planned CSP projects. In China currently there are several CSP plants with cumulative capacity of over 1500 MW are under construction. Among these under construction projects, over 80% are based on SPT technology. The main reason for the present trend of installing SPT systems is the potential enhancement in efficiency of converting heat into electricity with SPT, and reduction in the initial installation cost (currently @ $4500/kWh) which now compatible with PTC technology. Moreover as the molten salt SPT technology is less mature than the thermal oil PTC system, but still projects claim similar costs, the near-term development will likely show falling tower costs, placing this configuration as the main CSP technology, assuming that further CSP deployment support is implemented (Lilliestam et al., 2021a). Therefore, the SPT could soon become the preferred CSP technology. Table 2, illustrate the comparison between SPT and PTC technologies.

Fig. 24. Gemasolar Concentrated solar power tower near Sevilla, Spain.
Table. 2. Comparison between SPT and PTC CSP systems (Kraemer, 2022d)

<table>
<thead>
<tr>
<th>CSP Technology Parameter</th>
<th>SPT</th>
<th>PTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Requirements</td>
<td>High requirements on logic control and tracking accuracy</td>
<td>Relatively simple and easy, low threshold of technology</td>
</tr>
<tr>
<td>Focusing Method</td>
<td>Point Focusing</td>
<td>Linear Focusing</td>
</tr>
<tr>
<td>Sunshine Tracking</td>
<td>Dual Axis</td>
<td>Single Axis</td>
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<tr>
<td>Thermal Loss</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>Insulation</td>
<td>Simple and Cheap</td>
<td>Complex and Expensive</td>
</tr>
<tr>
<td>Storage</td>
<td></td>
<td>3 Times larger than SPT</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>1 Set</td>
<td>2 Set</td>
</tr>
<tr>
<td>Medium Temperature</td>
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<td>390 °C</td>
</tr>
<tr>
<td>Turbine Efficiency</td>
<td>45%</td>
<td>38.5%</td>
</tr>
<tr>
<td>Medium Feature</td>
<td>Toxic-free</td>
<td>Toxic, Flammable, Explosive</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>24%</td>
<td>&lt;20%</td>
</tr>
<tr>
<td>Generation</td>
<td>Same Size Solar Field, 15% Higher</td>
<td></td>
</tr>
</tbody>
</table>
6.2.1. **Solar Receivers**
The most crucial component of an SPT system is the receiver which converts concentrated sunlight into thermal energy and can have a significant impact on the overall performance of the system (S. Wang et al., 2020). Receiver concepts are generally classified according to the state phase of the heat transfer fluid used; solid, liquid, or gas (Fig. 26). A brief description of the receivers is discussed in the following section.

![Fig. 26. Classification of solar receivers](image)

### 6.2.1.1. **Tubular Receivers**
Liquid based tubular represent the most dominant concept in the field of solar receivers for SPT systems. Liquid tubular receivers are broadly categorized as external and cavity receivers further classified on the basis of geometry tube material, flow rate and velocity, inlet temperature and outlet temperature of heat transfer fluid. Liquid tubular receivers are generally categorized as being internal (cavity) or external in configuration. Both internal and external configurations transport heat transfer fluid through irradiated tubes through inlet and outlet headers, with the final fluid temperature a function of irradiance, mass flow rate, tube geometry, thermal losses, and heat transfer fluid (Conroy et al., 2020). In the External type receiver, the absorber surface is equal to the area which is exposed to solar radiation around the receiver, also known as aperture. The absorber tubes are oriented vertically around the support structure, which forms a cylindrical shape and the receiver can withstand heat flux densities up to 1 MW/m² (Balusu, 2020). Most of the commercial SPT plants are equipped with external type receiver e.g. 121 MW Ashalim SPT Plant at Israel, 100 MW SPT Plant at Dubai Solar Park (see Fig. 27). Of all the novel receiver configurations that have been proposed in the literature for various HTFs, external tubular receiver designs have received greatest interest for deployment with next-generation chloride salts receiver operating above 700 °C to exploit the extensive familiarity, manufacturing
experience, and operation experience from nitrate salt technology dating back to the Solar Two demonstration project in 2002 and extending through current commercial molten salt power tower systems (Martinek et al., 2021).

![Solar Receiver](image)

**Fig. 27.** Solar Receiver (a) central tower with receiver of 110 MW Crescent Dunes SPT Plant in Nevada, USA (b) 121 MW Ashalim SPT Plant at Israel (c) 100 MW SPT Plant at Dubai Solar Park

As shown in **Fig. 28a**, a typical external type receiver basically comprises a single cylindrical face made up large number of vertical blocks of tubes of about 2” in diameter, all welded together into panels that absorb the highly concentrated sunlight reflected up off the surrounding heliostat field, in order to transfer the heat to the heat transfer fluid flowing down inside the tubes. Each panel consisting of several tubes are arranged parallel and series to each other which allow the heat transfer fluid to flow in serpentine fashion, so that they reside within the focal points of the solar heating in order to achieve the desired outlet temperature (see **Fig. 28c**). The flow pattern configuration can vary from one receiver to another, depending on the ambient conditions and the operation requirements. The arrangement of tubes and panels are shown below in **Fig. 28b**. Similar to the PTC tube receiver, there are optical and thermal losses associated with external tube receiver. The radiation loss due to reflection is the major loss in in external tube receiver. Of the incident solar radiation roughly 5 -7% is just reflected back to the environment and that radiation is lost, because it cannot be absorbed anywhere else. The tubes on an external receiver are aligned to form a quasi-billboard shape, and can be used as a flat panel billboard receiver for equator facing heliostat fields, or multiple billboard panels can be arranged to approximate a cylindrical shape for heliostat fields that surround a centrally located tower/receiver (Conroy et al., 2018). The receiver tube are usually made of nickel alloy, such as Inconel 625, Hastelloy C-276 and Haynes 230 and coated with a black paint.
6.2.1.1. Design requirements and Operational problems

In principle, the design parameters of the receiver are the average and peak allowable flux densities, the absorber tube diameter, the number of parallel and serial tubes in a panel and geometric arrangement of absorber surface. One of the greatest challenges in tubular receiver design is to find the best compromise between optical and thermo-hydraulic efficiency, material loads (thermal stresses) and costs (Frantz et al., 2017). However, the design parameters of the available commercial tubular receivers are confidential and there are few public reports on their technical parameters and operations (Yu et al., 2020). During operation of the external tube receiver the main problems are tube corrosion caused by the high corrosive effect of the molten salt at high temperature; cracks in the welded zones and problems related to material resistance due to thermal stresses and fatigue; tube overheating; and salt freezing during unsteady states (passage of clouds) (Rodríguez-Sánchez et al., 2014b). The tubular receiver often has to be exposed to non-uniform distribution of irradiation with a peak heat flux of up to 1 MW/m$^2$, and a higher heat flux increases the temperature gradient between inner and outer walls of the tubes. These temperature gradients cause a high thermal stress, which in turn can lead to plastic deformation of the tubes if the thermal stress is greater than the yield point. Moreover as the receiver tubes cannot move freely, mechanical stresses arise. So the total stress in this case will be the sum of thermal and mechanical stress components. In addition, the thermal stress or strain
would change repeatedly due to frequent startup and shutdown of receiver during day and night, resulting in fatigue fracture at the higher stress/strain locations similar to the occurrence thermal fatigue cracks in the boiler components (Du et al., 2016). The high corrosive nature of heat transfer fluid flowing through the receiver tubes can accelerate such cracking phenomenon (Pérez-Álvarez et al., 2021).

6.2.1.2. Cavity Tubular Receiver

The tubes in cavity type receiver are placed in a box-like insulated cavity structure with a small opening (inlet aperture) that allows concentrated solar irradiation to impinge on the tubes carrying the working fluid (see Fig. 29a). The difference compared to the External receiver is that the absorber tubes are arranged in a structure to protect from weather influences such as wind. The concept behind the cavity receiver is to minimize the radiation losses. From the radiation entering the inlet aperture, only small amounts are reflected back into the atmosphere through the inlet aperture (Alexopoulos and Hoffschmidt, 2013). This is due to the fact that the aperture opening is smaller than that of the absorber surface, which reduces thermal losses such as radiation and convection losses to the environment due to a decrease in the area of the absorber surface. However, these receivers have some limitations such as optical losses through spillage due to limited view factor offered by the cavity aperture, complexity in cavity design low temperature range and working fluid. A wider acceptance angle can be allowed by using multiple cavities, such as at 50 MW Khi Solar One CSP plant in South Africa, which uses three cavities each facing a different sector of the heliostat field (Fig. 29c&d). The view factor of the cavity receivers can also be enhanced by increasing the height of the tower, but it will result in an increase in overall installation cost. Parameters that affect the convective heat losses from cavity receivers include: the cavity shape, aspect ratio, aperture ratio, inclination and yaw angles, internal temperature and wind speed (Alipourtarzanagh et al., 2021).
6.2.1.2.1. Pressurized Cavity Tubular Receiver

Although the prevailing commercial cavity tubular receivers use liquid (molten salt) as heat transfer fluid, gaseous fluid can also be used in the tubular receivers. Such systems are known as pressurized tubular receiver. A pressurized tubular cavity receiver with a thermal power of 280 kW, preheating the air of a recuperated micro-turbine with 100 kWe, was developed and tested within the SOLHYCO project (Amsbeck et al., 2008; Amsbeck, 2009). The receiver was constructed using 60 parallel-connected nickel-based alloy tubes with an irradiated length of 2.5 meter (Fig. 30). The air from the compressor is sent to each of the tubes through a distributor. After passing through the absorber, the hot air reaches a manifold which sends it to the power unit, or storage system. The system was tested at the Solar Platform of Almería, Spain in 2006, reaching the design outlet temperature of 800°C. However, due to problems with the cavity insulation (enabling cold air streams through the cavity) the convection losses were quite high (Buck et al., 2017). As a result, the measured receiver efficiency at design point reached only 39% instead of the expected 77.7% (Lars Amsbeck, 2010).
In another attempt, under the European SOLUGAS project, a tubular cavity receiver with a thermal power of 3 MW was developed and tested (Fig. 31). The receiver was designed to handle the compressed air (up to 9 bar and 350 °C). The compressed air in the receiver is heated up to 800 °C by the concentrated solar radiation focused on the receiver from the heliostat field. The receiver design follows a modular approach using 10 circularly arranged panels. The solar radiation is absorbed and transferred to the fluid by 170 parallel absorber tubes with an inner diameter of 19.6 mm and an irradiated length of 5 m. The absorber tubes as well as the collector are made of a nickel-based alloy to withstand the high material temperatures while the distributor and the support frame are made of stainless steel. To compensate the different thermal expansions of the absorber tubes, every absorber tube was connected to the collector tube using a metallic bellow (Uhlig, 2011). The receiver was tested at Abengoa's Solucar Platform and reached all design goals. More than 1000 h of solar operations have been accomplished (Korzynietz et al., 2016).
6.2.1.3. Volumetric Receivers

Volumetric receivers are made up of a permeable porous structure, such as wire mesh, ceramic foam, metallic foam and honeycomb which receives concentrated solar radiation, allowing it to propagate within its structure where it is gradually absorbed. A porous surface, allowing the radiation to penetrate into the depth of the absorber, reduces reflection losses. The porous absorber is usually a matrix or a foam structure made of silicon-carbide ceramic mesh (see Fig. 32). The large specific area of the porous structure allows the receiver with gaseous heat transfer fluid (air) to absorb solar radiation deep inside the porous medium and heats the solid structure, unlike the conventional external tube receiver, where only the outer surface of the absorber tube is exposed to concentrated sunlight. Therefore high efficiency can be attained because the effective area for solar absorption and convective heat transfer is far larger than that for thermal losses. Moreover due to high service temperature of porous medium (e.g. SiC ceramic) outlet temperatures of up to 1000 °C or more can be achieved which is not possible in conventional tubular receiver due to limitation of service temperature around 600°C.

Although thermal conductivity of air is low (it cannot be used to store the thermal energy directly), it offers several advantages: it allows reaching very high temperatures and thus high turbine efficiency, it can directly drive a Brayton cycle, which in turn allows adoption of a highly efficient solar-driven combined cycle; it is free and abundant and there is no risk. During operation, the air is drawn in through the front end of the absorber, which propagates the heat transfer within absorber by convection. Ideally, the flow of cold air the inlet (front side) of the absorber and the propagation of heat due to solar flux cause the temperature at the outlet (rear side) of the absorber to be higher than its temperature at the inlet of the absorber. This phenomenon is known as the volumetric effect and is illustrated in Fig. 33. For a given outlet fluid temperature, the occurrence of the volumetric effect helps to reduce the convective and
radiative heat losses towards the environment. However, the volumetric effect has never been achieved in the receivers tested to date, at least considering large-scale experiments on receivers based on a standard honeycomb structure (Cagnoli et al., 2019). Requirements for a volumetric receiver are the resistance to temperature as high as 1000 °C, high porosity for a sufficiently large extinction volume such that the concentrated solar radiation penetrates through the receiver, high cell density to achieve large specific surface area and sufficiently high effective thermal conductivity to avoid possible thermal spots (Sano et al., 2012). Major disadvantages linked to volumetric receivers include: low convective heat transfer coefficient in the absorber tubes, which limits the heat transfer to the heat transfer fluid and reduces the efficiency of the receiver, the incorporation of structural elements inside the curved tubes that enhance the convective heat transfer is technologically more complex and expensive.

Fig. 33. Comparison of temperature distribution in tubular and in an ideal volumetric receiver (volumetric effect). Based on (Fend, 2010; Hoffschmidt, 1997; Romero et al., 2002)

### 6.2.1.3.1. Open volumetric receiver

An open volumetric receiver uses ambient air and is usually made of porous ceramics but can consist of a wire mesh. The receiver is assembled out of many individual rectangular or hexagonal porous ceramic absorber modules (Fig. 34). These several ceramic absorber modules absorb the concentrated solar radiation in the open volumetric receiver and are heated up to 1000°C. The ambient air that enters the open pores passes the ceramic structure and absorbs a large part of the heat. This hot air used to generate steam in steam generation vessel to drive the steam turbine. In parallel, heat can be fed to a thermal storage. The cooled down air from the vessel or storage is, together with residual heat at 100-150°C, recirculated to the receiver and led to the front of the irradiated receiver surface to be sucked in again. As not all of the air can be sucked in, it's a not closed air circuit. An important milestone for the open-air receiver was the construction of a first demonstration and test power plant with an output power of 1.5 MWe in Jülich, Germany (Alexopoulos and Hoffschmidt, 2017). The volumetric receiver developed by German DLR Institute of Solar Research has now reached a maturity level that enables the technology transfer to industrial partners for the deployment in commercial installations.
6.2.1.3.2. Closed/Pressurized volumetric receiver

The closed volumetric receiver, also called pressurized volumetric receiver, consists of an internally insulated pressure vessel that is closed by a dome-shaped quartz glass window (Fig. 35). In pressurized volumetric receiver, an air compressor sucks in ambient air and builds up the air pressure up to 220 psi, the pressure at which the air enters the receiver. This receiver type is used in order to transfer solar energy to the heat transfer medium (air) in a high pressure module of a gas turbine process. The compressed air (150 – 220 psi) is led to the double-wall pressure vessel of the receiver and passes by the quartz glass panel in front of the absorber. The air is heated with a metallic absorber material of up to 600°C and a ceramic absorber material of above 1000°C. These receivers can handle enormous high heat fluxes of up to 5300 kW/m² while obtaining efficiencies of 71%. However, the transparent window which lets incident irradiance through the window to the volumetric structure, suffers from problems related to durability and window design. Water-cooled window designs and more flexible structures could solve this problem (Ávila-Marín, 2011). The maximum size of these receivers is limited by its design. In order to achieve higher performance, several receivers have to be arranged next to each other and connected in parallel. Additionally these receivers are equipped with a secondary concentrator, which allows a gapless arrangement of several receivers in one tower.
The SOLGATE project used a modular and multistage approach combining three different receiver modules (i.e. external tubular, cavity and volumetric) connected in series (Fig. 36). The first stage used a tubular receiver consisting of 16 parallel connected nickel-based alloy tubes to heat the compressed air (7 bar) from 280 up to 550°C. The second and the third stage are used to heat the air up to more than 1000°C using volumetric receivers (Buck et al., 2017).

**Fig. 36.** SOLGATE LT Multi-tube coil pressurized receiver (a) schematic of design (b) prototype

### 6.2.2. Beam Down Solar Power Tower Concept

An alternative solution to the classic solar system with the receiver on the top of a tower is the "beam down" solution that simplifies the construction of the receiver as well as the tower with very positive impact on the CSP plant costs (Initiative for Global Leadership in Concentrated Solar Power, 2017). Beam-down solar concentrators employ double reflection (Fig. 37) with upper and lower focal points to direct solar radiations towards a receiver on the ground. Similar to SPT, solar radiations are first directed by the heliostat field towards an upper focal point of a central receiver. However, before the rays reach that point, they are intercepted and reflected by the central receiver towards a lower focal point of a set of compound parabolic concentrator (CPC) located over the ground for the further concentration. The concentrated solar radiation can be further converted to useful energy by the receiver mounted on the ground. The optimal integration of beam-down concentrator elements (heliostat field, central reflector, and final optical element) is not a simple task. The designer must properly adjust the positions of both focal points, the layout of the heliostat field, the sizes and shapes of both the central reflector and final optical element (Diago et al., 2020). This concept opens the door to the use of other heat transfer fluids and heat storage solution for high efficiency systems even for a medium size plant. Down-beam CSP technology is under development and many pilot scale installations have been developed in different countries including Japan, Israel, UAE, China, and Italy (Table 3). Currently 50MW Yumen Xinneng (China) is the only utility scale CSP plant using down-beam technology.
Fig. 37. Beam down solar concentrator (a) Picture of beam-down CSP system at the Masdar Institute of Science and Technology, UAE (b) schematic of working of beam-down system. Adapted from: (AlQaydi et al., 2017; Calvet et al., 2021; Diago et al., 2018; Hamer et al., 2017)

Table 3: Beam-Down demonstration plants main parameters (Zanut, 2021)

<table>
<thead>
<tr>
<th>Solar site</th>
<th>Miyazaki (Japan)</th>
<th>Weizmann (Israel)</th>
<th>Masdar (UAE)</th>
<th>Magaldi (Italy)</th>
<th>Yumen (China)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal design power</td>
<td>113 kW</td>
<td>650 kW</td>
<td>100 kW</td>
<td>2 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td>Heliostat field type</td>
<td>Semi-surrounded</td>
<td>Polar</td>
<td>Surrounded</td>
<td>Surrounded</td>
<td>Surrounded</td>
</tr>
<tr>
<td>Heliostat number</td>
<td>88</td>
<td>64</td>
<td>33</td>
<td>786</td>
<td>2603</td>
</tr>
<tr>
<td>Mirror shape</td>
<td>10 Circular</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Mirror dimension</td>
<td>D = 0.5m each</td>
<td>7x8 m</td>
<td>3.21x2.64</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SR type</td>
<td>Ellipsoid</td>
<td>Hyperboloid</td>
<td>Hyperboloid</td>
<td>Hyperboloid</td>
<td>Hyperboloid</td>
</tr>
<tr>
<td>SR height</td>
<td>14 m</td>
<td>45</td>
<td>16</td>
<td>-</td>
<td>60</td>
</tr>
</tbody>
</table>
Some of the major advantages offered by beam-down system over conventional SPT system include (Li et al., 2017; Santamarta, n.d.; Vijayan, 2015):

- All major equipment are at ground level including the receiver.
- Cost reduction generated by the installation of the receiver at ground level which can reduce energy losses resulting from pumping the fluid to an elevated receiver, raising operational efficiency and lowering electricity generation costs.
- A beam-down CSP plant is generally consist of modular tower system e.g. 50 MW Yumen Xinneng CSP plant (China) include 15 beam-down tower modules) which can offer greater revenue reliability, as faults in individual modules can be repaired while other units remain operational.
- Ease in installation, maintenance and operation.
- Retains advantages of power tower design for high temperature application such as solar thermochemistry for hydrogen production.
- Reduced radiation heat losses (receiver is insulated from all sides except the beam window)
- Moreover, beam-down concentrators offer the opportunity to operate novel top-irradiated receivers, such as volumetric receivers (Casati et al., 2019; Tetreault-Friend et al., 2017), packed beds (Yang et al., 2019), or thermochemical reactors (Kodama et al., 2014).

The major disadvantages of beam down arrangement are requirement of a well-supported large hyperboloid reflector mounted at roughly half height of a tower top arrangement and use of an array of secondary concentrators to recover the lost magnification (Vant-Hull, 2014). Such perceived issues are associated with the additional reflection at the central receiver (CR) and are manifest as a decrease in efficiency due to reflection losses, spillage outside its facets, misalignments, reflector defects, and possibly an unwanted magnification of the sun image if the CR is designed as an ideal hyperboloid (Diago et al., 2020). Therefore, a detailed cost-benefit analysis of beam-down system relative to SPT system is recommended. Other drawback include requirement of additional optical components (hyperboloid mirror) which can increase the cost as well as reflection losses. Moreover, due to the large surface area of the hyperboloid mirror, the beam-down system is exposed to high wind. However, as the application of beam-down systems may be suited to applications, such as solar thermochemistry, where the cost of the additional plant is justified by the value of the products (Miller, 2017).

Despite these difficulties, beam-down system is getting a lot of interest in the research field, and further development will undoubtedly bring beam-down designs closer to commercialization (Diago et al., 2020) (e.g., spillage reduction around central reflector (CR) mirrors and around the receiver aperture (Mokhtar et al., 2014), use of high-reflectivity and low-maintenance CR mirrors, demonstration of novel top-irradiated receivers (Gil et al., 2016), improved heliostat tracking and central reflector designs (Gordon and Feuermann, 2019), etc.).

6.2.3. Heliostat's Design, Tracking and Calibration

In SPT much attention has to be paid to the heliostat field because they are typically accounting for 30 – 50% (Amadei et al., 2013; Behar et al., 2013; ECOSTAR, 2005; Kelly, 2010; Kolb et al., 2011, 2007; Manente et al., 2016; Moya et al., 2013; Ortega et al., 2008; Rech et al., 2018;
Telsnig, 2015) of the investment cost of which 40–50% is tied to the cost of the drive system (gears, motors, etc.), therefore the cost reduction and efficiency improvement of heliostats can make this technology more competitive. Structurally an individual heliostat consists of reflectors, support structures, drivers, and foundation as shown in Fig. 38 (He et al., 2020). Heliostats exist in all sorts of sizes (e.g. 1.14 - 178.5 m²) but usually come in the size of range of 15 – 140 m² for commercial CSP plants. The larger the heliostat, the lower the cost of the driver. Moreover the large heliostats can raise up concentration ratio, while decreasing their number and control requirements (Merchán et al., 2021). However, if the heliostat is too large, it will add weight and can increase the cost of the support structure (He et al., 2020) and they have to suffer higher wind loads (Thirumalai et al., 2014). On the other hand, the small heliostats have the advantage lower support structure cost, high optical quality, lower shading and blocking in the field, feasible mass production, easily handling and installation and they are associated with smaller wind loads (Li et al., 2016; Thirumalai et al., 2014) but the costs per unit area, cost of foundation, control, and wiring can be significant (He et al., 2020). However smaller units offer better optical efficiencies which could result in lower LCOE values due to the lower tower height, smaller receiver area and lower number of heliostats with optical properties reminiscent of large heliostats (Kolb et al., 2007; Landman and Gauché, 2014). To develop efficient and cost-effective heliostats, the size of the heliostat should be optimized while considering the processes to design a high-performance heliostat structure (Zhang et al., 2019) (see Fig. 39). Major design issues are wind loads, shaping and dimensioning, the canting, components, manufacturing and assembly, and the qualification or the heliostat cleaning (Pfahl et al., 2017). There is no consensus (He et al., 2020; Merchán et al., 2021) regarding the optimal size of a heliostat, e.g. some studies recommend the optimal size in the range of 35 – 50 m² (Kolb et al., 2011; Pidaparthi and Hoffmann, 2017; Sastry et al., 2016) while other indicated that the lowest LCoE can be achieved by heliostat sizes larger than 50 m² (Kolb et al., 2007). The variation in heliostat size is also evident through the availability of large variation of heliostat size in commercial SPT plants. For example the individual heliostat size of the SPT plants including 121 MW Ashalim Plot B plant in Israel, 50 MW CEEC Hami plant in China, 110 MW Crescent Dunes plant in USA, 50 MW LuNeng Haixi plant in China, 50 MW Qinghai Gonghe plant in China, 20 MW Gemasolar plant Spain, 392 MW Ivanpah Solar plant USA, 50 MW Khi Solar One plant South Africa, 100 MW Shouhang Dunhuang-II plant in China and 50 MW SUPCON Delingha plant China are 21, 50, 116, 138, 20, 120, 15, 140, 116 and 20 m² respectively. This variation in the sizes of heliostats across CSP tower plants, poses a major challenge in maintaining the reflectivity of the heliostats during operation of CSP plants. Because depending on the location, a considerable investment is required to clean the heliostats surfaces regularly as every bit of dust on the surface will reduce the light that can be focused onto the receiver. Therefore, it is a major challenge to optimize the cleaning machinery, but because of variation of heliostats size, it is not easy to standardize.

Today’s utility scale SPT plants have tens of thousands of heliostats (e.g. 377 Ivanpah, the world's largest CSP tower plant in California, uses 173,500 heliostats while the 100 MW tower under construction at the Noor Energy 1 project in Dubai includes 70,000) which reflect the sun radiation over distances of between 1 and 1.77 kilometer from the central tower (Sattler et al., 2020). Although each heliostat uses two computer-controlled drives to track the bisector between the sun and the receiver individually, it is not known whether deviations between the targeted
and actual coordinates of heliostat exist (the so-called tracking error) or how large these deviations may be during operation. Moreover since the mirrors tracking the sun reflect the radiation over distances of up to one kilometer, even small angular deviation of aim points lead to large losses in power plant efficiency. Because of this, the tolerance for the tracking error is extremely small, as illustrated by the following example: for a heliostat 1 kilometer north of the central tower, a tracking error of 1 mrad (equivalent to a 0.057°) results in an offset of about 2 meter between the desired position point of the heliostat and the actual position of the solar focus on the receiver plane (Sattler et al., 2020). To validate the alignment of a heliostat, a periodic calibration is required. Alignment issues become more significant for larger projects due to the greater distances between heliostat and CSP tower. For example for Ivanpah SPT plant which commissioned in 2014, heliostat positioning problems caused by soiling and windstorms contributed to the facility missing production targets in its first 24 months of operations. Moreover misalignment can cause too much radiation to be concentrated on the central receiver, causing the receiver to overheat. This may damage the receiver and result in the plant being shut down. One such incident of overheating happened in May 2026, when one the three central tower receiver of 392 MW Ivanpah SPT plant caught fire caused by mirrors that did not track the sun properly, which focused sunlight onto the wrong part of the tower (Larson, 2016). Therefore a great care is required to avoid excessive solar energy concentration in a single spot by distributing it in an aiming strategy. Therefore, a very reliable control technology is required to control the heliostats with very high precision.

To avoid misalignment problems in SPT plants, a number of research teams are developing advanced heliostat calibration technology e.g. using latest camera and automation tools to develop self-calibrating heliostat systems. In this context, the Fraunhofer Institute for Solar Energy Systems, Germany developed a calibration and control system (called HelioControl) based on digital image processing for heliostat fields. With this method, the aim points of many heliostats can be determined for the first time during operation in a timely and cost efficient manner. After laboratory testing, the system was deployed in the heliostat field at the Themis tower power plant in France. The results are promising (only a few millimeters deviation from the actual aim point) and the technology could be deployed at commercial level by 2022. The project team of the HelioControl estimates the system could reduce heliostat field costs by around 5%, based on simulations and literature-based assumptions. Another notable development is made in European Union funded project “PHOTON” led by Spanish Tewer Engineering. The PHOTON project has developed a heliostat composite incorporating a spherically-curved sandwich of glass-foam-glass that reduces blocking issues and temperature-induced misalignment (Carrascosa et al., 2020). The system can achieve an enhanced optical quality of 0.6 milliradian (mrad) deviation, compared with 2 mrad deviation for existing state-of-the-art heliostat models ((Tewer), 2018). In addition, the system removes the need for foundations, trenches and wiring in the heliostat field, reducing costs (Carrascosa et al., 2020).
While designing and optimizing the solar concentration efficiency of a SPT plant, it is crucial to obtain the accurate solar flux distribution and optical efficiency for a given heliostat field (Hu et al., 2021). In this context, another important aspect of heliostats is their optimum arrangement in the solar tower field and therefore, current research is also focused on looking for optimum optical efficiencies in heliostat fields layouts (Belaid et al., 2020; Rizvi et al., 2021) since a compromise between optical performance and cost issues is required (Merchán et al., 2021). As it has been previously mentioned, the collector field of commercial scale SPT systems, with thousands of heliostats, can generate about the 40% of solar energy losses in the system (Kolb, 2011). Therefore, any improvement of the heliostat field efficiency, based on an optimized design of the collector field, will certainly reduce the LCoE (levelized cost of electricity) (Collado and Guallar, 2019). Heliostats can be arranged in solar tower field in several possible ways (Fig. 40). Although there are no standard procedures to select the most convenient layout pattern as there are several factors which need to be considered for an optimum layout e.g. plant location, number of heliostats, tower height and others. However there are three major systematic heliostat positioning approaches: staggered, cornfield, and biomimetic spiral layouts. Examples of the three mentioned layout are presented in Fig. 41. Among these three configurations, cornfield and staggered layouts can position the heliostat radially or grid-wise while the spiral
layout can only spread the mirrors radially (Gadalla and Saghafifar, 2018). Another way to classify the available heliostat field layouts is based on heliostats arrangement around the tower. Therefore, it is possible to have polar or surrounding fields. In summary, there are 10 possible combinations of the above-mentioned heliostat field design classes as depicted in Fig. 42 (Gadalla and Saghafifar, 2018). In particular, the radially staggered pattern is the most popular and commonly used field layout (Gadalla and Saghafifar, 2018; Thirumalai et al., 2014) not only for circular but also polar fields. In radial stagger layout heliostats are placed in circles with some offset with respect to the heliostat immediately in front (Barberena et al., 2016; Merchán et al., 2021; Thirumalai et al., 2014). The biomimetic layouts has recently been proposed by Noone et al. (Noone et al., 2012), in which heliostats follow a spiral pattern. In case of cornfield configurations, the heliostats are placed one just directly behind the other, and were also adopted in some small scale SPT projects e.g. 5 MW Sierra (California) and 1.5 MW Jülich (Germany). Although some studies (Zhang et al., 2016) which have considered one layout over another but it is worth to note that the differences between the field efficiency for the ‘regular’ layout and that of the actual optimum layout are well less than 1% (Collado and Guallar, 2019).

![Fig. 40. Possible heliostat field patterns based on Fermat’s spiral (not necessarily optimal).](image1)

![Fig. 41. Heliostat distribution patterns (Gadalla and Saghafifar, 2018, 2016; Noone et al., 2012; Saghafifar and Gadalla, 2016)](image2)
6.2.4. Future Research Directions

The major challenge of SPT fields is to enhance the operating temperature of the CSP plants while maintaining the overall solar to telecentric power generation efficiency. The future research will attempt to achieve optimum trade-off between high efficiency, low pressure drop, high durability, and low cost. Ongoing research projects aim to discover more effective material to be used both as heat transfer fluids and thermal energy storage medium in SPT plants. One such effort is the research on chloride molten salts which have higher thermal stability temperature than conventional nitrate molten salts. In SPT solar fields, the central receiver systems are on the verge of a major growth phase. Volumetric receivers using air or a gas as a working fluid are under development and can be used with higher temperature Brayton cycle engines at high efficiency. To take the full advantage of high-temperature receivers and power cycles, it is important that developments also need to be made for high temperature storage system (Vant-Hull, 2021). In this context, new heat transfer and storage media such as particles is of particular interest and is suited to the new developments in the supercritical CO2 turbine cycle. Another very important field of research activities will be the design and development of concepts for increasing the load hours of SPT plants. Among them are the fields of hybridization.
and the search for appropriate storage materials. In order to increase the share of SPT electric power as a dispatchable energy in global energy mix, it is necessary to examine how SPT can be hybridized with biomass energy to achieve around-the-clock 100% renewable energy.

6.3. Linear Fresnel Reflector (LFR)

Linear Fresnel Reflector (LFR) is similar to parabolic trough collectors, but use a series of long flat, or slightly curved mirrors placed at different angles to concentrate the sunlight on either side of a fixed receiver which is located several meters above the primary mirror field (see Fig. 43). Each line of mirrors is equipped with a single-axis tracking system (either in the South-North direction or East-West direction - Fig. 44) and is optimized individually to ensure that sunlight is always concentrated on the fixed receiver. The receiver consists of a long, selectively-coated absorber tube. LFRs are so-named due to their use of the Fresnel lens effect, which allows a mirror with short focal length and a large aperture therefore reducing the volume of reflector material. For LFR systems, there are a large number of parameters (Montes et al., 2017) to consider when designing the collector field. These design variable include such as the number of collectors, the spacing (Zhu et al., 2016), individual mirror widths, the curvature of the primary mirrors (Zhu et al., 2017), and the height and the position of the receiver (Abbas and Martínez-Val, 2017). Therefore, there is a high degree of freedom in the geometric design, which can be optimized based on Levelized Cost of Electricity (LCOE) minimization (Martínez-Val et al., 2015).

![Fixed receiver](image_url)

**Fig. 43.** Schematic of a typical Linear Fresnel Reflector (LFR) with fixed receiver
Similar to parabolic troughs but not prioritizing a parabolic shape to angle the sunlight, LFRs can facilitate large, fixed collectors mounted on the ground rather than to a raised parabola.

The most usual working fluids in LFR based CSP plants are thermal oils as Therminol VP1, Dowtherm A, Syltherm 800, Sandotherm, etc, while there are also applications with direct steam production (Bellos et al., 2018). This steam can be used directly in the turbine of a Rankine cycle or for an industrial process (Bellos, 2019). New type of HTFs are emerging, such as, molten salts, air, and CO$_2$. In recent years, a lot of research has been focused (Bachelier and Jäger, 2019; Bachelier and Stieglitz, 2017) on the utilization of molten salts in LFR because these working fluids will not only increase the working temperature of HTF from current 400 to 600 °C but can be also used as storage medium with high energy density.

Aside from the geometric differences, the system functions of LFR are virtually identical to those of PTC – when sunlight hits a receiver filled with transfer fluid, the fluid is heated and passed through the appropriate heat exchange for the desired application (Mills, 2004). Based on Fresdemo prototype of Almeria, Spain (LFR system with single-tube absorber with secondary concentrator, non-evacuate, water–steam as HTF), Montes et al., (Montes et al., 2016) carried out a study of the thermal performance of LFR working with different heat transfer fluids (HTF), comparing these results to those obtained for conventional PTC. The main conclusion of this work is that, although the overall performance of LFC is worse than in PTC, due to the optical efficiency, the thermal performance of the LFC receiver is better than PTC receiver.

In contrast to PTC system the LFR technology offers the following advantages (R Abbas et al., 2012; Ahmadi et al., 2018; Bellos, 2019; Bellos et al., 2018; El Gharbi et al., 2011; Nixon et al., 2013; Qazi, 2017):

- Cheaper due to its inexpensive flat or slightly curved mirrors in comparison to parabolic ones.
- They do not require tracking the position of the sun, so no need for high pressure swivel joints as the PTC system do at the end of each collector line.
- Unlike PTC the receiver of the LRF is constant which makes simpler the connections in the LFR because they can be stable and not flexible as in the PTC. So, the risks for
working fluid leakage are lower something that reduces the safety measures that have to be taken (Bellos, 2019).

- They do not necessarily have metal–glass welds at the ends of each receiver tube module for maintaining vacuum within the outermost tube.
- They require lower maintenance and operation costs.
- Being more compact than PTC makes them more suitable for Integrated Solar Power Plants, such as the one being built in Liddell, Australia, which will give more than 9 extra MW to a coal power station.
- They bear lower wind loads as the flat concentrating mirrors are segmented and located close to the ground at vary distances from a central tower.
- As the central receiver is a fixed absorber located at the top of each individual module of a solar collector assembly, the need for high pressure flexible piping is eliminated as in the case of PTC system.
- These systems greatly reduces the length of the required piping loop, especially not just because of high concentration, but also due to solutions like the one described in Section 6.3.1., where a double receiver is placed on a single tower.

The drawbacks of the LFR system include: lower energy yield per unit of area; need high amount of direct normal irradiance (DNI); need repeated cleaning to prevent dust trapping in grooves.

LFR systems are typically installed with one-axis east-west rotational tracking, which inevitably results in cosine losses, shading, blocking and end losses due to changes in the sun’s position (Sharma et al., 2016). The aforementioned losses in LFR system and can described as:

- Cosine effect: when the incident ray is not perpendicular to the surface (which is often the case with fixed-tilt systems), the angle of incidence is not zero ($\theta \neq 0$), and part of the incident energy will be lost due to so-called cosine effect (Fig. 45a).
- Shading: when one reflector blocks the incident sun rays falling on other reflector (Fig. 45b).
- Blocking: when one reflector blocks the reflected rays from another reflector directed towards the receiver. Thus, the complete reflector-aperture area is not utilized (Fig. 45c).
- End losses: when reflected rays from some portions of reflectors are not completely intercepted by receiver due to the non-zero angle incidence of sun rays in the axial direction (Fig. 45d). In small-scale LFR system, end losses and their influence on the energy performance are crucial issues (Zhu et al., 2016). In addition, the high ratio of the focal distance to the length (F/L) in LFR system also contribute the optical end losses.
Keeping in view the above mentioned losses, improving the optical efficiency of LFR systems has been the subject of numerous investigations in recent decades (Yang et al., 2018). In this context, many alternative designs have been investigated in order to eliminate or to reduce the problem of high optical end losses. One promising remedial measure for the end losses is to extend the receiver at the mirrors end (Hongn and Flores Larsen, 2018) in order to exploit the solar radiation of the end losses (Fig. 46). Yang et al., (Yang et al., 2018) performed an optimization of this idea by using movable mirrors to avoid using a longer receiver length which is associated with an increase in cost. This idea can be an effective way to enhance the performance of the systems without high length because these systems suffer from high optical end losses (Bellos, 2019). However, it is worth noting that increasing the focus length will increase the tracking accuracy requirement, the system cost and the Cosine losses (Yanqing et al., 2014; Zhu et al., 2017). Another interesting idea according to Bellos et al., (Bellos, 2019) is the use of tilted primary mirrors to reduce the angle of incidence between the mirrors and the sun. This idea has been explored in References (Ma and Chang, 2018; Pulido-Iparraguirre et al., 2019) with significant improvements. However, tilted mirrors can be applied in short solar field and not in lengthy solar fields due to geometric constraints related to the distance of the mirrors from the ground. In another attempt to reduce the gap between the adjacent mirrors, a compact linear Fresnel reflector (CLFR) has been proposed (Mills and Morrison, 2000), which can be interpreted as a combination of a number of LFR collectors placed close to each other. Although the gap between adjacent mirrors is reduced in this design, it has two drawbacks, including blocking of the reflected radiation and shading of the incident solar radiation (Sharma et al., 2016), and can seriously affect the efficiency of the LFR collector (Zhu et al., 2016).
6.3.1. Secondary Reflector

The secondary reflector as part of receiver assembly is used to improve collector performance and—in the cases when non-evacuated absorbers are used—to reduce heat loss of absorbers (Zhu, 2017). They are used for reducing the number of off-target rays (Fig. 47), which do not strike the receiver after reflection by the primary mirrors, since the optical spot sent by the mirrors is often larger than the diameter of the receiver considering the range of beam-spreading angles due to specularity and mirror slope errors, and the energy losses can increase further, considering additional errors related to mirrors or receiver misalignment, inaccurate tracking etc (Vouros et al., 2019). Secondary reflectors come in different shapes but most widely used option is a compound parabolic concentrator (CPC) (Abbas et al., 2016). Other examples of LFR secondary-reflector shapes include trapezoidal, parabolic, or other profiles defined by a higher-order polynomial. The trapezoidal shape provides a fabrication-friendly engineering design and facilitates the addition of an insulation layer to reduce heat loss from non-evacuated absorbers (Singh et al., 2010). The parabolic shape can naturally concentrate the incoming parallel sun rays to its focal point (Grena and Tarquini, 2011), but the reflected light from the primary reflector is not parallel, thus leading to non-ideal optical performance (Zhu, 2017). It is important to consider that, instead of increasing the optical efficiency, a poor design of a secondary reflector can reduce the performance of an LFR system. Therefore, shape of the secondary reflector is crucial towards the increase of the optical performance of LFR. In this context, a higher-order polynomial will provide more design parameters to optimize the secondary profile, but this often requires more intensive computational efforts (Zhu, 2017). Optimized shapes offer the opportunity to work with smaller receiver diameters, which promote the higher concentration of incident flux and lead to higher temperatures of the working fluid so that the potentials for steam generation and electricity production increase. The most important problem with secondary reflector design is that it is very difficult to establish a one-on-one relationship between primary and secondary reflector segments which make it hard to produce a shape that could potentially redirect all the off-target rays back to the center of the receiver (Vouros et al., 2019).
6.3.2. Compact Linear Fresnel Reflector (CLFR)

The classic LFR has only one receiver on a single linear tower. This prohibits any option of the direction of orientation of a given reflector. In case of a utility scale LFR based CSP field, it can be assumed that there will be many linear receivers in the system. Therefore, if the linear receivers are close enough together, the individual reflectors will have the option to direct the reflected solar radiation to at least two receivers. This additional factor offers the potential for more densely packed arrays, since patterns of alternative reflector inclination can be set in such way that closely spaced reflectors can be placed without blocking and shading. This relatively new concept LFR system known as compact linear Fresnel reflector (CLFR) is developed to minimize energy losses as depicted in Fig. 48. Different from the classical LFR system, one receiver is installed at each side of the solar field, which allows consecutive mirrors to redirect the sunlight to the two receivers respectively. The CLFR system enhances the optical efficiency compared to a conventional LFR, but it adds complexity to the reflector tracking mechanism (Zhu et al., 2014). This technology has better system cost effectiveness (Montes et al., 2014) and is promising for applications with limited ground availabilities (Barlev et al., 2011). In order to enhance the optical and thermal efficiencies of the CLFR systems, further research is needed to study the interaction between the receiver internal geometry and the layout configuration of primary mirrors, as this affects the amount of radiation that is ultimately absorbed by the receiver (Rungasamy et al., 2019).
6.3.3. LFC receivers and thermal performance

The LFR receiver technology used has a major impact on the solar power plant, and will influence the optical design of the solar field (Abbas et al., 2013). Until now, several receiver shapes have been proposed that can be basically grouped in two configurations: single-tube receivers and multi-tube. In the current state of technology there is no agreement that one of the two basic Fresnel receiver configurations is better than the other (Montes et al., 2017).

6.3.4. Single Tube Receiver Design

The single-tube receiver design consists of one tube, inside a cavity with a compound parabolic concentrator (CPC) or other optimized shape, working as a secondary reflector. The diameter of the single tube design usually varies between 7 cm and 18 cm, although other sizes can be applied if suitable optics and products are available (Zhu et al., 2014). A single tube receiver does not lead to high intercept factor and thus the use of secondary concentrators is generally preferred. Three types of single-tube receivers are being used in RFL: glass-plate receiver, evacuated receiver and non-evacuated receiver (Fig. 49). For a complete system, it should be noted that for a large LFR based CSP plant (e.g. 125 MW Dhursar plant in India) the whole solar field does not all operate at the highest temperatures, so the two different receiver options has been developed for such LFR system: one with evacuated tubes for high-temperature operation, and one without evacuation for lower temperatures, could be used in different sections of one solar field for an overall techno-economically optimized result (Platzer et al., 2021).

Fig. 49. Configurations for single-tube receivers with secondary reflector (a) Glass plate single-tube receiver (b) Evacuated single-tube receiver (c) Non-evacuated single-tube receiver

The glass-plate receiver (Fig. 49a) is characterized because its cavity incorporates a glass plate at the aperture. This glass plate reduces convection heat loss but, as in the case of multi-tube receivers, it is difficult to guarantee vacuum inside the cavity, and thus the bare tube is not painted with a conventional selective coating (Montes et al., 2017).
In the evacuated receiver design, the absorber tube is passed through a glass envelope, which allows to create a vacuum in the annular space (Fig. 49b). In addition, vacuum reduces convection and radiation losses, and it enables the existence of a selective coating, which improves the optical characteristics of the tube, especially at high temperatures. It has been found that the CPC design is the most usual and efficient choice for the secondary reflector (Bellos, 2019). An evacuated single-tube configuration with CPC offers higher annual thermal performance, compared to other non-evacuated single-tube proposals (Montes et al., 2017). This design has been used for the receiver in Puerto Errado II (PE II) plant (30 MWe).

The design of non-evacuated receiver is similar to that of the evacuated receiver, except that the tube is not covered with a glass envelope (Fig. 49c). Non-evacuated receivers are generally used for lower-temperature applications e.g., industrial process heating and therefore they are not suitable for utility scale CSP application.

6.3.5. Multi-tube Receiver Design

The multi-tube receiver consists of a series of tubes arranged horizontally in a cavity (usually trapezoidal design) without secondary reflector. The number of tubes is usually from 4 up to 8, while there are some designs with one, two or three tubes (Bellos, 2019). The cavity can be opened to the ambient or have a glass plate at the opening of the cavity. The main mission of this glass plate would be to reduce thermal losses: the convection heat loss would be minimized inside the cavity (Montes et al., 2022). Besides, it could create a greenhouse effect that benefits the thermal performance. However, there are significant technical drawbacks, caused by the high temperature of the glass plate (Montes et al., 2022). In both cases, the large width of the window makes it difficult to create vacuum inside, causing in a convection heat transfer from the tubes to the glass cover. The resulting thermal convection will make it difficult to use selective coatings on absorber tubes as they will be susceptible to reactions with the oxygen in the air, unless nitrogen is used instead of air (Abbas et al., 2013). This, in turn, implies that it is complicated to guarantee the useful life of the selective coating that increases the optical performance of the tubes, especially at high temperatures (Montes et al., 2017). Because of this difficulty, receiver tubes are usually painted with black paint. However, to address this problem, research has focused on selective coatings that can withstand ambient pressure (Soum-Glaude et al., 2014), although these coatings are not yet in a commercial phase (Montes et al., 2022). There are number of research studies available in the literature demonstrating the advantages of selective coatings over black paints. For example by comparing the thermal performance of selective coatings with black paint, Sahoo et al., (Sahoo et al., 2013); Manikumar and Arasu (Manikumar and Valan Arasu, 2014) and Larsen et al., (Flores Larsen et al., 2012) reported a reduction in heat loss of 20 to 30%; 16%; and 37 to 47% respectively. This is due to the fact that selective coatings specifically reduce radiative losses, which have been found to dominate heat loss, especially at higher absorber temperatures (Rungasamy et al., 2022). To avoid the degradation of selective coating on the tubes in oxygen environment, some authors suggest the use of pressure compensated nitrogen.

In side cavity, the tubes are arranged in an outer and central pattern so that the heat transfer fluid (HTF) flows through the outer tubes and returns through the central tubes, all of the same diameters (Fig. 50). The reason for using outer and central tube assemblies instead of a combined assembly is to manage the problem of minimizing the entropy generation in transforming energy
from concentrated radiation to heat the circulating fluid (Martinez-Val et al., 2015). From the principle of thermodynamics, any mixture of energy flows of different temperatures generates entropy, and therefore the efficiency of the system decreases. Since radiation intensity is a measure of the radiation temperature, mixing the energy of different solar rays reduces their ability to achieve a high temperature in the heat transfer fluid. Therefore, the purpose of outer/central arrangement of the tubes in the multi-tube receiver is to transform the radiation energy into a fluid which is preheated in the outer tubes, and passes to through central tubes where it gets hotter as it receives higher radiation intensity. Tubes should be placed close together and at the back of the cavity to restrict natural convection loss and create the conditions for thermal stratification to take place (Moghimi et al., 2015). In addition, a smaller internal spacing between the absorber tubes reduces the temperature differences between them (Dey, 2004). Regarding the absorber tube size, Abbas et al., (R. Abbas et al., 2012) found that reducing the tube diameter increased thermal efficiency, however it also increased the pumping power requirements. Therefore, to achieve maximum exergy efficiency, a trade-off should be made between tube size and the pumping energy requirement. Contrary to this, necessarily, the increase in the sizes of tubes does not lead to increase or decrease in heat transfer rate to the tube walls. Various values of heat transfer and average heat transfer are obtained for various values of tubes sizes.

Dabiri et al. (2018) investigated the effect of varying the tube diameter and number of tubes without considering the pumping power requirements, and the results did not display any clear trends.

**Fig. 50.** Schematic cross-sectional sketch of a multitube Trapezoidal type cavity receiver.

To reduce to thermal losses, the cavities are well-insulated in their back-side. While increasing the thickness of the insulation on the outside of the receiver reduces heat loss, this reduction must be compared with the increase in shadowing on the collector field (Facão and Oliveira, 2011) and with the cost of the insulating material (Moghimi et al., 2017). Among other possible options, Trapezoidal type cavity receivers are suitable for CSP applications because hot air is mainly found near the top surface of the cavity (Natarajan et al., 2012), which can be properly insulated. In addition, there is no direct radiation heat loss to the sky, as tubes are facing to the ground – obviously there is indirect radiation via the mirrors, but the ratio between the solid angle to the sky and the one to the ground and receiver surfaces is very small compared to trough collectors. The heat transfer mechanisms in and around the Trapezoidal type cavity are illustrated in **Fig. 51.** Many researchers have modeled the heat transfer mechanism in cavity receivers for
convective, conductive and radiative heat losses and optimized the design to minimize the losses. In most of Trapezoidal type cavity receiver designs, radiation loss often dominates the heat loss of a receiver assembly (Qiu et al., 2016; Saxena et al., 2016) due to the high receiver tube surface temperature (Sahoo et al., 2012). The CFD analysis of the energy conversion process in the trapezoidal cavity receiver shows that radiation heat loss from tubes contributes around 80%–90% (Qiu et al., 2016; Sahoo et al., 2012).

Fig. 51. Heat transfer mechanisms for cavity receiver (Moghimi et al., 2015)

The cavities based receivers have a lower cost compared to the evacuated tubes but they have lower thermal efficiency, especially in high temperatures. Thus, the cavity receivers are preferred in low and medium temperatures up to 300 °C (Bellos, 2019). The multi-tube trapezoidal receiver is a popular design for large LFR solar fields, and the optical and thermal characteristics of this design have been studied extensively (Dabiri et al., 2018; Manikumar and Valan Arasu, 2014; Moghimi et al., 2015; Mohan et al., 2018; Reddy and Kumar, 2014; Saxena et al., 2016; Tsekouras et al., 2018). Commercial use of this type of receiver can be found in the 5 MW Kimberlina CSP plant (California), and 125 MW Dhursar CSP plant (India).

6.3.6. Commercial Status of LFR technology

Although a decade ago there was no large commercial CSP plant based LFR technology, however very recently, this technology is gaining popularity and some of the recently commissioned CSP plants (e.g. 125 MW Dhursar, India; 50 MW DCTC Dunhuang, China) are based on LFR technology. Fig. 52 shows the aerial view of the China Dunhuang Dacheng 50MW molten salt linear Fresnel CSP plant which commenced commercial operation on June 19, 2020. This is the first ever molten salt Fresnel CSP plant in the world that uses molten salt as the heat transfer fluid and thermal storage medium.
6.3.7. Future Directions

Although maturity of LFR technology has already been demonstrated in many aspects, including optics, flexibility, compatibility with heat transfer media, thermal efficiency, and system integration, there are still not enough demonstration plants worldwide to easily convince investors and money lenders that LFR is a viable CSP option for the net-zero energy system. However, as disused LFR systems have great cost reduction potential, but are associated with low efficiency conversion from solar to electricity due to some inherent problems which need to be addressed. These problems are mainly related to the optical losses due to the cosine effect. In this context, the major technical challenge for LFR technologies is the difficulty in maintaining the optical efficiency while increasing the concentration ratio. Unless these problems are resolved, the future of LFR technology will primarily be limited to low-temperature application such as industrial process heat or other niche markets. In this context, future developments will be strongly linked to more advanced designs and layout configurations, seeking maximum concentration, and maximum efficiency to compensate for the optical losses (Collares-Pereira et al., 2017) discussed earlier. These research activities will lead to better, longer-lived reflectors and absorbers, which will proportionately reduce the size and cost of RFL systems delivering a specific power. Currently, there are only a few utility scale RFL solar power plants and the technology is expected to follow an 80-85% learning curve (i.e. costs will decrease by 15-20% for each doubling of the installed system) until irreducible materials costs dominate. Moreover, to show that the CSP is a necessary part of a 24 h/7 electric power system, almost all newly commissioned utility scale CSP plants have been equipped with thermal energy storage (TES) system with an average 8 hours storage capacity, therefore to compete in the electric power market with other rival CSP technologies (i.e. PTC and SPT), successful demonstrations of
integrating commercial-scale LFR system with high density energy storage system like molten salt will be required.

The late development of LFR systems has left many research opportunities for their optimization. However, due to the involvement of a large number of optimization objectives, the results of these studies are not consistent and therefore do not provide a well-defined design. This problem can be addressed by comparing the results of a thermal and optical optimization study with an economic optimization study of the same LFR configuration (Moghimi et al., 2017). Another important research opportunity is to study the interaction between the receiver internal geometry and the collector should be investigated, as this impacts the amount of radiation that is ultimately absorbed by the receiver. As for the receivers, a cost comparison of the LFR system with evacuated and non-evacuated absorber tubes is required.

The involvement of large number of parameters in the designing of linear Fresnel collector field has led to three broad avenues of research for LFR systems (Rungasamy et al., 2021): (i) design for peak conditions, (ii) design optimization in the conventional LFR layout, and (iii) novel LFR layout configurations. Several design novel configurations have been proposed for LFR, noting however that only a limited number have reached prototype scale, while even fewer have been demonstrated in full scale setup. The three major contributions of novel LFR configurations are the alternating of targets, the changing of mirror heights and the curving of Fresnel mirrors. While these configurations offer enhanced optical performance, the added complexity of the designs is likely to increase the cost of the primary mirror field. To fully assess the potential competitiveness of these configurations, the performance and cost of the novel layout configuration should be compared to that of a conventional LFR and PTC field. Another future trend might be the availability of more efficient high-temperature turbines (supercritical CO$_2$) so adopting LFR technology for CSP system, it should be able to efficiently generate high temperatures.

6.4. Parabolic Dish Collector (PDC)

Parabolic dish collectors (PDC) also known as Stirling dish system, consists of a parabolic dish shaped concentrator (Fig. 53) that reflects direct solar irradiation onto a receiver at the focal point of the dish. Heat is then supplied to the receiver at temperatures in the range of 700 - 800 °C, where a gas (helium or hydrogen) drives a closed Stirling or Brayton thermodynamic cycle inside the motor, producing mechanical work which is subsequently converted into electricity by an asynchronous generation. Among all the CSP technologies PDC systems has the highest ability to concentrate the sun rays and operate at a concentration of about 3000 suns (Mancini et al., 2003). The gasses used inside a Stirling engine never leave the engine. There are no exhaust valves that vent high-pressure gasses, as in a gasoline or diesel engine, and no explosions take place. Because of this, Stirling engines are very quiet (Fig. 54). The fact that Stirling engines are externally heated gas-phase engines makes them an ideal choice for coupling with solar applications (Karellas and Roumpedakis, 2019). The peak conversion efficiency of Solar Dish/Stirling system is around 25%.

The receiver in a PDC system has a similar operation as in SPT and PTC systems, by means that it absorbs the concentrated solar flux and heats the engine's working fluid (Karellas and Roumpedakis, 2019). PDC systems use two main types of receivers based on the method of heat transfer to the working fluid. The direct illumination receivers which heat the same fluid (helium
or hydrogen) that is eventually used as working fluid in the Stirling engine. Cavity type direct receivers are mostly used in these applications to minimize the radiation losses which are enhanced by the high temperatures developed in the dish. However due to often random and uncontrollable nature of the solar irradiance, the direct illumination receivers poses a challenge in the control of the PDC solar engine. The temperature of the absorber will affect the Stirling engine efficiency, due to the limitation of the thermal rating for absorber and receiver material (Geok Pheng et al., 2015). To address this problem, the important parameter to be controlled is the absorber temperature. The control systems maintain the maximum safe operating temperature by changing the pressure of the working fluid (Helium or Hydrogen gas), which effectively changes the rate of heat exchange between the Stirling engine and the absorber (Howard and Harley, 2010). This is considered necessary to improve the performance of the Stirling engine (Geok Pheng et al., 2015). Due to this temperature control issue, PDC systems most often operate in the controlled temperature region to maximize the efficiency of the Stirling engine (Geok Pheng et al., 2015). To minimize thermal rating mismatches between absorber and receiver material, indirect receivers have been introduced which heat an HTF and allow the decoupling of the solar and power subsystems. The most efficient type of indirect receiver is the heat pipe receiver, which vaporizes a liquid metal—for example, sodium—and condense it in the Stirling engine's heater, transferring heat to the Stirling cycle (Karellas and Roumpedakis, 2019). These receivers allow for a more uniform temperature profile in the heaters and thus prolong the lifetime of the absorber and the heater itself (Gupta et al., 2015).
The power capacity of a typical single solar dish ranges from 3 - 25 kW with diameter 3.5 - 11 m, respectively. Generally, the aperture area of a solar dish varies from 35 – 170 m$^2$ however they can be fabricated in size over 300 m$^2$ e.g. Big Dish installed in Phoenix, Arizona has aperture area of 320 m$^2$. Big Dish was developed by Southwest Solar Technologies Inc. and installed in Phoenix, Arizona. At present there are only few operating CSP plants based PDC e.g. 1.5 MW Maricopa CSP Plant and 1.5 MW Tooele Army Depot CSP Plant at USA started operation in 2013 (in 2018 it was out of service). PDC system has 50–100% higher solar-to-electric efficiencies than SPT) and PTC, respectively, on an equivalent basis of the systems (Lovegrove et al., 2003; Tian and Zhao, 2013).

PDC systems are the least developed of the four CSP technologies. This technology is still at the demonstration stage and the cost of mass-produced systems remains unclear due some associated technical challenges e.g. the working gas leaks (as engine operates under high pressure of ~2850 psi). The leakage is due to the use of hydrogen or helium gas as working fluid in the solar Stirling engine, which makes the engine's piston seals a critical part. The gas refilling and the piston seals replacement are, nowadays, a critical point to have a reliable system. Also the pistons (in particular the cooler ones) are a critical part of the Stirling engine because they can rapidly be damaged (Sayma, n.d.). Therefore, although the promising expectations, the reliability problems of the engine prevent the PDC from commercialization.

6.5. Summary of main stream CSP technologies:

Table 4 summaries the main features of the above four types of CSP technologies.
CSP plants in terms of thermodynamic cycle and the cycle efficiency can be classified into three generations (Fig. 55). The first-generation CSP plants employ Rankine cycle with the design cycle efficiency of 28–38%, where the peak cycle temperature is as low as 240–440 °C, and the PTC, SPT and LFR are usually used (He et al., 2020). Most of the first-generation CSP plants were not equipped with thermal storage thus the plant can just operate in sunny conditions during the day time. To date, first-generation CSPs still account for the majority of installed CSP capacity, with PTC systems accounting for 77%. Most second generation CSP plants comprise of PTC, SPT and LFR with a Rankine cycle efficiency of 38-45% and with maximum cycle temperatures rising to 565 °C. Almost all newly installed second generation CSP plants are equipped thermal energy storage system. Due to their high cycle efficiency, these second generation CSP plants can achieve an annual solar-electric efficiency of around 10-20%, compared to 9-16% for the first-generation CSP systems (He et al., 2020). The 3rd generation CSP plants focus on enhancing the maximum cycle temperature by employing more advanced materials for heat transfer, thermal storage and working fluid in thermal cycle. However, all 3rd generation CSP technologies are still in the demonstration stage and no commercial applications are yet available. The 3rd generation CSP technologies are discussed in detail in Section 10.

### Table 4. Characteristics of CSP technologies (Behar et al., 2013; Bracken et al., 2015; Chen et al., 2020; DOE, 2012; Fernández-García et al., 2010; Ho, 2016b; IRENA, 2012; Islam et al., 2018; Iverson et al., 2013; Kuravi et al., 2013; Liu et al., 2016; Moser et al., 2013; Pavlović et al., 2012; Raza et al., 2016; Reddy et al., 2013; Turchi et al., 2010; Xu et al., 2016; Zhang et al., 2013)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PTC</th>
<th>SPT</th>
<th>LFR</th>
<th>PDC</th>
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<td>Medium, pilot plants, commercial projects under construction</td>
<td>Low, demonstration projects</td>
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<td>250 - 565</td>
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<td>20 - 35</td>
<td>~ 10 -16</td>
<td>25 - 35</td>
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<td>Superheated steam Rankine, steam @ 540 °C/125–140 bar</td>
<td>Superheated steam Rankine (steam @ 380 °C/50 bar)</td>
<td>Stirling/Brayton</td>
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<td>43 - 45</td>
<td>41 - 44</td>
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<td>Direct two-tank molten salt storage (280–565 °C),</td>
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7. **CSP Cooling System**

All commercial CSP technologies (PTC, SPT and RFC) rely on steam Rankine power cycles that are essentially the same as those used in coal and nuclear power plants. Completing the cycle in a Rankine power block requires a cooling system to condense steam back into water. While most water is reused in the cycle, water is still needed for the steam cycle make-up. The water is used to ensure the steam generation (4 - 8%), the cooling of the power-block (82 - 94% in case of wet cooling) and the cleaning of the solar field collecting solar thermal energy (2 - 10%). In terms of gallons per MWh, CSP systems with recirculating cooling technologies have higher water consumption rates than many other wet-cooled technologies (Bracken et al., 2015) e.g. 45% more than coal/nuclear plants and 200% more than combined-cycle natural gas power plants. In general, the water usage in a typical CSP plant is divided into three main parts; parabolic trough washing, steam generation, and the cooling system. Although some CSP technology can utilize air/hybrid cooling techniques to reduce dependency on water, water will still be needed in some capacity for cleaning the mirror surfaces. Frequent mirror cleaning is vital to ensure efficient plant operations e.g. the solar collectors are washed (Fig. 56) once or twice every week at 100 MW Shams-1 (Abu Dhabi) PTC type CSP plant (Raza et al., 2016). A typical consumption of water required to wash the mirrors is 0.5-0.7 lit/m² (total annual consumption of washing water per square meter depends upon the geographic location of the solar field). Although the photograph shown in Fig. 56 was taken in the morning, mirrors are usually washed at night, so the entire solar field will continue to operate during day time to maximize solar radiation collection and conversion (Moya, 2021a).
CSP systems with recirculating cooling technologies have higher water consumption rates (in terms of gallons per MWh) than many other wet-cooled technologies (Bracken et al., 2015). As per the statistics of the currently operating CSP plants in various countries, the total annual water demand for wet cooled PTC/RFC plants is 750-850 USG/MWh and 550-600 USG/MWh for SPT plants, while dry cooling requires ~75 USG/MWh and ~85 USG/MWh respectively. This results in water consumption of around 400000-500000 m³/year for a typical 50 MW PTC plant equipped with wet cooling. Of this water consumption ~90% goes to the cooling tower and ~8% consumed by mirror washing and remaining 2% by steam generation. Considering that highly irradiated areas are usually water deficient together with high water prices (up to $10/m³, with water transportation costs for some regions), the profitability of CSP plants may be questionable. Therefore saving water is so a key issue to ensure a financially competitive position of CSP and its sustainable implementation, as well as being a humanitarian and environmental consideration.

To reduce the water consumption most of the recently commissioned CSP plants are equipped with dry cooling (with air) technology. Dry cooling is more efficient than the wet cooling at the expense of reducing water loss to the environment. For example, in a typical CSP wet cooling plant, steam cycle cooling has been reported to account for over 90% of water consumption (Turchi et al., 2010). Switching from a wet-cooled system to a dry-cooled system results in a 90% - 93% reduction in water consumption (Bracken et al., 2015; Mai et al., 2012). Large amounts of water consumption can be constrained by policies or cost effective in dry remote areas, where CSP plants most likely to be deployed in the future. Therefore, dry cooling will be the cost-effective option for CST plants. While CSP plants using dry cooling dry cooling have the advantages of saving water, protecting the environment and flexible selection of site locations (Hooman et al., 2017), but, dry-cooled power plants suffer lower efficiencies when the ambient air temperature is high (Kröger, 2004). In general the design efficiency of dry cooled PTC type CSP plants is about 1 - 2% lower than that of a wet-cooled plant, the actual values depend on the ambient temperature of the site and the size of the air-cooled condenser (Pitz-Paal, 2020). Dry cooling systems installed on PTC plants located in hot deserts, reduce annual
electricity production by 7% and increase the cost of the produced electricity by about 2.5% to 10% (Zhang et al., 2013). To overcome the disadvantages of either only-dry or only-wet cooled plants, a hybrid cooling systems can be used (Asfand et al., 2020) which can reduce the water consumption by 60–80% at an expense of 3–5% increase in the capital cost (Colmenar-Santos et al., 2014). Besides the plant size and cooling method, the water consumption rate in CSP units depends on several site specific factors e.g. dust properties (particle size, composition etc.), humidity and rainfall (IRENA, n.d.). The CSP plants situated in hot humid climate (e.g. MENA region), the humidity increases the tendency of dust particles to stick to the collector surface which increase the water consumption, while CSP plants situated in rainy region (e.g. Spain), rainfall provides a natural cleaning of the mirrors and can reduce water consumption. Generally, decision makers must choose between wet, dry cooling, or hybrid cooling technologies for each prospective CSP project.

Another potential supplemental cooling technology is radiative cooling that has recently garnered widespread interest (Huang et al., 2021; Zhao et al., 2019). To reduce water usage for cooling CSP plants, recently Aili et al., (Aili et al., 2022) have developed a supplemental cooling technique for wet cooled CSPs that integrates radiative cooling with cold storage (Fig. 57). Radiative cooling with cold storage is a dry cooling technique involving coolers created of highly solar reflective material with the ability to direct heat dissipation at selective infrared wavelengths into deep space in the lack of absorption in the environment. The results demonstrate that the annual consumption of water could decrease by 40 - 60% in the hot southwestern region of the United States by accepting daytime-only radiative cooling whereas the annual potential water saving can be as much as 65%–85% if the radiative cooling system works both day and night with cold storage.
Fig. 57. Schematic of a recirculating wet-cooled CSP plant supplementally cooled by a radiative cooling system. (a) a parabolic-trough CSP plant with an evaporative wet cooling tower and a supplemental radiative cooling system placed before the cooling tower. (b) a single radiative cooling module laminated with a highly solar-reflective and selectively emissive radiative cooling film (c) Spectral emissivity of the radiative cooling film and the atmosphere (PW = 5 mm, zenith = 45°) along with spectral solar irradiance and blackbody radiation. Proposed by Aili et al., (Aili et al., 2022)

8. Next Generation CSP with Advanced HTF and TES

The prime focus of next generation (3rd generation) CSP is to reduce the LCoE by improving solar-electric efficiency with increase in the operational temperatures (>600 °C) above the state of art application. To achieve high thermal-to-electric conversion efficiency and to lower
electricity production from renewables, different initiatives have been launched across different countries. Some of the major initiatives include:

- **European DISTOR Project**: The aim of this project (funded by the European Commission) is to develop high temperature TES system for integration in CSP plants using absorbers with direct steam generation. The project developed PCM-based TES system and heat transfer concepts to overcome disadvantages related to PCMs (Cáceres et al., 2016).

- **US SunShot Initiative**: The aim this project (launched by the United States Department of Energy in 2011) is to reduce the LCOE of CSP-generated electricity to less than $0.06/kWh by 2020 with the cost of thermal storage less than $15/kWh (Gary et al., 2011). As per the goal of this project, the main driver is the potential for reducing the LCOE from CSP plants using a high temperature Brayton cycle to achieve efficiency higher than 50% (Turchi et al., 2013).

- **US Gen3 CSP Program**: In order to achieve the SunShot Initiative 2030 goals for CSP, in 2018 U.S. Department of Energy, Solar Energy Technologies Office started to fund the Generation 3 Concentrating Solar Power Systems (Gen3 CSP) program with a total funding of $77.7 (DOE, 2018). The leading research institutions in energy research such as Sandia National Laboratories (SNL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory (SRNL), Idaho National Laboratory (INL), Massachusetts Institute of Technology (MIT), and energy companies like Brayton Energy, Hayward Tyler, Mohawk Innovative Technology, and so on, are included in the program. The goal of this initiative is to advance solar collector field, receiver, thermal energy storage, and power cycle subsystems to improve performance and achieve ambitious targets for the cost-effectiveness of CSP systems. A central goal of the Gen3 CSP initiative is to lower the cost of CSP systems to approximately $0.05 per kilowatt-hour to help make solar baseload configurations cost competitive with other dispatchable power generators throughout the sunny, southern half of the United States. Key to decreasing system costs and fulfilling Gen3 CSP goals is increasing plant efficiency by raising the temperature of the heat delivered to the power cycle to over 700°C (from current level of 550°C).

- **Australian Solar Thermal Research Initiative (ASTRI)**: The aim of this project (funded by the Australian Government) is to lower the cost of solar thermal power to AUD$0.12/kWh by 2020 (Liu et al., 2016).

- **NEXT-CSP**: Launched in 2016, the European Next-CSP project gathers ten partners institutions with one objective to improve the reliability and performance of CSP plants through the development and integration of a new technology based on the use of high temperature (800°C) fluidized particles in tube as HTF and TES medium. To achieve this objective, the project will demonstrate the technology in a relevant environment (TRL5) and at a significant size (4 MWth) (Next-CSP, 2016).

### 9 Conclusions and future directions

This work provides an extensive review on all major subcomponents of a CSP system. The following points can be inferred from the article.
Over the past ten years, there has been a significant growth in the installed capacity of CSP. Any large-scale CSP deployment in the next decade, however, will happen with existing technologies, both the recently commercialized molten-salt towers and the more proven parabolic troughs. Especially in the tower segment, economies of scale have yet to be realized and a large pipeline of future projects could trigger substantial cost reductions from technological learning, especially if lessons from past failures can be internalized. Among the four different types of CSP technologies, SPT is expected to dominate the CSP market and to be the most developed ones in the near future. In SPT technology, external molten salt tube receivers will continue to dominate in the near future, but modifications from the current salt to provide a wider temperature range and lower freezing point will result in considerable improvements in efficiency, along with improved high absorptive coatings with long-life at higher temperatures. LFR technology being low cost and easy to construct, will likely to play its role in low income countries that intends to install CSP plants without thermal storage system e.g. India, Pakistan. Key challenges in PTC system to be met in the future are to extend durability and to reduce manufacturing cost and maintenance.

To reduce the levelized cost of electricity (LCoE), most CSP plants in the future will be deployed in the areas with higher DNI’s e.g. areas with hot, dry climates where water is scarce. Therefore the development of an efficient and cost-effective dry cooling system is crucial for the future of CSP technologies.

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