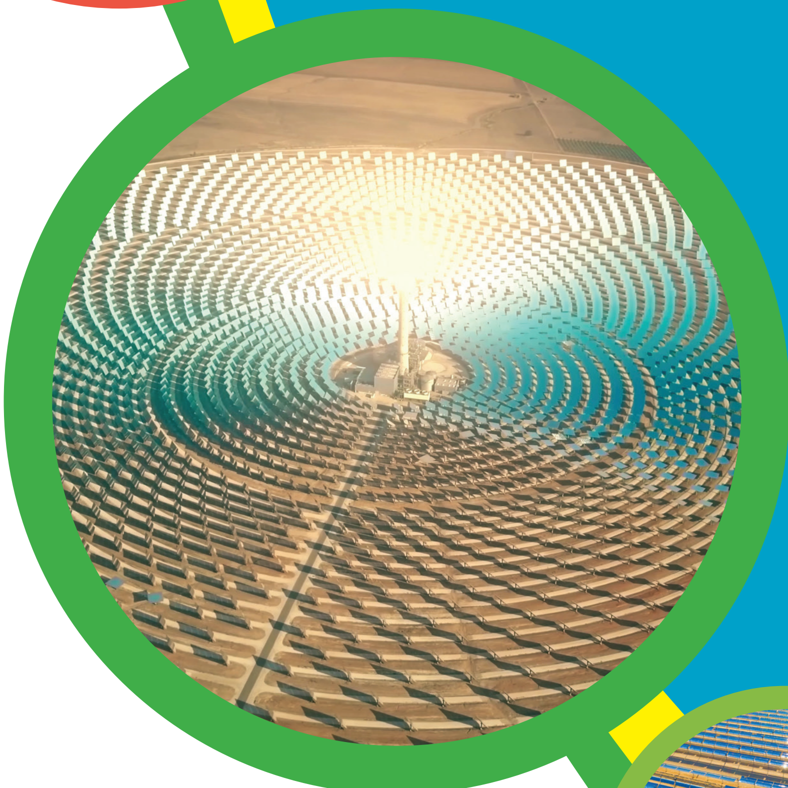
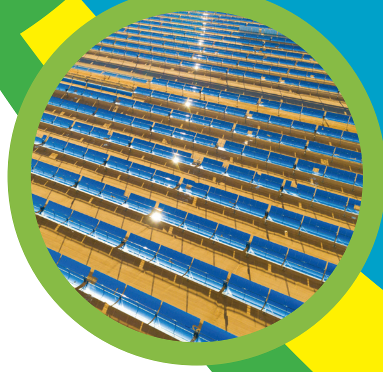
February 2024

CONCENTRATING SOLAR POWER PLANTS WITH STORAGE

Deployment Essential Now

Ajay Shankar | A K Saxena | Robin Mazumdar





The Energy and Resources Institute
Creating Innovative Solutions for a Sustainable Future

Concentrating Solar Power Plants with Storage: Deployment Essential Now

Ajay Shankar I A.K. Saxena I Robin Mazumdar

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From The Desk of Director General

India's continued commitment to achieving the clean energy transition is well recognized worldwide. At COP26, India announced the highly ambitious goal of decarbonizing energy to 50% and achieving 500 GW of fossil fuel-free generating capacity by 2030.

In the TERI's discussion paper titled "Roadmap to India's 2030 Decarbonization target", the creation of 500 GW non-fossil fuel capacity by 2030 was found to be feasible though challenging. The paper articulated that for achievement of India's 2030 targets announced at COP26, there is a need for creation of large storage projects, including setting up concentrated solar power (CSP plants with storage).

The paper spelt out that concentrated solar power (CSP) plant can deliver power on demand, making it an attractive renewable energy storage technology, and concluded that various measures would be required to develop CSP in the country in order to reach the ambitious target of 500 GW by 2030.

The report "Concentrated solar power (CSP) plants with storage: Deployment essential now" provides a roadmap for actions required to be taken for developing CSPs in the country.

Dr. Vibha Dhawan

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Acronyms & Abbreviations, Units of Measure and Conversion

BoP	Balance of Plant
CBC	Closed Brayton cycle
CERC	Central Electricity Regulatory Commission
CIEMAT	Centre for Energy, Environmental and Technological Research
CLFRs	Compact linear Fresnel reflectors
CPV	Concentrating photovoltaic
CRS	Central receiver systems
CSP	Concentrated solar power
CUF	Capacity utilization factor
DNI	Direct normal irradiance
DSG	Direct steam generation
FOE	Final optical element
GGEL	Godawari Green Energy Ltd.
HTC	Heat transfer coefficient
HTF	Heat transfer fluid
HTM	Heat transfer media
LBE	Lead-bismuth eutectic
LCOE	Levelized Cost of electricity
LECI	Lauren Engineers & Constructors (I) Private Ltd
LFR	Linear Fresnel reflectors
NA	Not available
NASA	National Aeronautics and Space Administration
NDRC	National Development and Reform Commission
NISE	National Institute of Solar Energy
NREL	National Renewable Energy Laboratory
NVVN	NTPC Vidyut Vyapar Nigam Ltd.

O&M	Operation & maintenance
PPA	Power Purchase Agreement
PTC	Parabolic Trough Collector
PV	Photovoltaic
R&D	Research and development
RPO	Renewable Purchase Obligation
sCO_2	Supercritical carbon dioxide
SPSR	Solid particle solar receiver
ST	Solar Tower
STP	Standard temperature and pressure
TES	Thermal Energy Storage
VGF	Viability gap funding

Units of Measure

$	United States dollar
¢	Cent
€	Euro
^{0}C	Degree Celsius
GW	Giga Watt
H	Hours
Ha	Hectare
K	Kelvin
kW	Kilo Watt
kWh	kilowatt hour
m	Meter
m^2	Square meter
m^3	Cubic meter
MW	Mega Watt
Pa	Pascal
USD	United States dollar

Conversion

1 Bar	0.1 Megapascal (MPa)
0 ^{0}C	273.15 K
1 Ha	10,000 square meters (m^2)
1 kW	1000 watts
1 GW	1000 MW
1 MW	1000 kW

Executive Summary

India's commitment at COP26 held at Glasgow in November 2021 was for creation of 500 GW non-fossil power generating capacity by 2030. In the TERI's discussion paper titled *"Roadmap to India's 2030 Decarbonization target"*, the creation of 500 GW non-fossil fuel capacity by 2030 was found to be feasible though challenging. The paper articulated that for achievement of India's 2030 targets announced at COP26, there is a need for creation of large storage projects, including setting up concentrated solar power (CSP) plants with storage.

The paper spelt out that concentrated solar power (CSP) plant can deliver power on demand, making it an attractive renewable energy storage technology, and concluded that various measures would be required to develop CSP in the country in order to reach the ambitious target of 500 GW by 2030.

As per the National Institute of Solar Energy (NISE), the estimated solar potential of India is about 750 GW. India has around 250 to 300 days a year of clear sunny weather, with annual radiation ranging between 1600 and 2200 kWh/sq. m.[1] The initiative to develop CSP plants was mainly through the implementation of Jawaharlal Nehru National Solar Mission (JNNSM) launched in 2010. Out of the total CSP capacity of 329.5 MW installed during the initial years, only 101 MW of CSP plants are operational as of now. While solar PV projects were continued to be selected through a tariff based competitive/reverse bidding process since 2010, no further competitive bidding, therefore, was carried out by any PSU, for setting up the CSP projects.

This report titled "*Concentrated Solar Power (CSP) plants with Storage: Deployment essential now*" presents the growth and status of CSP plants in the world and India. A brief account of CSPs in some of the countries such as Spain, USA, China and Dubai (UAE) provide the macroscopic view in regard to the progress made in these countries. Development of new heat transfer media has been briefly described in the report. The impact of DNI on CUF, storage hours and cost has also been brought out in the report.

The demand for CSP was created in the United States mainly due to the ability of CSP with thermal storage to provide solar power on demand and improve grid integration for renewables.

The 950 MW CSP-PV hybrid plant recently set up in Dubai provides solar power at $7.30 cents per kWh, a price competitive with fossil fuel-based power generation, on round-the-clock basis, thereby helping the grid to shift away from dependency on fossil fuel. The energy stored can be used as needed, even multiple times a day, if necessary.

The report articulates the various range of services and benefits of CSP that complement other generation options to meet growing demand for affordable, secure, and clean power while offering opportunities for domestic, industrial and social development.

Further, CSP can provide storage and generation of solar power for remote areas where other storage options such as pumped storage hydro plants are not possible to set up.

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1 https://mnre.gov.in/solar-rpo-and-rec-framework/#

India endowed with vast potential of solar resources, has the opportunity to adopt CSP technology considering the benefits and the global development of CSP. Competitive Bidding in a phased manner as mentioned in the report, would pave way for lower tariff comparable with conventional power. With scaling up of CSP capacity in future, the need for new fossil fuel based thermal stations would reduce.

Domestic manufacturing of CSP components can further bring down CSP tariff as compared to conventional power tariff.

In view of above, the following recommendations would provide a roadmap for actions required to be taken for developing CSPs in the country:

» **Identification of new sites**

i. Solar irradiance data:

CSP projects being dependent on locational solar irradiation a satellite-based solar map providing realistic value of direct normal irradiance (DNI) on a Pan-India basis needs to be developed through any authorized agency like NREL, CIEMET, CIWET, NASA. Ground-based measurement would further facilitate in locating sites with optimum DNI suitable for setting up CSPs in India.

ii. Developing of solar parks for setting up CSP plants

Solar parks can be developed based on identified sites with optimum DNI based on satellite & ground-based measurement, as detailed above.

The solar parks will provide contiguous parcels of land with all clearances, transmission system, water access, road connectivity, communication network, etc. The solar parks will facilitate and speed up installation of grid connected CSP plants on a large scale in the range of 20 MW to 100 MW.

Financial institutions such as PFC, IREDA, etc., may provide the required finance to park developers for site selection, preparatory works, preparation of detailed project reports, and for obtaining environment and forest clearances, etc.

The solar parks are required to be developed in collaboration with State Governments and their agencies. Developing and maintaining the solar parks are required to be done by the state designated agencies.

iii. Natural phenomena

Sites identified for CSP should avoid such areas with history of such natural phenomena such as earthquakes and storms as they generally have an impact on the costs of energy systems.

- **Bidding for CSP plants: Tariff based competitive bidding in a phased manner**

  i. Bidding for smaller capacities

  In order to promote CSP plants, the initial bidding may be carried out considering capacities in the range between 20 MW and 50 MW in the areas identified in solar parks. The selection of projects needs to be technology agnostic. Bidders may be invited with tariff based on capacity and number of hours of operation to deliver power.

  The timeline for bidding may be of the order of 180 days, to provide the potential bidders enough time to decide the technology, optimal capacity and select technology partner as well as EPC contractor. This will increase competition and result in lower price bids. This will also reduce the time for completion of the project after the award of the contract as the site being within the solar park and technology being agnostic, bidders would have finalized the technical details during the bid process.

  A bankable PPA between CSP project developers and the buyers of solar power would provide guaranteed payment to the project developers.

  ii. Bidding for larger capacities

  The success of initial round of bidding for smaller capacities would build bidder's confidence and provide platform for larger capacities. The next round of bidding could include larger capacity in the range between 50 MW and 100 MW in the areas identified in solar parks. The bidding parameters and the bidding methodology would be same as detailed above for smaller capacities. Future capacities may be increased to 150 MW and above.

- **Reducing import dependency**

  With the maturity of CSP in India, import dependency can be reduced in a phased manner, and encourage domestic manufacturing of CSP components under the Aatma Nirbhar Bharat scheme of the Government of India, with Govt. subsidies or incentives like PLI scheme, etc.

1. Introduction

India presented its ambitious commitment towards climate action at COP26 held in Glasgow, of reaching 500 GW Non-fossil energy capacity by 2030, amongst other commitments.[2] India's non-fossil fuel capacity was 157 GW out of total capacity of 392 GW[3] in November 2021 when the commitment was made.

TERI's discussion paper on "Roadmap to India's 2030 Decarbonization Target" (*https://www.teriin.org/sites/default/files/files/Roadmap-to-India-2030-Decarbonization- Target.pdf)*, termed setting up of 500 GW non-fossil fuel capacity by 2030 feasible though challenging.

The paper articulated that for achievement of India's 2030 targets announced at COP26, there is a need for creation of large storage projects, including setting up concentrated solar power (CSP) plants with storage. The paper spelt out that CSP plant with storage can deliver power on demand, making it an attractive renewable energy storage technology, and concluded that various measures would be required to be taken to develop CSP plants in the country in order to help reach the ambitious target of 500 GW by 2030.

2 PIB Release ID: 1795071 – India's Stand at COP26

3 CEA: Executive Summary on Power Sector, November-2021

2. Concentrated Solar Power (CSP) Plants

2.1 About Concentrated Solar Power (CSP) Plants[4]

Solar energy is the cleanest and most abundant energy source available. Among the various ways to harness this resource, there are three primary technologies by which solar energy is commonly harnessed: photovoltaics (PV), which directly convert light to electricity; concentrated solar power (CSP), which uses heat from the sun (thermal energy) to drive utility-scale, electric turbines; and heating and cooling systems, which collect thermal energy to provide hot water and air conditioning.

2.2 Working principle of CSP system

The CSP system operates using solar concentrator (or solar mirror field) which reflect the incident solar radiation to the solar receiver. The heat transfer media (HTM) flowing in the solar receiver absorb the concentrated solar radiation through the receiver wall increasing its temperature. The high-temperature HTM transfers heat to the working fluid in the heat exchanger which increases the temperature and pressure of the working fluid, which drives the turbine to generate electric power.

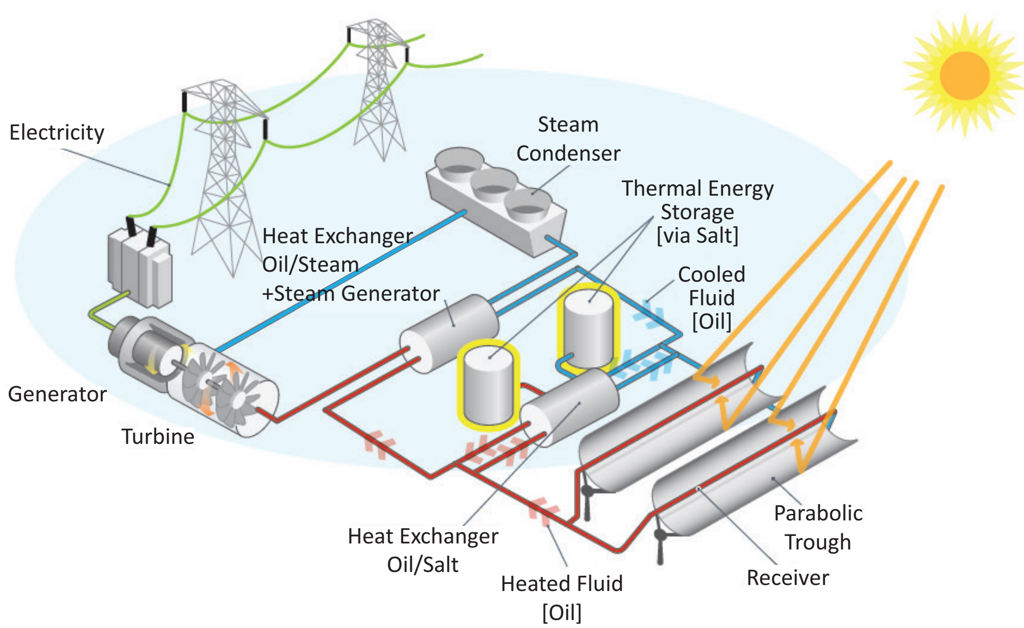

Figure 1: Working principle of CSP

[4] TERI compilation based on: World Bank, 2021- Concentrating Solar Power: Clean Power on Demand 24/7; https://www.seia.org/sites/default/files/inline-files/SEIA-Solar-Energy-Technologies-Factsheet-2018-April.pdf; Wang et al., 2022

Box-1

Tiny solid and liquid particles suspended in the atmosphere are called aerosols. Windblown dust, sea salts, volcanic ash, smoke from wildfires, and pollution from factories are all examples of aerosols. Satellite measurements of aerosols, called aerosol optical thickness, are based on the fact that the particles change the way the atmosphere reflects and absorbs visible and infrared light. An optical thickness of less than 0.1 (palest yellow) indicates a crystal-clear sky with maximum visibility, whereas a value of 1 (reddish brown) indicates very hazy conditions (https://earthobservatory.nasa.gov/global- maps/MODAL2_M_AER_OD#:~:text=An%20opt ical%20thickness%20of%20less,places%20and%2 0times%20of%20year

CSP systems are subject to periodic timeliness of solar energy as well as variation in solar radiation intensity during cloudy and rainy weather.

Thermal energy storage (TES) can provide heat for CSP systems when the solar radiation is insufficient.

Heat transfer media (HTM) refers to the fluid or other material that is used to transport heat from the solar receiver to TES and from TES to the turbine or industrial process. Existing CSP plants use a liquid, molten nitrate salts, as both the TES and HTM.

Direct normal irradiance (DNI) or direct sunlight, available at a given site, is the primary driver of a CSP plant's performance. Typical requirement of annual DNI threshold is between 1,900 and 2,100 kWh/m^2. Sites with suitable DNI for CSP are found in arid and semi-arid areas with reliably clear skies and low aerosol optical depths (Box-1).

Apart from DNI, HTMs are important for CSP systems and their accessory TES devices. TES devices are important for CSP systems as they can ensure the long-time stable solar power output even in conditions of low solar radiation due to cloudy and rainy weather, and also during night. Thus, the performances of HTMs can impact the operational behavior of CSP systems along with TES devices.

2.3 Current CSP technologies for power production[5]

At present, there are four main CSP technologies, which can be categorised by the way they *focus* the sun's rays and the technology used to *receive* the sun's energy, namely,

(i) focus type: linear focus, point focus and (ii) receiver type: fixed, mobile. Table 1 presents the four CSP technologies.

[5] IEA Report on " Technology Roadmaps: Concentrating Solar Power

Table 1 The four CSP technologies

Focus type		Line focus	Point focus
Receiver type		Collectors track the sun along a single axis and focus irradiance on a linear receiver. This makes tracking the sun simpler	Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows for higher temperatures
Fixed	Fixed receivers are stationary devices that remain independent of the plant's focussing device. This eases the transport of collected heat to the power block.	Linear Fresnel Reflectors	Towers (CRS)
Mobile	Mobile receivers move together with the focussing device. In both line focus and point focus design, mobile receivers collect more energy.	Parabolic Troughs	Parabolic Dishes

Source: IEA Report on " Technology Roadmaps: Concentrating Solar Power

Linear Fresnel reflectors (line focus, fixed receiver): Linear Fresnel reflectors (LFRs) resemble the parabolic shape of trough systems but by using long rows of flat or slightly curved mirrors to reflect the sun's rays onto a downward-facing linear, fixed receiver.

Compact linear Fresnel reflectors (CLFRs), use two parallel receivers for each row of mirrors.

The main advantage of LFR systems is that their simple design of flexibly bent mirrors and fixed receivers requires lower investment costs and facilitates direct steam generation (DSG), thereby eliminating the need for – and cost of – heat transfer fluids and heat exchangers. LFR plants are, however, less efficient than troughs in converting solar energy to electricity and it is more difficult to incorporate storage capacity into their design.

Solar towers (point focus, fixed receiver)

Solar towers, also known as central receiver systems (CRS), use hundreds or thousands of small reflectors (called heliostats) to concentrate the sun's rays on a central receiver placed atop a fixed tower. Some commercial tower plants now in operation use DSG in the receiver; others use molten salts as both the heat transfer fluid and storage medium.

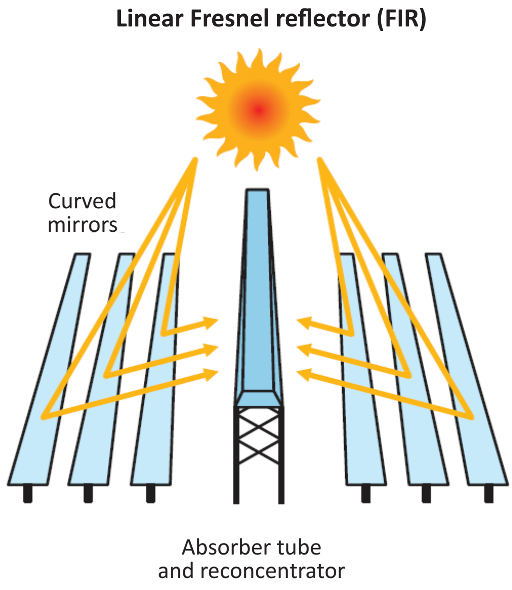

Figure 2: Linear Fresnel reflectors

The concentrating power of the tower technology achieves very high temperatures, thereby increasing the efficiency at which heat is converted into electricity and reducing the cost of thermal storage. In addition, the technology is highly flexible; designers can choose from a wide variety of heliostats, receivers, transfer fluids and power blocks.

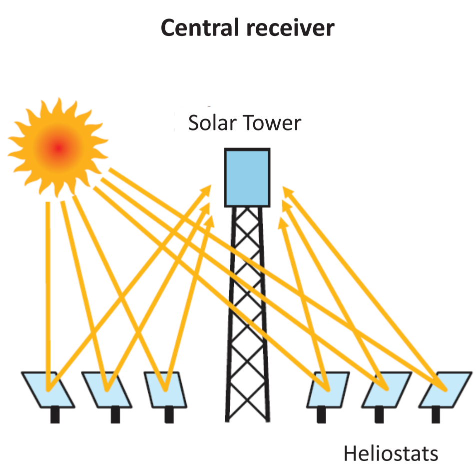

Figure 3: Central receiver system

Parabolic troughs (line focus, mobile receiver)

Parabolic trough systems consist of parallel rows of parabolic shaped mirrors (reflectors) to focus the sun's rays. The mirror arrays can be more than 100 m long with the curved surface 5 m to 6 m across. Stainless steel pipes (absorber tubes) with a selective coating serve as the heat collectors.

The coating is designed to allow pipes to absorb high levels of solar radiation while emitting very little infra-red radiation. The pipes are insulated in an evacuated glass envelope. The reflectors and the absorber tubes move in tandem with the sun as it crosses the sky.

All parabolic trough plants currently in commercial operation rely on synthetic oil as the fluid that transfers heat (the heat transfer fluid) from collector pipes to heat exchangers, where water is preheated, evaporated and then superheated. The superheated steam runs a turbine, which drives a generator to produce electricity. After being cooled and condensed, the water returns to the heat exchangers.

Parabolic trough

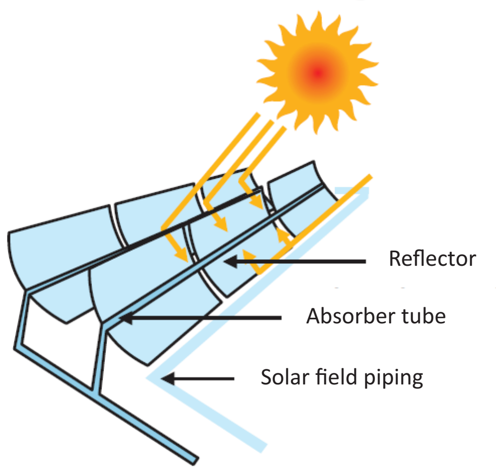

Figure 4: Parabolic trough

Parabolic troughs are the most mature technology amongst other CSP technologies and form the bulk of current commercial plants. Most existing plants, however, have little or no thermal storage and rely on combustible fuel as a backup to firm capacity. For example, all CSP plants in Spain derive 12% to 15% of their annual electricity generation from burning natural gas. Some newer plants have significant thermal storage capacities.

Parabolic dishes (point focus, mobile receiver)

Parabolic dishes concentrate the sun's rays at a focal point placed above the centre of the dish. The entire apparatus tracks the sun, with the dish and receiver moving in tandem. Most dishes have an independent engine/generator (such as a Stirling machine or a micro-turbine) at the focal point. This design eliminates the need for a heat transfer fluid and for cooling water. Dishes offer the highest solar-to-electric conversion performance of any CSP system.

Parabolic dishes are limited in size (in kW range) and each produces electricity independently, which means that number of Parabolic dishes would need to be co-located to create a large-scale plant. By contrast, other CSP designs (towers, LFR and parabolic) capacities range from 1 MW to 100 MW and above.

Parabolic dish

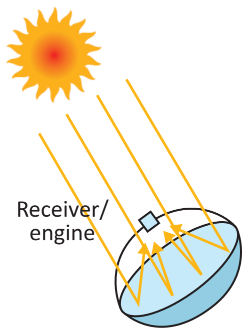

Figure 5: Parabolic dish

The key features of the four CSP technologies are presented in Table 2.[6]

Table 2: Key features of CSP technologies

Features	Parabolic Trough	Central Receiver	Compact Linear Fresnel	Parabolic Dish
Maximum fluid temperature (°C)	390 - 550	250 - 565	270	>800
Annual Capacity Factor (%)	25-28 (no TES) 29-43 (with TES)	55 (with 10h TES)	22-24	25-28
Collection Concentration (suns)	70-80	>1,000	>60 suns (with secondary reflector)	>1,300
Steam Conditions (°C/bar)	380-540/100	540/100-160	260/50	Not applicable
Water Requirement (m^3/MWh)	3 (wet cooling) 0.3 (dry cooling)	2-3 (wet cooling) 0.25 (dry cooling)	3 (wet cooling) 0.2 (dry cooling)	0.05-0.1 (mirror washing)
Land use (ha/MW)	2	2-2.5	2.5	1-1.5

[6] USDOE - National Solar Thermal Facility (NSTTF) presentation: Next Generation Concentrating Solar Energy for the 21st Century"; IEA-ETSAP and IRENA,2013: Concentrating Solar Power | Technology Brief

3. Global Status of CSP

3.1 Background[7]

Globally, CSP is a proven technology. The first commercial operation of plants began in California during the period 1984 to 1991, encouraged by federal and state tax incentives and mandatory long-term power purchase contracts. A drop in fossil fuel prices then led the federal and state governments to discontinue the policy framework that had supported the development of CSP. CSP market re-emerged again in 2006, in Spain and the United States, due to government measures such as feed-in tariffs (Spain) and policies obliging utilities to obtain some share of renewable power (from large solar in particular). In the early 2010, global CSP capacity was about 1 GW, which grew to about 6.2 GW as on 2023. Spain with 2.3 GW leads the global CSP capacities, followed by USA (1.5 GW), China (596 MW), Morocco (533 MW) and South Africa (500 MW).

Operational CSP capacities and average solar irradiance of major countries as on 2023 is shown in Figure 6.

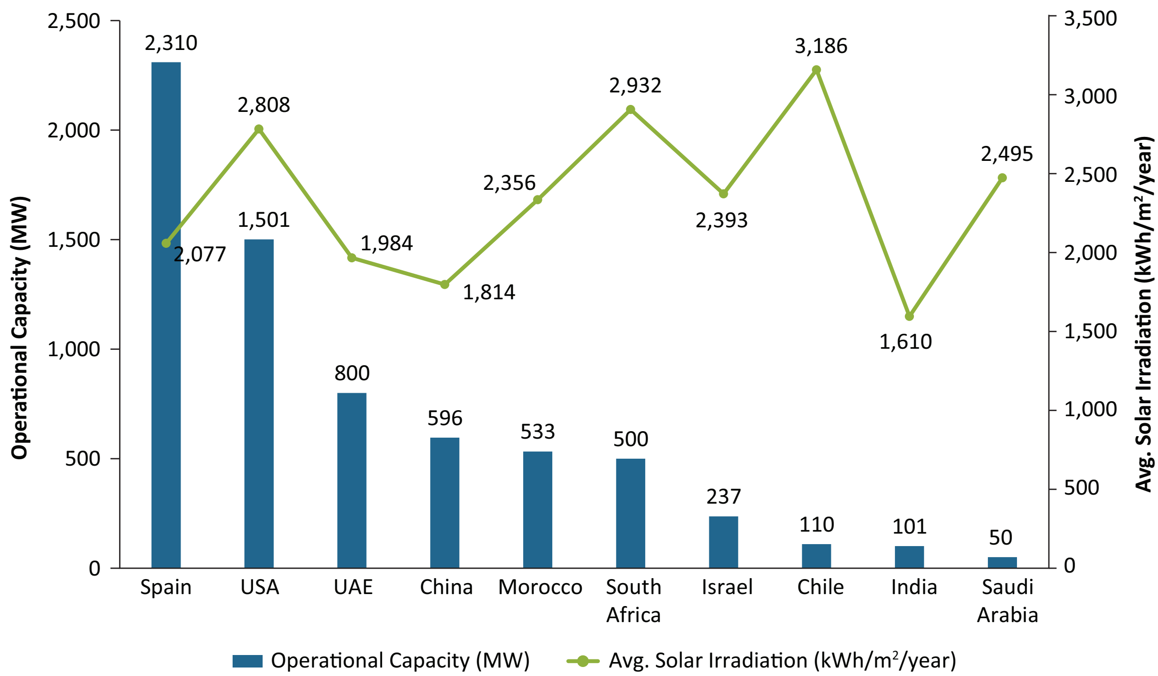

Figure 6: Operational CSP capacities & avg. solar irradiance of major countries

Source: TERI Analysis

Among the CSP technologies, Parabolic Troughs account for about 76% of the current share of CSP capacity, followed by Power Tower (21%), Linear Fresnel (2%) and Beam Down (1%), as shown in Figure 7.

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[7] TERI compilation based on: IEA: Technology Roadmaps-Concentrating Solar Power; International Journal of Thermo-fluids: Concentrating solar power (CSP) technologies: Status and analysis.

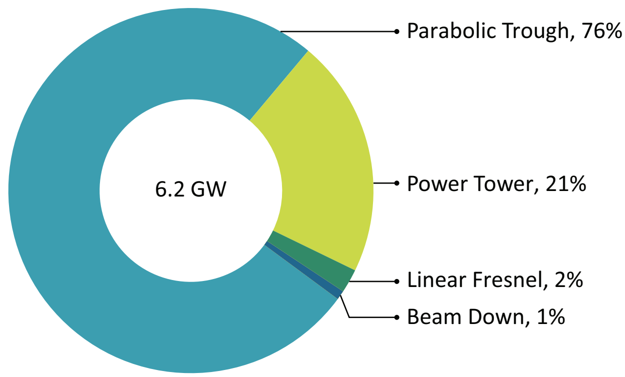

Figure 7: Share of CSP technologies (2023)

Source: TERI Analysis

3.2 Global CSP: Installed cost, thermal storage, capacity factor, LCOE

3.2.1 Installed cost[8]

The cost component in respect of Parabolic Trough Collector (PTC) based CSP and Solar Tower (ST) based CSP are detailed in Tables 3 and 4, respectively.

In Parabolic Trough Collector (PTC) based CSP, the cost component of solar field contributes the major share in the total installed cost, followed by the cost of Balance of Plant & Engineering, etc., Power Block, Receiver/ Contingencies, Thermal energy storage, and Tower. The installed cost declined from USD 10,265/kW in 2010 to USD 4,761/kW in 2020, indicating an annual average decline of around 7.4% in the cost during this period. The installed cost breakdown of PTC based CSP plant in 2010 and 2020 is presented in Table 3.

Table 3: PTC based CSP cost component, (2010 and 2020)

Particulars	Installed cost (USD/kW) 2010	Share of cost (%)	Installed cost (USD/kW) 2020	Share of cost (%)	Average annual Decline in Cost (%)
Solar field	4,503	44%	1,440	30%	10.8%
Power Block	1,499	15%	892	19%	5.1%
HTF system	948	9%	503	11%	6.1%
Thermal energy storage	873	9%	706	15%	2.1%
Balance of plant, Engineering, etc.	1,598	16%	859	18%	6.0%
Contingencies	845	8%	361	8%	8.2%
Total	**10,265**	**100%**	**4,761**	**100%**	**7.4%**

Source: TERI Compilation

8 IRENA: Renewable Power Generation Costs, 2022

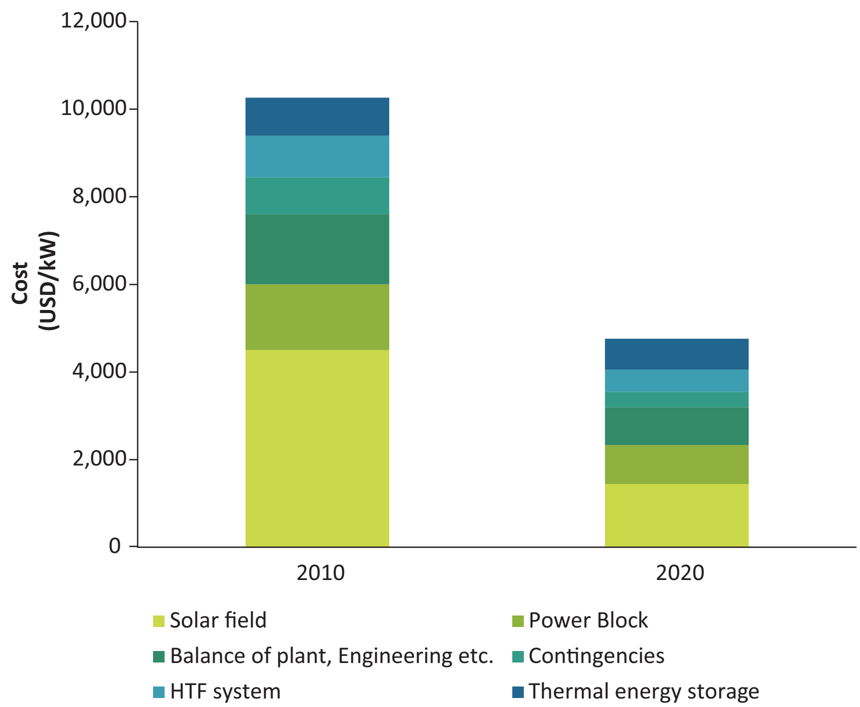

Figure 8: Component wise cost of Parabolic Trough CSP in 2010 and 2020

Source: TERI Analysis

Similarly, in Solar Tower (ST) based CSP, the total installed cost is majorly due to Heliostat field, followed by the cost of balance of plant & engineering, etc., power block, receiver / contingencies, thermal energy storage, and tower. The installed cost declined from USD 18,909/kW in 2011 to USD 6,354/kW in 2019, indicating an average annual fall in cost of around 12.7% from 2011 to 2019. The total installed cost breakdown of ST based CSP plant in 2011 and 2019 is presented in Table 4.

Table 4: ST based CSP cost component, (2011 and 2019)

Particulars	Installed cost (USD/kw) 2011	Share of cost (%)	Installed cost (USD/ kw) 2019	Share of cost (%)	Average annual Decline in Cost (%)
Heliostat field	5,916	31%	1,768	28%	14.0%
Receiver	3,069	16%	876	14%	14.5%
BoP & Engineering, etc.	3,988	21%	1,086	17%	15.0%
Power Block	2,339	12%	993	16%	10.2%
Thermal energy storage	1,763	9%	622	10%	12.2%
Contingencies	1,520	8%	878	14%	6.6%
Tower	315	2%	130	2%	10.5%
Total	**18,909**	**100%**	**6,354**	**100%**	**12.7%**

Source: TERI Compilation

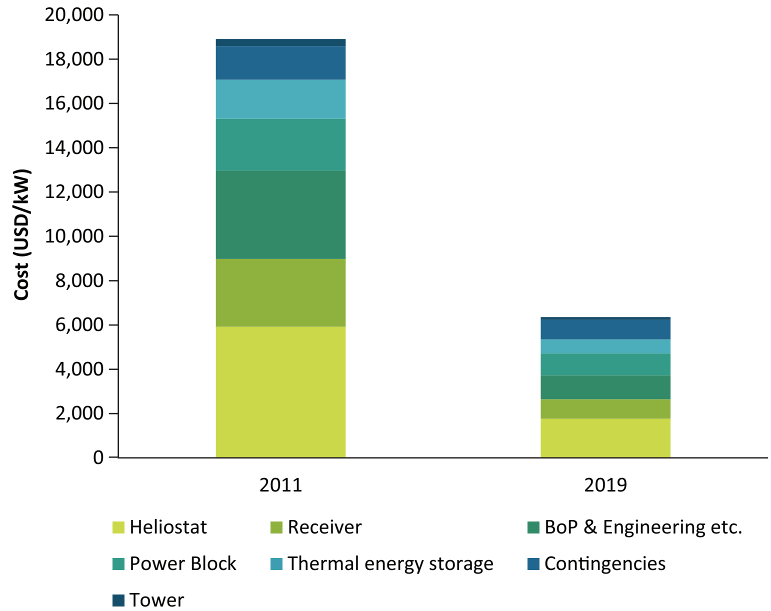

Figure 9: Component wise cost of Solar Tower CSP in 2011 and 2019

Source: TERI Analysis

3.2.2 Thermal storage[9]

Declining cost of thermal energy storage with the maturity of market have led to the increase in storage capacity. Both declining costs and higher operating temperatures, which allow larger temperature differentials in the storage systems, have resulted in an increase in the weighted average number of storage hours through time. Between 2010 and 2020, the average storage hours rose from 3.5 hours to 11 hours (three-fold increase). The 110 MW Cerro Dominador project in Chile which started in 2021 features the highest known storage capacity in the world, at 17.5 hours. The average storage hours in 2019 and 2022 were 9.1 and 9.0 hours, respectively.

The average project size and average storage hours of CSP projects between 2010 and 2022 is shown in Figure 10.

3.2.3 Capacity factor[10]

At a given location, the quality of solar resources, along with the technology configuration, are the determining factors for achieving the desired capacity factor. The excellent solar resource in Chile's Atacama Desert, the location of the Cerro Dominador CSP project, provided a very high-capacity factor value of 80% when the project started in 2021.

[9] IRENA: Renewable Power Generation Costs, 2023

[10] IRENA: Renewable Power Generation Costs, 2023

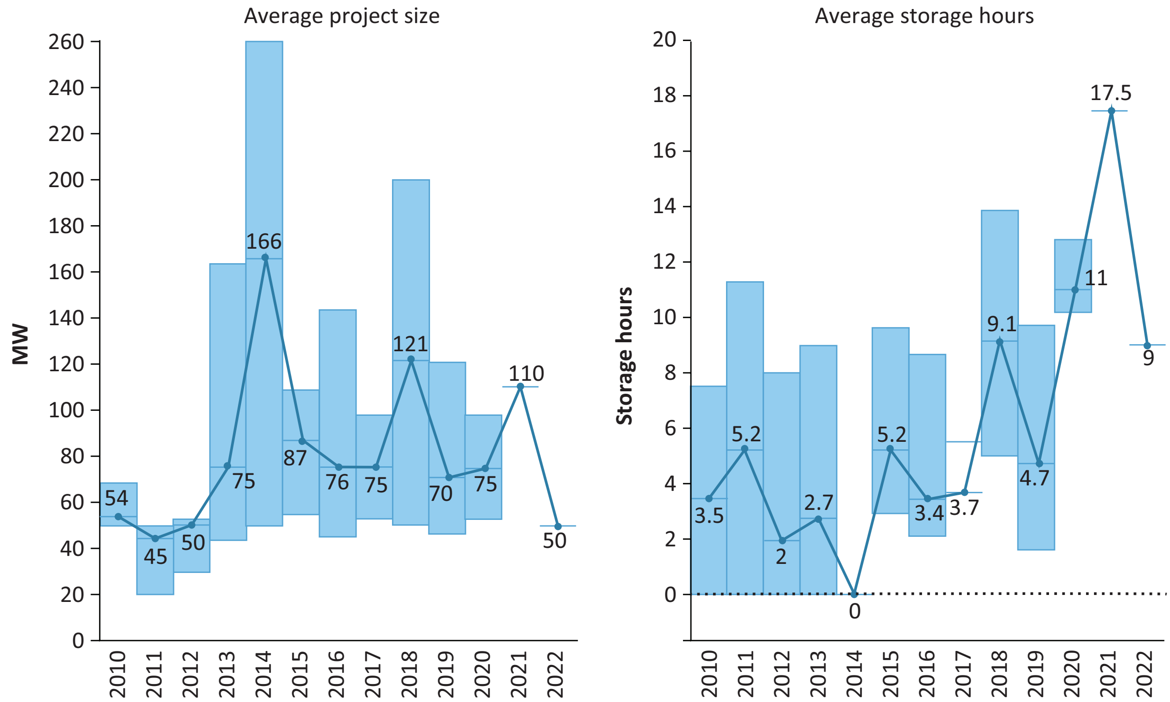

Figure 10: Average project size and average storage hours of CSP projects between 2010 and 2022

Source: IRENA: Renewable Power Generation Costs, 2023

Falling costs of thermal storage and increased operating temperatures have been important developments in improving the economics of CSP, over the last decade. For a given DNI level and plant configuration conditions, higher HTF temperatures allow for a larger temperature differential between the "hot" and "cold" storage tanks, which provide for greater storage duration and energy for a given physical storage size. Over time, CSP projects have been commissioned with longer storage durations. Figure 11 presents the correlation between capacity factor & storage hours and between capacity factor & DNI.

The increasing capacity factors for CSP plants due to increased storage capacity and increased DNI can be seen from above figures. The global weighted average capacity factor of newly-commissioned plants increased from 30% in 2010 to 42% in 2020 and further to 80% in 2021, with improved technology, declining costs of thermal energy storage and increased storage hours.

3.2.4 Operation and Maintenance Cost[11]

The operation & maintenance (O&M) costs (including insurance and other asset management costs) for all CSPs are substantial, as compared to solar PV and onshore wind. The O&M cost

[11] IRENA: Renewable Power Generation Costs-2023

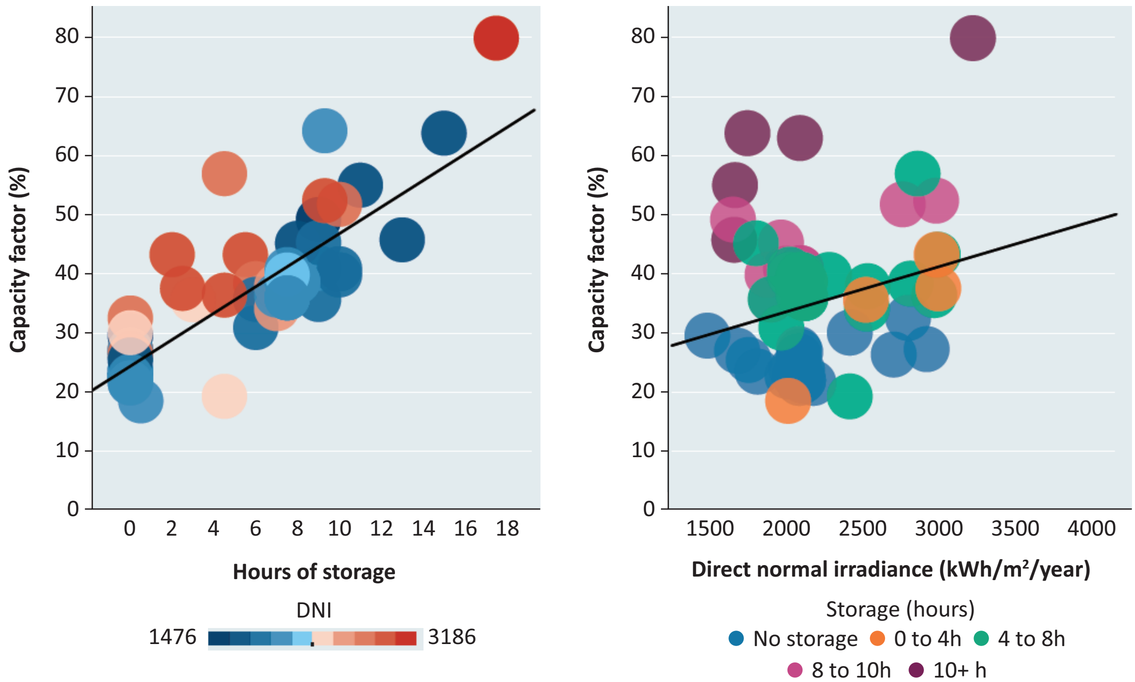

Figure 11: Correlation between capacity factor & storage hours and between capacity factor & DNI

Source: IRENA: Renewable Power Generation Costs, 2023

vary from location to location, depending on differences in irradiation, plant design, technology, labour costs and individual market component pricing. The expenditure on receiver and mirror replacements, formed the largest individual O&M cost for CSP plants in the early period of CSP development. Maturity of market, experience over time, as well as new designs and improved technology have helped in reduced failure rates for receivers and mirrors, thereby driving down these costs.

The O&M costs for early CSP plants built in around 2010 globally, which are still in operation today range between USD 0.02/kWh and USD 0.04/kWh. The O&M cost estimates (insurance included) for CSP plants in selected markets are shown in Table 5.

3.2.5 Levelized cost of electricity[12]

With the decline in installed costs, O&M costs and financing costs with rise in capacityfactors, the LCOE for CSP too declined significantly between 2010 and 2022. During this period, the global weighted average LCOE of newly commissioned CSP plants declined 69%, from USD 0.380/kWh to USD 0.118/kWh, as shown in Figure 12.

[12] IRENA: Renewable Power Generation Costs-2023

Table 5: O&M cost estimates (insurance included) for CSP plants in selected markets

Country	Parabolic trough collectors (2022 USD/kWh)	Solar tower (2022 USD/kWh)
Argentina	0.028	0.026
Australia	0.030	0.029
Brazil	0.022	0.022
China	0.024	0.020
France	0.035	0.030
India	0.017	0.017
Italy	0.028	0.026
Mexico	0.018	0.017
Morocco	0.014	0.013
Russian Federation	0.027	0.025
Saudi Arabia	0.013	0.012
South Africa	0.014	0.013
Spain	0.027	0.025
Türkiye	0.020	0.018
United Arab Emirates	0.020	0.022
United States of America	0.027	0.024

Source: IRENA: Renewable Power Generation Costs-2023

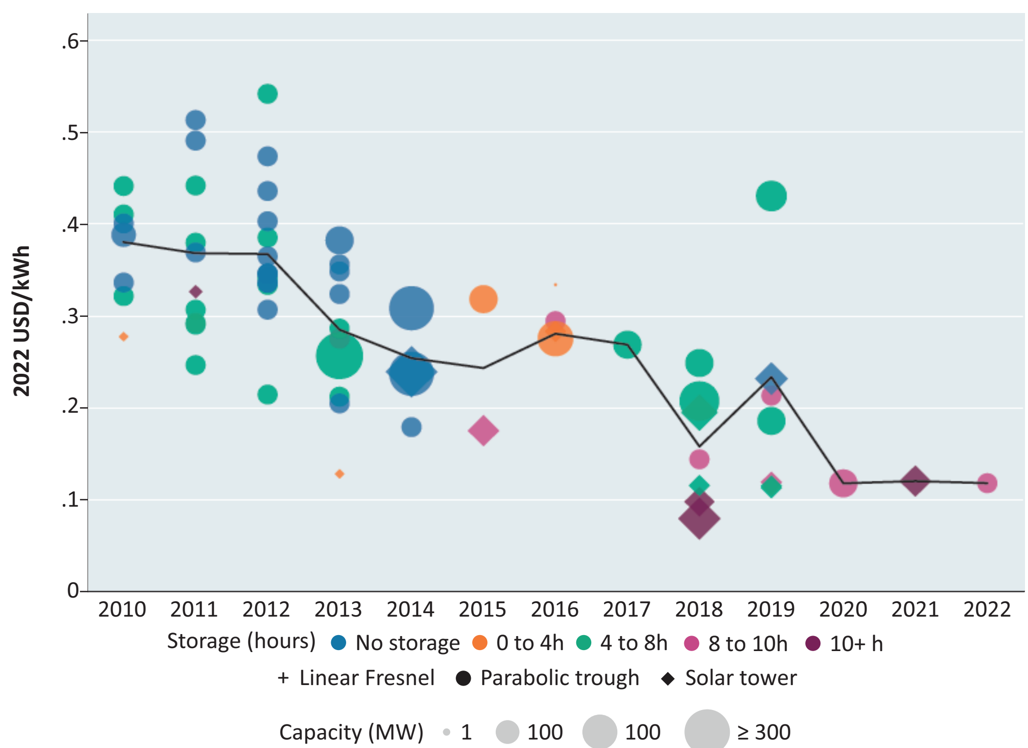

Figure 12: Declining LCOE from 2010 to 2022

Source: IRENA: Renewable Power Generation Costs-2023

The decline in global weighted average LCOE of CSP from USD 0.380/kWh in 2010 to USD 0.118/kWh in 2022 along its main constituents is presented in the figure below.

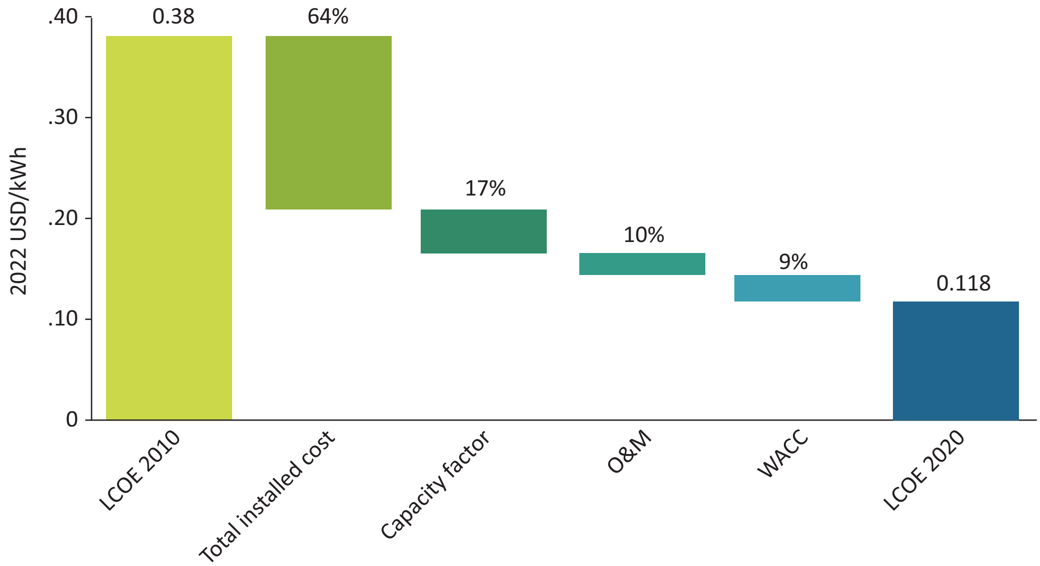

Figure 13: Decline in LCOE from 2010 to 2020 along with its main constituents

Source: IRENA: Renewable Power Generation Costs-2023

The largest share of decline of 64% is due to fall in the total installed cost of CSP plants over the period. Improvements in technology and longer storage duration due to cost reductions in thermal energy storage, have led to improvement in capacity factor, which accounted for 17% reduction in LCOE. Lower O&M costs and reduction in weighted average cost of capital accounted for decline of 10% and 9% respectively, in LCOE during the above period. Increasing experienced developers over time, also accounted for reduction in costs during the stages of development, construction and commissioning. The global weighted total installed costs, capacity factors and LCOE for CSP during the period from 2010 to 2022 is presented in Figure 14.[13]

3.3 Development of CSP plants in leading countries

3.3.1 Development of CSP plants in Spain[14]

Spain has about 2.3 GW of CSP plants operating as on 2023, consisting of about 96.4% of Parabolic Trough based CSP, 2.2% of Power Tower based CSP and about 1.4% of Linear Fresnel based CSP, as shown in Figure 15.

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[13] IRENA: Renewable Power Generation Costs-2023

[14] TERI compilation based on: " IJTF: Concentrating solar power (CSP) technologies: Status and analysis; solarPACES: Spain-Latest CSP in Development:2023; Greenpeace-Estia-SolarPACES: Concentrated Solar Thermal Power-Now, 2005

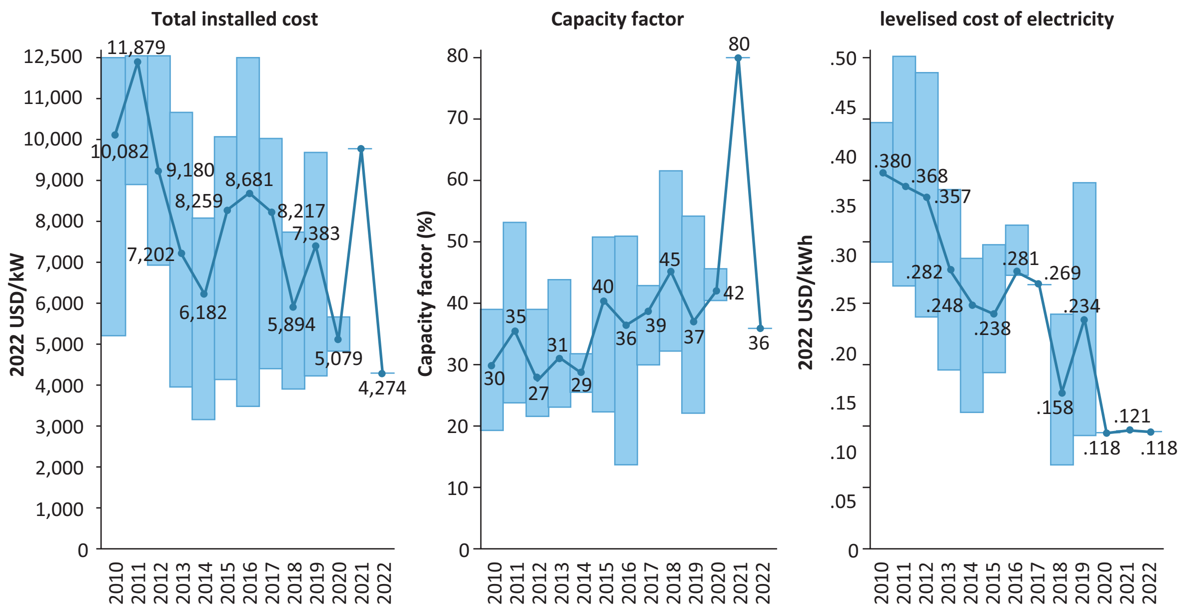

Figure 14: Global weighted total installed cost, capacity factor and LCOE for CSP, 2010-2022

Source: IRENA: Renewable Power Generation Costs-2023

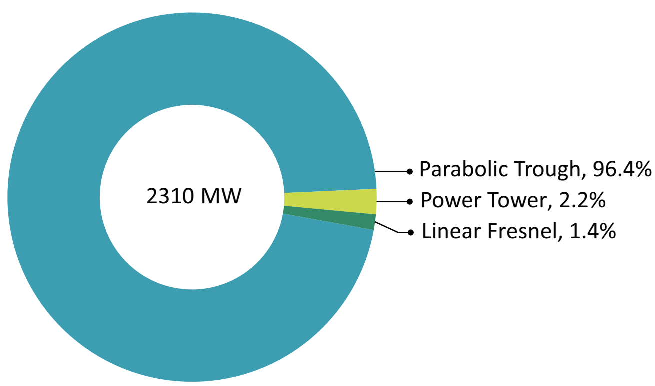

Figure 15: Operating CSPs in Spain

Source: TERI analysis

Spain's bulk capacity is from CSP plants employing parabolic trough technology as given above, comprises mostly of 50 MW; capacity of CSP plants with power tower technology ranges between 11 MW and 20 MW and capacity of two CSP plants with Linear Fresnel technology are 1.4 MW and 30 MW. The annual solar irradiance ranges between 1,878 and 2,260 kWh/m^2. The growth of CSP plant capacity from 2007 to 2013 is shown in Figure 16.

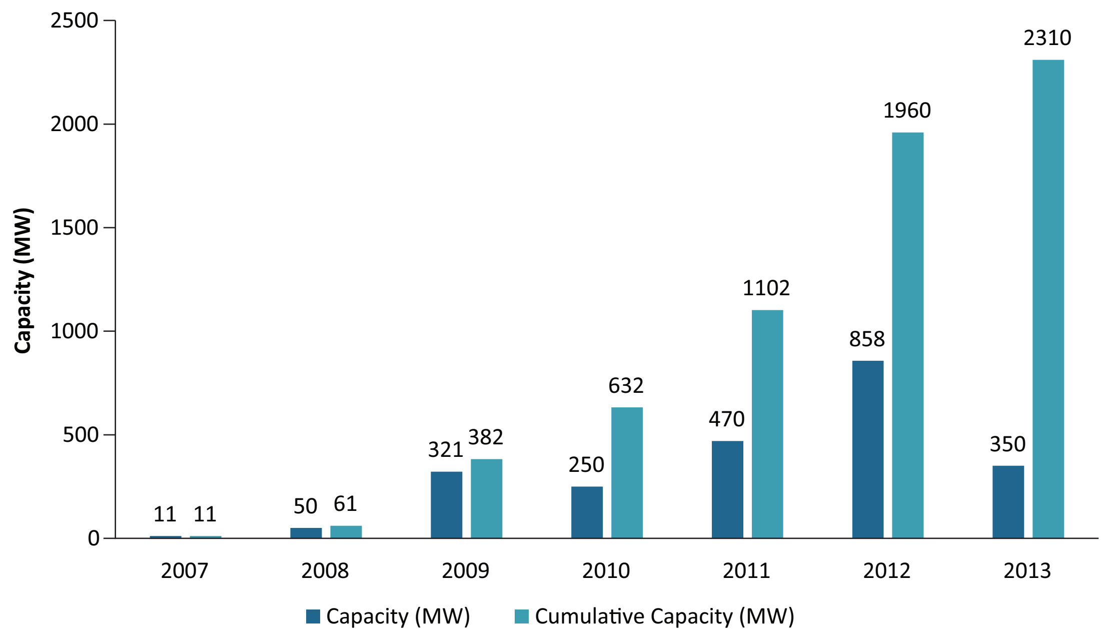

Figure 16: Growth of CSP plant capacity from 2007 to 2013

Source: TERI analysis

In September 2002, Spain was the first European country to introduce a “feed-in tariff” funding system for concentrating solar thermal power. This funding system granted a premium payment of 12 € cents for each kWh output of a solar thermal plant between 100 kW and 50 MW capacity, which could be changed every four years. It turned out that this was not bankable and that the amount did not cover the cost and risks to make the initial projects feasible.

The Spanish Royal Decree 436 in 2004, increased the solar thermal feed-in premium by 50% from 12 to 18 € cents/kWh and made solar thermal power projects bankable again, as they were during the time of California’s Standard Offers in the late 1980s.

The main elements of Spain’s Royal Decree are:

- To grant the same tariffs for PV and solar thermal from 100 kW to 50 MW with a premium on top of the electricity pool price of 0.18 €/kWh, which roughly equates to a total price of 0.21€/kWh
- Bankable with 25-year guarantee
- Annual adaptation to electricity price escalation
- 12-15% natural gas back-up allowed to grant ‘dispatchability’ and reliable capacity

Following an increase in the Spanish solar thermal incentive premium from 12 to 18 € cents/kWh in March 2004, numerous 50 MWe solar thermal parabolic trough project developments were started.

The "Feed-in-tariff" regulations of RD 436/2004 were refined with Royal decree 661/2007, with respect to the decoupling from the market reference price, which increased with oil price increases and automatically increased renewable tariffs with the oil price. A fixed tariff of 0.269375 Euro/kWh was granted for CSP plants up to 50 MW for 25 years, increasing yearly with inflation minus 1 percent point.

In January 2012, the feed-in tariff (FiT) programme 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.

Seven CSP projects totaling 350 MW were completed in 2013. As of 2023, 51 CSP plants with an aggregate capacity of 2.3 GW are in operation.

3.3.2 Development of CSP in USA[15]

USA has about 1.5 GW of CSP plants operating as on 2023, consisting of about 67% of Parabolic Trough based CSP and 33% of Power Tower based CSP, as shown in Figure 17.

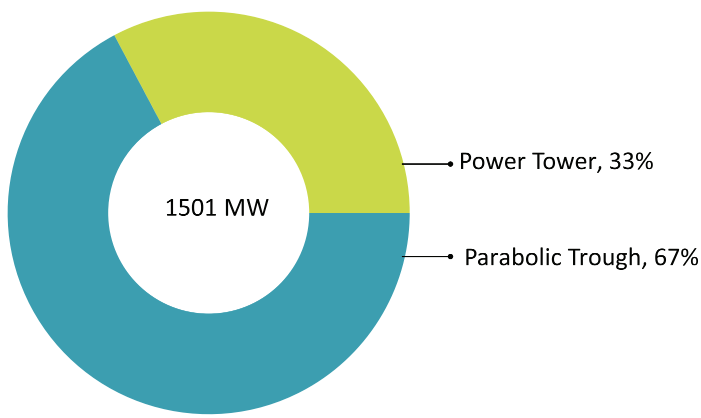

Figure 17: Operating CSPs in USA

Source: TERI analysis

[15] TERI compilation based on: " IJTF: Concentrating solar power (CSP) technologies: Status and analysis; DOE: Loan Programs Office – Powering New Markets: Energy Storage, 2016

The CSP capacity developed till 2010, were in the range between 5 MW and 80 MW. In 2013, the first 250 MW Parabolic Trough CSP (Solana) was commissioned, followed by Power Tower based CSP of 377 MW (Ivanpah), two Parabolic Trough based CSP of 280 MW (Mojave) and 250 MW (Genesis) were commissioned in 2014. In 2015, one Power Tower based CSP of 110 MW (Crescent Dunes) and one 2 MW (Stillwater GeoSolar) were commissioned in 2015. The annual solar irradiance ranges between 1,799 and 2,987 kWh/m^2.

The growth of CSP plant capacity from 1976 to 2015 is shown in Figure 18.

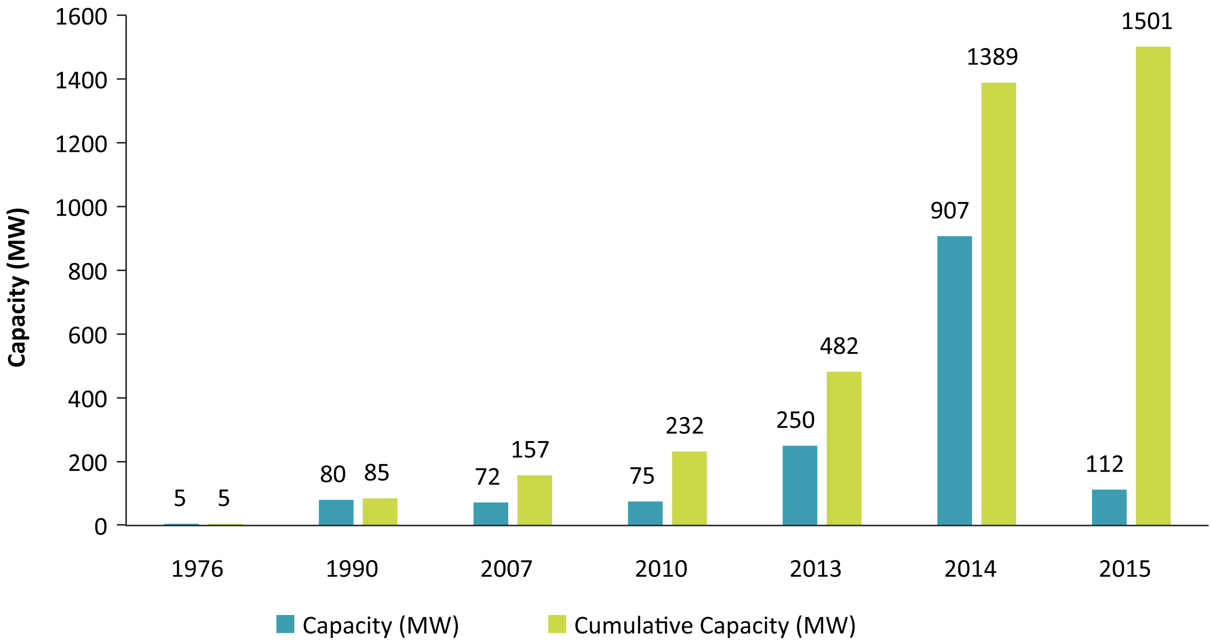

Figure 18: Growth of CSP capacity from 1976 to 2015

Source: TERI Analysis

The demand for CSP was created in the United States mainly due to the ability of CSP, and especially CSP with thermal energy storage, to provide solar on demand and improve grid integration for renewables.

Loan Programs Office (LPO) played a crucial role in financing which enabled the construction of five of the world's largest CSP projects, as detailed in Table 6. The first CSP power tower in the country (Ivanpah in California), the first CSP plant with thermal energy storage in the country (Solana in Arizona) and the CSP power tower with thermal energy storage (Crescent Dunes in Nevada). Two Parabolic Trough based CSP (Mojave and Genesis in Mojave Desert). All five projects are operational.[16]

[16] U.S. DOE: LPO-Powering New Markets: Energy Storage Poised for Growth, October 2016; US DOE: Concentrating Solar Power Projects; IJTF: Concentrating solar power (CSP) technologies: Status and analysis

Table 6: CSP projects developed with support from LPO

S. No.	CSP Plant	Capacity (MW)	CSP Technology	Year of commissioning
1.	Solana	250	Parabolic Trough with thermal energy storage	2013
2.	Ivanpah	377	Power Tower	2014
3.	Mojave	280	Parabolic Trough	2014
4.	Genesis	250	Parabolic Trough	2014
5.	Crescent Dunes	110	Power Tower with thermal energy storage	2015
	Total	**1,267**		

Source: TERI Compilation

Development of CSP in USA as per SETO Multi-Year Program Plan[17]

The U.S. Department of Energy's Solar Energy Technologies Office (SETO) launched the SunShot Initiative in 2011, to make solar-generated electricity competitive with conventional sources by 2020 across most of the country. Utility scale PV installations achieved the goal three years early. In 2020, large utility-scale PV systems generated electricity at a levelized cost of 5 ¢/kWh in locations with average solar radiance and 3 ¢/kWh in the sunniest parts of the country, making solar based generation the least expensive form of electricity generation.

The reduction in cost along with solar policy incentives led to rapid growth in solar PV generation capacity from less than 0.1% of the U.S. electricity supply in 2011 to over 3% in 2020.

Compared to Solar PV, CSP had not achieved widespread adoption in the U.S. Further adoption needed reaching lower costs of CSP through technology advancements and increase in private-investment by reducing financial risk associated with emerging technology.

In 2016, SETO set a goal for CSP with 14 hours of thermal energy storage to provide electricity at an LCOE of 6.5 ¢/kWh by 2025 and 5 ¢/kWh by 2030. Reaching the goal by 2030 needed multiple performance and cost improvements, which includes cost reductions for the collector field, receiver, energy storage, and operations and maintenance. The three scenarios considered by SETO that would achieve LCOE target for CSP are shown in Table 7.

The low-cost scenario focused on reduced cost with only a marginal improvement in efficiency. The high-performance scenario focused on increasing the power block's efficiency, with higher costs for the system components to achieve the same target LCOE. An intermediate scenario matches the high-performance scenario except for the field cost, which matches the low-cost scenario, thereby reducing the required net power-cycle efficiency to 50%.

[17] U.S.DOE: SETO Multi-Year Program Plan, May 2021; U.S.DOE: 2030 Solar Cost Targets, August 2021

Table 7: Benchmark parameters for a 100 MW CSP system with 14 hours storage along with SETO's with three scenarios

Parameter	2018 Benchmark	2030 Low-Cost	2030 Intermediate	High-Performance scenari
Net power-cycle efficiency	37%	40%	50%	55%
Power block cost	\$1330/$kW_{ac\text{-}gross}$	\$700/$kW_{ac\text{-}gross}$	\$900/$kW_{ac\text{-}gross}$	\$900/$kW_{ac\text{-}gross}$
Solar field cost	\$140/m^2	\$50/m^2	\$50/m^2	\$70/m^2
Site preparation cost	\$16/m^2	\$10/m^2	\$10/m^2	\$10/m^2
Tower and receiver cost	\$137/$kW_{thermal}$	\$100/$kW_{thermal}$	\$120/$kW_{thermal}$	\$120/$kW_{thermal}$
Thermal storage cost	\$22/$kWh_{thermal}$ year	\$10/$kWh_{thermal}$	\$15/$kWh_{thermal}$	\$15/$kWh_{thermal}$
Levelized O&M cost	\$9/$kW_{thermal}$ per year	\$6/$kW_{thermal}$ per year	\$7/$kW_{thermal}$ per year	\$7/$kW_{thermal}$ per year
Levelized capacity factor	68.9%	69.2%	70.7%	71%
LCOE (2019 US\$)	**9.8¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**

Source: US DOE: 2030 Solar Costs Targets

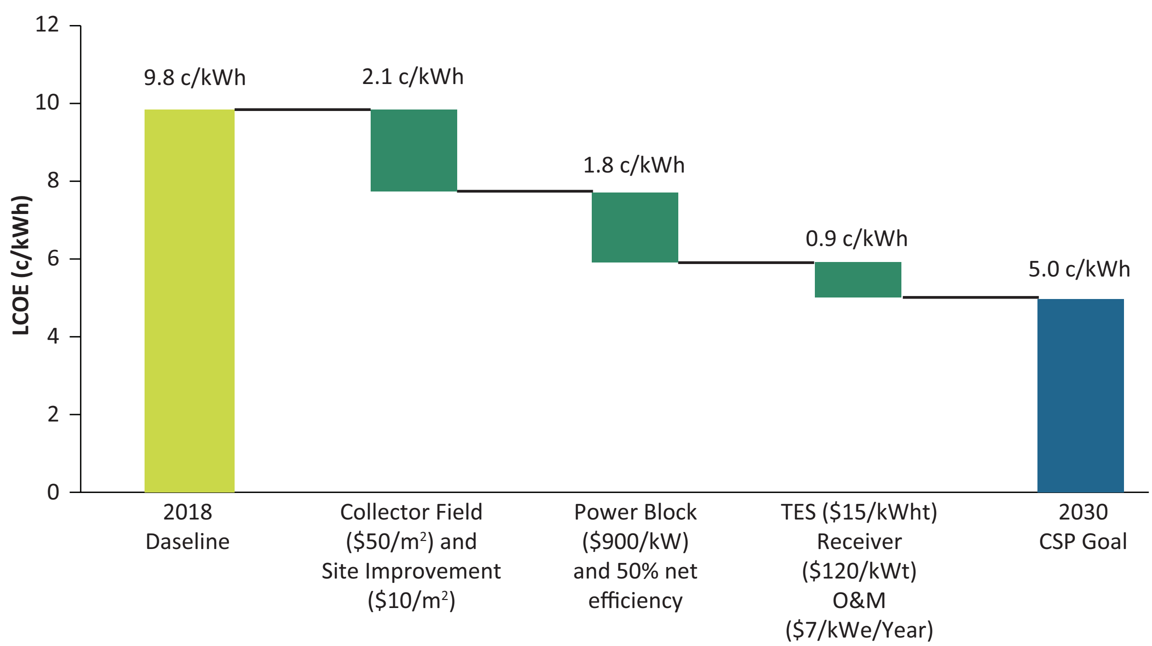

Figure 19: Performance and cost improvements contribute to reach the 2030 target for CSP LCOE

Source: TERI Analysis

Figure 19 illustrates how the individual improvements in key parameters achieve LCOE targets for the intermediate scenario shown in Table 7.

3.3.3 Development of CSP in China[18]

China has about 596 MW of CSP plants operating as on 2023, consisting of about 25% of Parabolic Trough based CSP, 54% of Power Tower based CSP, 13% of Linear Fresnel based CSP, and 8% of Beam-Down Tower based CSP, as shown below. The annual solar irradiance ranges between 1,290 and 2,170 kWh/m².

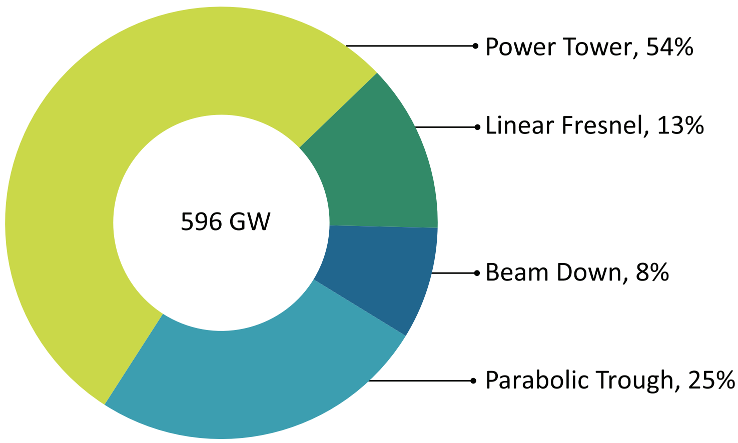

Figure 20: Operating CSPs in China

(Source: TERI Analysis)

In addition to above, 310 MW of CSP plants are under construction, as shown inTable 8.

Table 8: CSP plants under construction

Power Plant	CSP Technology	Capacity (MW)	Expected Commission year
CEIC Dunhuang	Linear Fresnel	100	2023
Huidong New Energy Akesai	Beam-Down Tower	110	2023
Jinta Zhongguang	Power Tower	100	2023
	Total	**310**	

Source: TERI Compilation

The growth of CSP capacity from 2012 to 2021 is shown in Figure 21.

[18] TERI compilation based on: " IJTF: Concentrating solar power (CSP) technologies: Status and analysis; ASME 2017 proceedings: An Origami-Inspired Design of a Thermal Mixing Element Within a Concentrated Solar Power System

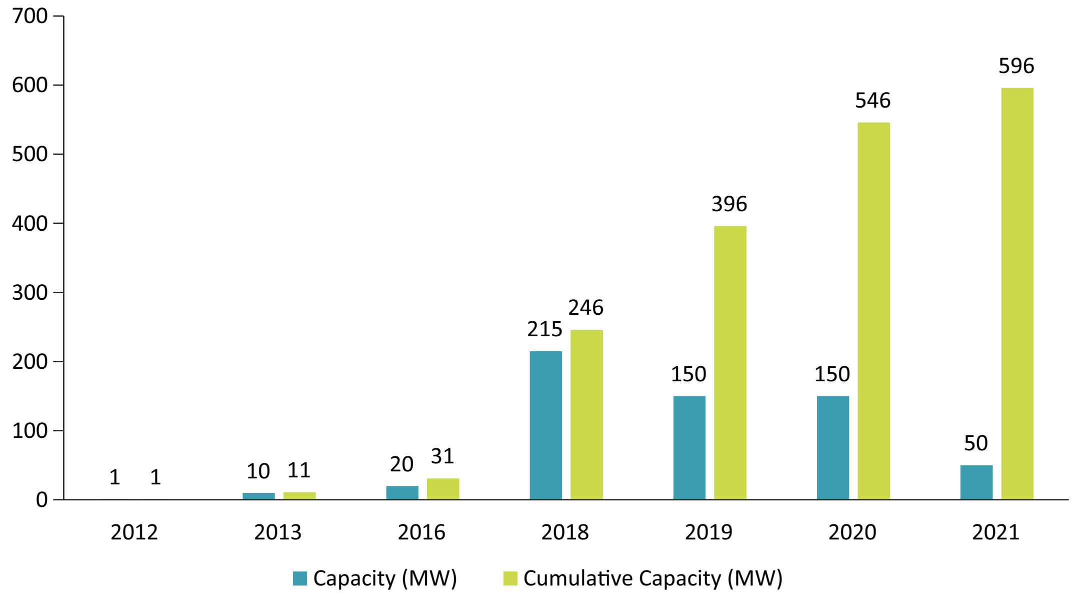

Figure 21: Growth of CSP capacity from 2012 to 2021

Source: TERI Analysis

China has deployed the Beam-down Tower technology[19] (Box-2) for developing CSP plants, in addition to the existing CSP technology, namely, Parabolic Trough, Power Tower and Linear Fresnel.

Policy Framework and Financial Incentives for CSP Development and Innovation in China[20]

China has a policy framework for the development of CSP but very limited financial incentives. CSP as part of China's 13th Five Year Plan for energy, is included in China's *Guidance Catalogue for Industrial Structure Adjustment: 2011–2015*, which the State Council released in 2012. CSP is also a part of *China Manufacturing 2025*: *Energy Equipment Implementation Plan*, which highlights the importance of completing field demonstrations of core CSP technologies.

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[19] ASME 2017 proceedings: An Origami-Inspired Design of a Thermal Mixing Element Within a Concentrated Solar Power System

[20] TERI compilation based on: "NREL: Analysis of the Cost and Value of Concentrating Solar Power in China

Box-2

In a beam-down CSP, heliostat (motorized mirrors tracking sun) focuses the incoming sunlight into tower- mounted beam-down mirrors. These beam-down mirrors redirect the sunlight into a final optical element (FOE), which focusses the sunlight into a tank of molten salt known as a receiver. The molten salt is separated into hot region at 550^{0}C, in which the energy from the sunlight is stored, and a cold region at 280^{0}C, by a thermal insulating element. To generate electricity, the insulating element moves upward, to allow flow of hot salt into the heat exchanger where it can be used to generate steam and drive turbine.

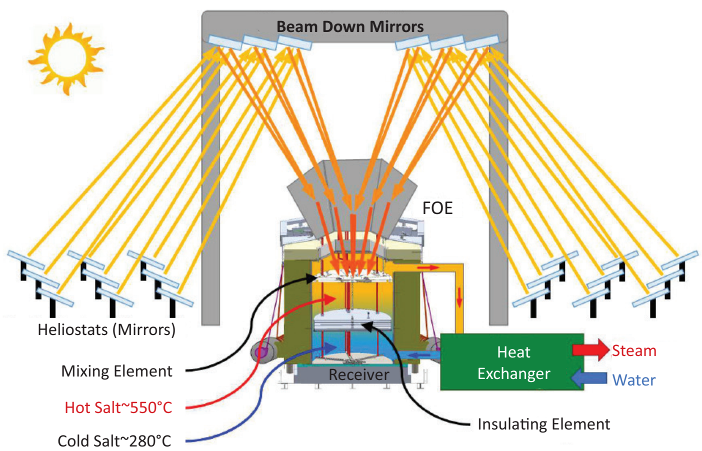

Figure 22: Schematic of the beam-down CSP

Source: ASME 2017 proceedings: An Origami-Inspired Design of a Thermal Mixing Element Within a Concentrated Solar Power System

Multiple CSP components and technologies have been included as “strategic new industrial products and services” in a category released by China’s National Development and Reform Commission (NDRC 2017) that is used to direct investments into specific industrial sectors and to enable more detailed accounting of the strategic sectors.

In addition, CSP is included in China’s new National Renewable Obligation Mechanism launched in May 2019, which requires each province to meet certain percentage of generation with non-hydro renewable sources.

China’s three major instruments to stimulate the development and innovation of CSP, include (a) the auction scheme; (b) feed-in tariffs; and (c) research, development, and demonstration support. CSP receives preferential loans, in very limited circumstances.

The auction scheme as the dominant instrument used to support CSP deployment internationally, was implemented in many countries, including Australia, Chile, China, Morocco, South Africa, and United Arab Emirates. Auctions although effective in driving down costs, could risk the financial viability of the winning entity. Since the first tender in October 2010 for a 50-megawatt (MW) CSP plant in Inner Mongolia, China has announced several CSP tenders. The early winners were dominantly state- owned enterprises, but with growth of industry, more private companies entered the CSP business in China.

The second policy instrument for stimulating CSP development in China being the feed-in tariff, was recognized as an effective, although costly, measure to boost renewable technology deployment. China's National Energy Administration established a benchmark feed-in tariff of $0.172/kWh for CSP in 2017. Due to the slow progress of CSP development in China, feed-in-tariff was extended to projects originally due for commissioning in 2018, to end of 2020, at a reduced tariff.

In terms of research, development, and demonstration support, the Ministry of Science and Technology and the National Energy Administration established a series of CSP research and demonstration projects. Participants in these projects include research institutes (e.g., the Institute of Electrical Engineering at the Chinese Academy of Sciences, China, Electric Power Planning and Engineering Institute, China, Renewable Energy Engineering Institute, Peking University, and Shanghai Jiaotong University), organizations such as China National Solar Thermal Energy Alliance, and state-owned as well as private companies. The first 20 CSP demonstration projects were approved in September 2016, but since then, many of them have experienced delays and four of them have been cancelled. By August 2019, three CSP plants were in operation in China. The 50-MW China General Nuclear Power Group project at Delingha, which began operating on October 10, 2018, was the first among the 20 demonstration CSP projects in China.

CSP received limited financial incentives beyond the three main drivers, mentioned above. Preferential loans are available only to a very limited number of CSP projects. For instance, the 50 MW Delingha project (CSP with Parabolic Trough), received 47% of the necessary capital as a preferential loan from the Asian Development Bank at the interest rate of 3%, as compared to commercial loan of 6.345% as of 2017.

Despite the policy support, the development of CSP in China had been slow – and is attributed to the high cost of CSP systems and the lack of assessment of the value which the CSP projects provides to the power system.

3.3.4 Development of CSP-PV hybrid project in United Arab Emirates[21]

The 950 MW Noor Energy 1/ DEWA IV is a CSP-PV hybrid project was launched by the UAE Vice-President and Prime Minister on 6th December, 2023, within the fourth phase of the Mohammed bin Rashid Al Maktoum Solar Park in Dubai, UAE.

[21] https://noorenergy.ae/a-about/;https://www.siemens-energy.com/global/en/home/stories/csp-resurgence-dubai.html; https://solarpaces.nrel.gov/project/csp-pv-hybrid-project-noor-energy-1-dewa-iv-700mw-csp-250mw-pv

The 950 MW CSP-PV hybrid project uses three different hybrid technologies: (i) 600 MW parabolic trough CSP (three units of 200 MW each), (ii) 100 MW solar tower CSP (based on Molten Salt technology), (iii) 250 MW bifacial photovoltaic solar panels.

The Dubai Electricity and Water Authority (DEWA) awarded a build-operate-transfer (BOT) contract for the 700 MW Noor Energy 1 CSP plant to a consortium of ACWA Power and Shanghai Electric in September 2017. The contract included a 35-year power purchase agreement, under which DEWA will off-take electricity from the independent power producer (IPP) project at $7.30 cents per kWh, a price competitive with fossil fuel-based power generation.

The CSP plant's total investment of about AED 15.8 billion (USD 4.4 billion) to be met by $2.9 billion of debt and $1.5 billion of equity. DEWA to provide $750 million, half of the project equity. ACWA Power to provide 51% and China's Silk Road Fund 49%.

The ACWA-led consortium (49%) (ACWA Power holds 25%, and the Chinese Silk Road Fund owns 24%) together with DEWA (51%) formed the project company Noor Energy 1 to design, build, and operate the plant, in the same year. DEWA and ACWA power signed an amendment to increase the plant's generating capacity to 950 MW by adding a 250 MW PV facility, in November 2018. ACWA Power signed a co-operation agreement with ICBC, Shanghai Electric, and Abengoa for the 950MW solar power facility in the same month.

Chief Technical Officer of Noor Energy 1, mentioned that *the CSP plant helps the grid shift away from a dependency on fossil fuels, and provides a stable daily baseload throughout the year, but also throughout the night. This is a crucial key advantage of CSP technology. Energy can be stored and used as needed, even multiple times a day if necessary.*

Details of CSP indicating capacity, start year, technology, solar irradiation, solar fieldand status in respect of Spain, USA and China is presented in **Annexure-1**.

4. Heat Transfer Media (HTM) (existing and new)

As per the study being carried out globally, heat transfer media (HTM) are classified under three broad categories: liquid, gaseous and solid HTM.[22]

- liquid HTM: include water, heat transfer oil, molten salt, liquid metal, and nanofluid, of which heat transfer oil, molten salt and water are currently more mature.
- gaseous HTM: include steam, helium, air and sCO_2.
- solid HTM (mainly the granular flow material): includes silica sand, alumina, coal ash, calcined flint clay and ceramic proppants.[23]

Table 9 presents the scope of application, advantages and disadvantages of different kinds of HTM.

Table 9: Comparison of different kinds of heat transfer media (HTM)

HTM	Scope of application	Advantages	Disadvantages
Water/ steam	Low and medium temperature CSP systems	» Low cost, » non-toxic » low corrosiveness, » simpler CSP system structure, » environmental protection	» High temperature and pressure requirements; » low heat storage capacity of water/ steam; » uneven two-phase flow and temperature distributions of water/ steam in solar » absorber or receiver tubes.
Inert Gases » Air » Helium » sCO_2	Medium and high temperature CSP systems	» Wide variety of sources; » Environmentally friendly; » Thermally stable	» Low heat transfer coefficient (HTC); » No direct thermal energy storage (TES).
Heat transfer oils » Mineral » Synthetic	Medium-temperature CSP systems	» Strong fluidity; » Low freezing point; » Good heat transfer performance » Low corrosiveness	» High cost; » Short service life (3–5 years) » Low applicable temperature; » Flammable; » Easy to leak; » Explosion hazard.

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22 TERI compilation based on: Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials; EcoMat- Wiley,2022: NIE et al - Solid particle solar receivers in the next-generation concentrated solar power plant

23 Ceramic proppants are ceramic particles made by ceramic sintering of mixture of quality bauxite, coal and other raw materials; https://bariteworld.com/industrial-minerals-products/ceramic-proppants/

Table 9: Comparison of different kinds of heat transfer media (HTM)

HTM	Scope of application	Advantages	Disadvantages
Molten salts » Sodium nitrate salt; » Chloride slat	Medium and high temperature CSP systems	» High specific heat; » Strong heat storage capacity; » Not easy to burn; » Good safety; » Low working pressure; » Non-toxic » High HTC; » Direct TES	» Easy to decompose, oxidize, and corrode at high temperature; » High melting point » Strongly corrosive; » High price.
Liquid metals » Sodium; » Lead-Bismuth alloy	Medium and high temperature CSP systems	» Excellent thermal conductivity; » Low melting point; » High boiling point; » Wide operating temperature range	» High cost; » High chemical activity of some metals; » High corrosiveness at high temperature; » Toxicity of some metals.
Solid particles » Desert sand; » Ceramic particles	High temperature CSP systems	» Wide variety of sources; » Environmentally friendly; » Direct TES	» Low effective thermal conductivity; » Low HTCs for the indirectly irradiated solid particle solar receivers (SPSRs); » Difficulty in the transport of the high temperature solid particles.

Source: TERI Compilation: Wang et al-A brief review of liquid transfer materials used in CSP and TES devices; NIE et al-Solid particle solar receivers in the next-generation CSP plant)

Few HTM, such as Water/Steam, inert gases, supercritical CO_2, heat transfer oils, molten salts, molten metals and solid particles are briefly described below.

Water/ Steam[24]

Water as HTM, is mainly used in the direct steam generation (DSG) CSP systems or some solar-based multi-energy hybrid systems (e.g., integrated solar-gas combined cycle systems). In these CSP systems, water serves as the HTM and working fluid for the steam turbine simultaneously. The

[24] Wang et al-A brief review of liquid transfer materials used in CSP and TES devices

high-temperature and high-pressure steam generated as a result of solar energy being absorbed in the heat absorber or thermal receiver tube, drive the steam turbine to generate electric power (Rankine cycle). This process is similar to the coal-fired thermal power generation process.

Direct steam generation based CSP systems have simpler system configurations and lower power generation costs, but the thermal performance of water is not so high as those of molten salts, and the heat storage capacity of water/ steam is not high when used in TES systems.

Inert gases[25]

Inert gases such as air, helium, sCO_2 etc., are other alternatives of HTM are thermally stable, for use directly as working fluid in appropriate turbines or thermal engines. Thus, intermediate heat exchangers are avoided increasing the energy available for electricity generation. Main advantages of using air are its availability from the ambient, environmentally-friendly characteristics, no phase change requirement, higher working temperatures, easy operation and maintenance and high dispatchability. It is a suitable heat transfer fluid in desert areas, where water availability is scarce. However, its low heat transfer coefficient poses challenges for receiver design, while their low densities make the integration of energy storage difficult.

Supercritical CO_2[26]

Supercritical CO_2 (sCO_2) as HTM can operate at very high temperatures, provide suitable thermophysical properties related to the supercritical state and can be directly used as working fluid in sCO_2 turbine.

Supercritical carbon dioxide is a fluid state of carbon dioxide where it is held at or above its critical temperature (304.25 K/ 31.1^{0}C) and critical pressure (73.8 Bar/ 7.38MPa). Carbon dioxide usually behaves as a gas in air at standard temperature and pressure (STP), or as a solid called dry ice when frozen. If the temperature and pressure are both increased from STP to be at or above the critical point for carbon dioxide, it can adopt properties midway between a gas and a liquid but without any phase transition as the temperature is varied at a constant pressure. At this state, sCO_2 can be used efficiently throughout the entire Brayton cycle (**Annexure-2**).

A closed Brayton cycle (CBC) recirculates the working fluid, and the turbine exhaust is used in a recuperating heat exchanger to heat the turbine feed. A “supercritical cycle” is a closed Brayton cycle in which the working fluid (sCO_2) is maintained above the critical point during the compression phase of the cycle.

The benefits of sCO_2 Brayton Cycle, for power conversion include:

- Broad applicability to a variety of heat sources,
- Higher plant efficiency,
- Reduced fuel consumption,

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[25] Helioscope: Jose Gonzalez- New heat transfer fluids: Increasing performance in solar thermal power plants

[26] US DOE- Quadrennial Technology Review 2015: Technology Assessments

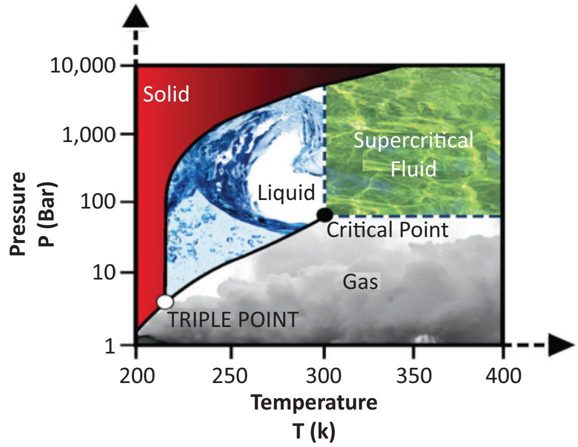

Figure 23: CO_2 Phase Diagram

Source: US DOE- Quadrennial Technology Review 2015: Technology Assessments

- » Smaller size relative to steam system suggesting reduced capital cost,
- » Environmental improvement from greenhouse gas reduction,
- » Vastly reduced water consumption, and
- » Dry cooling capability suitable for arid environments.

The key property of the fluid near its critical point is its higher gas density, closer to that of a liquid than of a gas, allowing for the pumping power in the compressor to be significantly reduced, which in turn increases the thermal-to-electric energy conversion efficiency. The resulting higher conversion efficiency (up to 50%) translates to increased electricity production for same thermal input.

Heat transfer oils[27]

Heat transfer oils (heat carrier oils) were the traditional HTMs, have advantages of good heat transfer effect, big operating temperature range, strong antioxidant activity and very low volatility. Compared to molten salt HTMs, heat transfer oils have relatively lower corrosiveness, are economical and practical, and the probability of fire or explosion is extremely low under normal operation when they are used in different fields: parabolic trough and linear Fresnel reflector CSP systems.

Oils are divided into mineral and synthetic oils, according to the chemical compositions. Several typical mineral oils available are presented in Table 10.

[27] Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

Table 10: Mineral oils manufacturer, specification, applicable temperature and flash point

Manufacturer	Specification	Applicable temperature (⁰C)	Flash point (⁰C)
Mobil Oil Corporation	Mobiltherm 605	-12 to 315 (closed system)	230
Shell Oil Company	Shell Themia oil B	-12 to 320	232
Exxon Oil Company	32	-42 to 329	218
British Petroleum	Transcal	-12 to 320	221

Source: Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

Apart from mineral oils, synthetic oils are mainly symmetric alkyl aromatic compounds with benzene rings. Synthetic oils usually have high initial boiling point and short distillation range, and their molecular bond structures are generally complete conjugated structures, as shown in Figure 24.

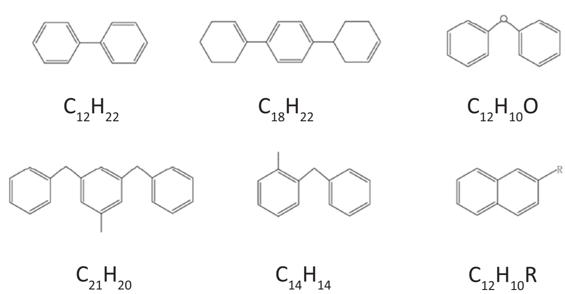

Figure 24: Molecular structures of several typical synthetic oils

Source: Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

Hence, they have better stabilities, higher thermal conductivities, lower viscosities and higher enthalpies (Box-3). Currently, synthetic oils are mainly biphenyl compounds, including biphenyl ($C_{12}H_{22}$), hydrogenated terphenyl (C_8H_{22}), diphenyl ether ($C_{12}H_{10}O$), dibenzyl toluene ($C_{21}H_{20}$), benzyl toluene ($C_{14}H_{14}$), methylnaphthalene ($C_{11}H_{10}$), etc. Some typical synthetic oils are presented in Table 11.

Table 11: Synthetic oil manufacturer, specification, composition & applicable temperature

Manufacturer	Specification	Composition	Applicable temperature (⁰C)
DOW of US	Dowtherm A	$C_{12}H_{22} - C_{12}H_{10}O$	12 to 400
	Dowtherm G	$C_{12}H_{22} - C_{12}H_{10}O$	29 to 371
	Dowtherm Q	$C_{12}H_{22} - C_{12}H_{10}O$	-80 to 315
Solutia of US	Therminol VP-1	$C_{18}H_{22}$	12 to 400
SASOl of Germany	Marlotherm SH	$C_{14}H_{14}$	-5 to 350
WACKER of Germany	Helisol 5A	PDMS (poly-di-methyl-siloxane)	-5 to 430
TOTAL of France	DBT	$C_{14}H_{14}$	-10 to 350
Kureha of Japan	KSK-300	$C_{11}H_{10}$	-10 to 340

Source: Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

Box-3

Enthalpy is total energy of heat in the system which is equivalent to the sum of total internal energy and resulting energy due to its pressure and volume, and can be represented as:

$$H = U + PV$$

where,

H is Enthalpy

U is Internal Energy

P is Pressure

V is Volume

Molten Salts[28]

Molten salts have advantages of high thermal stability, high specific heat capacity, high convective heat transfer coefficient and low viscosity, which make them good HTMs for CSP systems. Some of the disadvantages are molten salt pipeline blockage due to their high melting temperatures and decomposition phenomenon at high temperature. Molten salts are mainly divided into the nitrate, carbonate, chloride, fluoride, and sulphate salts. The most common molten salt is a binary mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3).

Studies have revealed the use of chloride molten salts in high-temperature CSP and TES systems. Some chloride salts have big phase change latent heat,[29] good thermal stability, and relatively wide operating temperature range, but their melting temperatures are usually high. The corrosion problem of chloride salts can be solved by using the firebrick as the internal insulation in the pipeline and TES tanks of CSP systems.

Key features of sodium nitrate salts and chloride salts indicating their mass composition, solidification temperature, stability limit, density, specific heat viscosity and thermal conductivity are shown in Table 12.

28 Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

29 The energy required to change the phase of a substance (from solid state to liquid state, and then from the liquid state to gaseous state) without raising its temperature is called latent heat

Table 12: Key features of sodium nitrate salt and chloride salt

Parameter	Sodium nitrate salt	Chloride salt
Mass composition	Binary 60% $NaNO_3$ 40% KNO_3	Ternary MgCl-KCl-NaCl blend
Solidification Temp (^{0}C)	238	426
Stability Limit (^{0}C)	600	>1418
Density (kg/m^3)	1770 @ 500°C	1590 @ 700°C
Specific Heat (J/g-K)	1.53 @ 500°C	1.1 @ 700°C
Viscosity (cP)	1.30 @ 500°C	1.40 @ 700°C
Thermal Conductivity (W/m-K)	0.54 @ 500°C	0.40 @ 700°C

Source: National Solar Thermal Test Facility (NSTTF): Next Generation Concentrating Solar Energy for the 21st Century

Liquid metals[30]

Liquid metals were used as HTMs in nuclear fast reactors at early stages due to their good thermal characteristics. Typical liquid metals include sodium, sodium potassium alloy, lead, lead-bismuth eutectic[31] (LBE) alloy, and so forth. These materials can have relatively wider operating temperature ranges with low melting temperature as well as very high boiling temperature. Liquid metals are potential alternatives to molten salts and heat transfer oils used in the next generation CSP systems.

Sodium

Liquid sodium as the HTM in CSP systems has many advantages such as wide operating temperature range, low melting temperature, high boiling temperature, and high thermal conductivity. In addition, higher solar receiving efficiency can be obtained, wall overheating can be partly avoided, and radiation and convection heat losses can be reduced. It also has some disadvantages when it serves as the HTM in CSP systems, such as the high corrosiveness under high-temperature condition, relatively high cost, safety challenges due to high chemical activity.

Lead-bismuth eutectic

LBE alloy made of lead and bismuth has many good physical properties, including low melting temperature (150–200°C), high boiling temperature (about 167°C), wide operating temperature range, low chemical activity, high thermal mobility, strong heat storage capacity, and so forth. But the high corrosiveness of high-temperature liquid LBE is also a key problem which requires to be addressed through R&D for future use in CSPs.

30 Wiley: Engineering Reports,2022- Wang et al – A brief review of liquid heat transfer materials

31 A eutectic system or eutectic mixture is a homogenous mixture that has a melting point lower than those of the constituents

Solid particles[32]

The use of solid particles as the HTM is another option, capable of reaching temperatures of 1000°C when ceramic particles are used. Solid particle HTM are also ideally suited for storage applications, which can be easily implemented through simple bulk storage of hot particles. The solid particles are typically directly irradiated by the concentrated sunlight, allowing for very high heat fluxes as there is no interposing material to limit heat transfer.

i) Falling Particle Receiver[33]

Falling particle receiver works by dropping small sand-like ceramic particles through a beam of concentrated sunlight to heat them up. These particles then act as a heat storage medium for electricity production using a steam turbine. The working principle of storage system using particles is given below.

i. Particles fall through the top receiver where they are exposed to concentrated sunlight through the aperture. This causes the particles to heat up.

ii. The heated particles fall into an insulated storage tank, where they accumulate.

iii. This tank is called the "hot storage tank".

iv. The heated particles are transferred from the hot storage tank into a heat exchanger where they transfer their heat to water. This water heats up to a high temperature and produces high-pressure steam, which is then used to drive a turbine, generating electricity for use in the electrical grid.

v. The particles, now cooler, fall into another storage tank called the "cold storage tank".

vi. The cooled particles are brought up via an elevator to the top receiver to heat up again. The cycle then repeats.

Hot storage tank can store enough heated particles to enable electricity production even when it is cloudy outside or during the night. There needs to be enough heated particles stored in the hot storage tank to last for long stretches of time.

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32 Helioscope: Jose Gonzalez- New heat transfer fluids: Increasing performance in solar thermal power plants

33 Franco Normani: Falling Particle Receiver Boosts Solar Energy Storage Efficiency, 2020; US DOE-SunShot: High-Temperature Falling Particle Receiver for Concentrating Solar Power

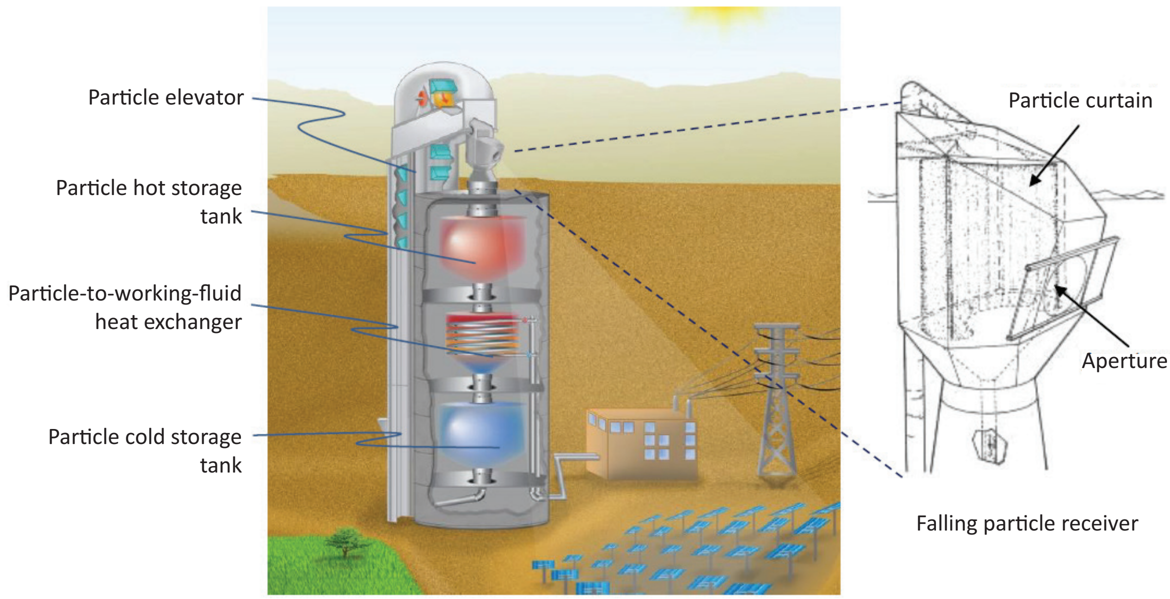

Figure 25: High temperature falling particle Receiver

Source: US DOE-SunShot: High-Temperature Falling Particle Receiver for Concentrating Solar Power

The best time to accumulate heated particles in the storage tank is when there is minimal demand for electricity and the sun is shining. At this point, the supply of particles into the heat exchanger, from the hot storage tank, can be reduced or stopped, since electricity generation is not as important. This will allow the number of particles in the hot storage tank to be increased, creating a thermal energy "buffer", so that when the demand for electricity increases once more, and/or when it is night/cloudy, the heated particles can be fed into the heat exchanger to produce electricity.

The use of solid particles as the heat-transfer and storage media—rather than conventional fluids such as liquid molten salts or air—is unique. The falling-particle receiver appears well-suited for power tower systems ranging from 10–100 megawatts. Such flexibility, combined with lower costs of thermal energy storage, could enable higher penetrations of CSP systems and help meet targeted goals.[34]

[34] US-DOE: Project Profile-High Temperature Falling-Particle Receiver

5. Status of CSP in India

India is endowed with vast potential for solar energy. The National Institute of Solar Energy (NISE), an autonomous institute under Ministry of New & Renewable Energy, Government of India has estimated the total solar potential of India of about 750 GW.[35] Among the various renewable energy resources, solar energy potential is the highest in the country. In most parts of India, clear sunny weather is experienced 250 to 300 days a year. The annual radiation varies from 1600 to 2200 kWh/m^2, which is comparable with radiation received in the tropical and sub-tropical regions.[36] The Direct Normal Irradiance of India is shown in Figure 26.[37]

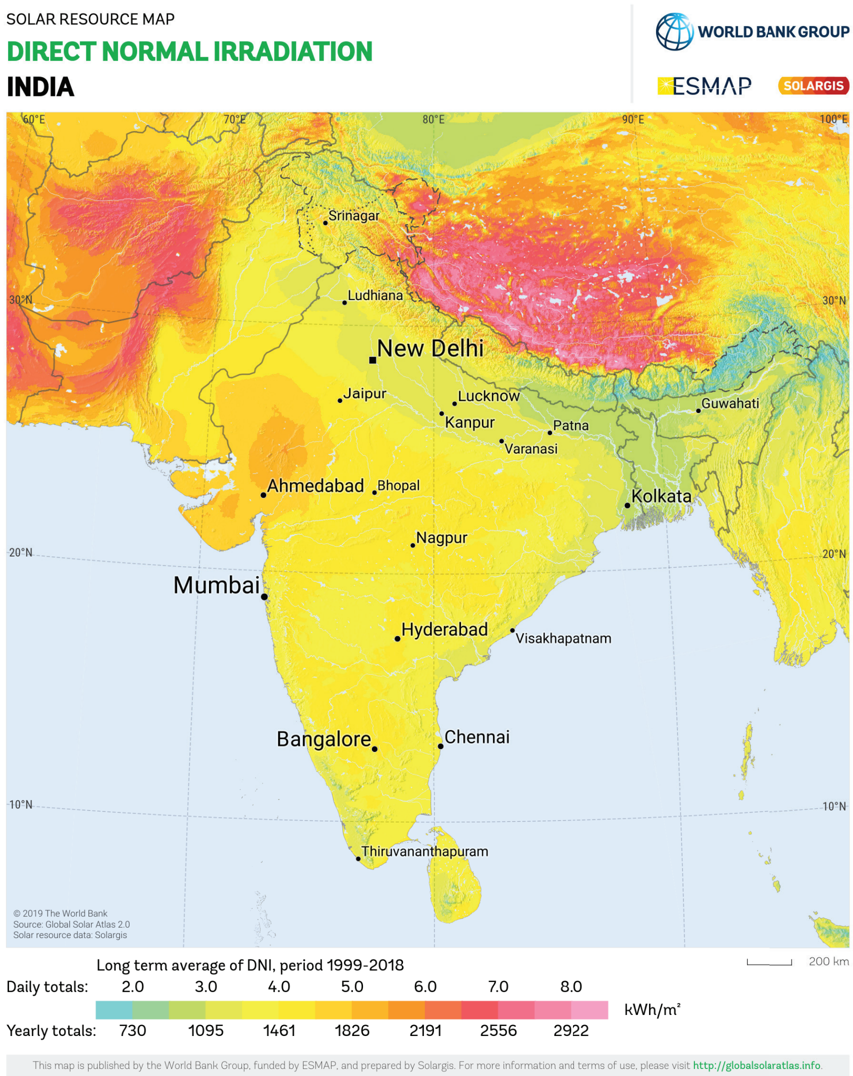

Figure 26: Solar DNI Map of India

35 MNRE Annual Report,2022

36 https://mnre.gov.in/solar-rpo-and-rec-framework/

37 https://globalsolaratlas.info/download/india

The initiative to develop CSP plants by the Government of India was mainly through the implementation of Jawaharlal Nehru National Solar Mission (JNNSM) launched in January, 2010. The developers of CSP plants were selected through the process of reverse bidding. The status of CSP projects[38] as on 2023 is shown in Table 13:

Table 13: CSP Projects in India

Sl. No.	CSP Project	Capacity (MW)	Location	Technology	Solar irradiation (kWh/m²/ year	Start year	Status
1.	ACME Solar	2.5	Bikaner, Rajasthan	Power Tower	-	2011	Non-operational
2.	National Solar Thermal Power facility	1	NISE, Gurgaon	Parabolic Trough	N.A.	2012	Non-operational
3.	Godawari Solar Project	50	Nokh, Rajasthan	Parabolic Trough	1667	2013	Operational
4.	KVK Energy Solar Project	100	Askandra, Rajasthan	Parabolic Trough	1940	2013	Non-operational
5.	Rajasthan Sun Technique Energy Pvt. Ltd.	125	Dhursar, Rajasthan	Linear Fresnel	1742	2014	Non-operational
6.	Megha Solar Plant	50	Anantapur, Andhra Pradesh	Parabolic Trough	1476	2014	Operational
7.	India One	1	Abu Road, Rajasthan	Parabolic Dish	N.A.	2017	Operational
	Total capacity	**329.5 MW**					
	Operational Capacity	**101**					

Source: TERI Compilation: MNRE, NVVN, NREL

[38] International Journal of Thermofluids: Concentrating solar power (CSP) technologies: Status and analysis; MNRE; NVVN

5.1 Capital cost of CSP based on parabolic trough technology[39]

The capital cost of CSP project is dependent on the solar irradiation level at a particular location. Variation of solar irradiation level at different locations result in variation in electricity output, capacity utilization factor (CUF) and capital costs. For CSP projects, the electricity output is computed as under:

=Annual average solar irradiation (kWh/m^2/year) x Plant Efficiency (%) x Solar Field size (m^2)

In CSP technology, unlike PV projects, the size of the solar field (expressed in terms of "number of loops") determines the yield, project cost and CUF. The solar field, comprising of multiple mirrors, concentrates the incident solar irradiation onto heat absorber tubes which absorb the thermal energy and transfers it to a heat transfer fluid. Heat exchangers transfer thermal energy to generate steam that drives a conventional turbine. Designing the 'right' size of solar field to generate sufficient thermal heat required to drive the turbine continually throughout its operation depends on the solar irradiation level which varies according to the 'time of day' (maximum in the afternoon, low in the mornings and evenings) and 'month of year' (lower during monsoon, higher during summer months). A larger than necessary (or a smaller) solar field may result in excess (or deficient) solar energy required to drive the turbine thereby causing solar energy to be dumped.

The Annual DNI in India from solar resources from different sources is shown in Table 14.

Table 14: Solar resource from different sources

Source	NREL	CIEMAT	Meteonorm	NASA	Ground	CWET
Annual DNI (kWh/m^2/year)	2,084	1,847	1,794	2,044	1,893	1,678
Comment	2002-07 average	TMY[40]	Average	22-year average	2011	2012

Source: CERC Tariff Order for FY2014-15

The capital cost determined by CERC for the period 2014-15 for a 55.55 MW CSP based on parabolic trough technology (under JNNSM-I) having the solar field (expressed in terms of "number of loops") already installed, considering DNI of 1,847 kWh/m^2/year, as given in Table 15, presents an example to understand the correlation between solar field and capital cost.

39 CERC Order dated 7th January,2014 for 'Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY2014-15

40 Typical meteorological year (TMY) is a collation of selected weather data for a specific location, listing hourly values of solar radiation and meteorological elements for a one-year period

Table 15: Capital cost of a 55.55 MW CSP based on parabolic trough technology as determined by CERC for FY2014-15

Particulars	Unit	Rate	No.		Total
Plant capacity (name plate rating)	MW	55.55			
CUF	%	23			
Euro conversion (last 6 months avg.	Rs./Euro	76.55			
US$ conversion (last 6 months)	Rs./$	60			
Loops	S/Loop	5,50,000	120	loop	3,96,00,00,000
HTF System	$/m$_2$	70	392400	m^2	1,64,80,80,000
Inter-connect piping	$/m^2	10	392400	m^2	23,54,40,000
Turbine	Euro/kW	120	55.55	MW	51,02,82,300
BOS	Rs./MW	80,00,000	55.55	MW	44,44,00,000
Land	Rs./Acre	2,00,000	350	Acre	7,00,00,000
Site development	Rs./Acre	50,000	350	Acre	1,75,00,000
Total Cost	Rs.				6,88,57,02,300
Cost/ MW	Rs./MW				12,39,55,037
Cost/ MW	Rs.Cr./MW				12.40

Source: CERC Tariff Order for FY2014-15

5.2 Tariff: trend during the period, 2010 to 2016-17

The generic tariff determined by CERC for CSP projects during the period 2010-11 to 2016-17 is presented in Figure 27.

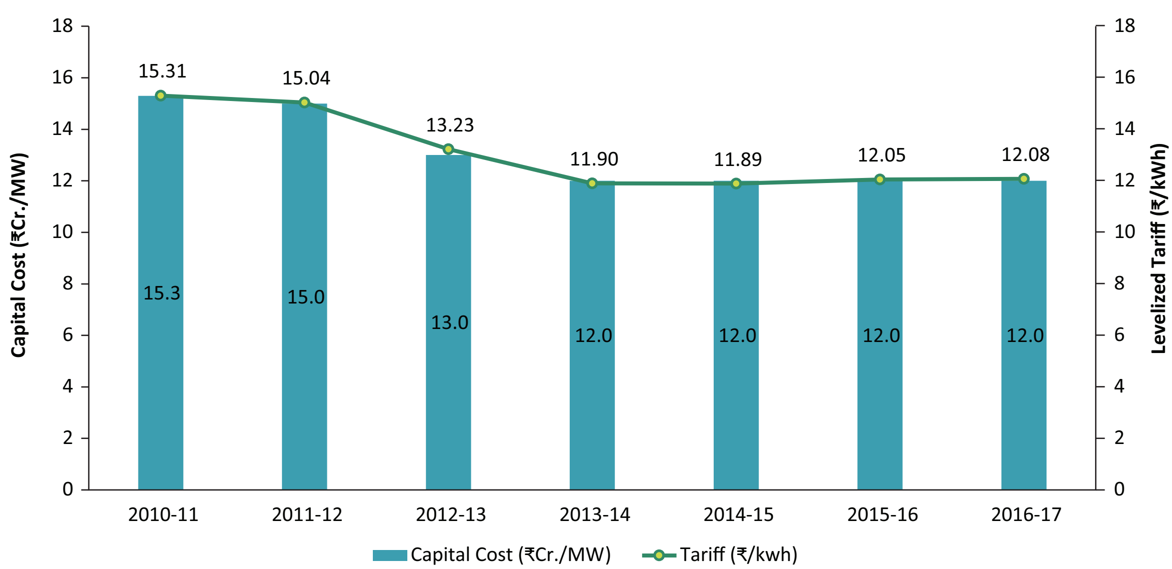

Figure 27: Capital cost and generic tariff of CSP project as determined by CERC

Source: TERI Analysis

CSP Projects were selected through a process of reverse bidding, under JNNSM Phase-1. The CSP tariff ranged between Rs.10.49/kWh and Rs.12.24/kWh, with average tariff being Rs.11.48/kWh. However, with the bundling mechanism introduced in JNNSM, the bundled power tariff ranged between Rs.4.49/kWh and Rs.4.81/kWh, as shown in Table 16.[41]

Table 16: Tariff discovered through reverse bidding and effective tariff after bundling

JNNSM Scheme	Technology Type	CERC Tariff (Rs./kWh)	Discount Tariff (Rs./kWh)		Wtd. Avg. tariff (Rs./kWh)	Bundled Rate range (Rs./kWh)	
			Minimum	Maximum		Minimum	Maximum
Batch-I	Solar Thermal	15.31	10.49	12.24	11.48	4.49	4.81

Source: TERI Analysis

While solar PV projects were continued to be selected through a tariff based competitive/reverse bidding process since 2010, no further competitive bidding thereafter, were carried out either by NTPC or by any other CPSU, for setting up the CSP projects.

5.3 Successful CSPs in India

5.3.1 Godawari Green Energy Ltd. (GGEL)[42]

Godawari Green Energy Ltd. (GGEL) commissioned the 50 MW Solar Thermal Power Project at Village-Nokh, Tehsil-Pokhran, Distt. -Jaisalmer, Rajasthan on 19th June, 2013. With this achievement, GGEL became the nation's first CSP Plant under JNNSM, Phase-1.

Overview of the CSP Plant

GGEL is India's first ever utility to generate electricity by using CSP parabolic trough technology for the 50 MW project contracted by Lauren Engineers & Constructors (I) Private Ltd (LECI). The key features of the CSP project are shown in Table 17.

GGEL had signed power purchase agreement (PPA) with NTPC Vidyut Vyapar Nigam (NVVN) for sale of power at a tariff of Rs.12.20/kWh for 25 years.

The Process

GGEL's CSP plant runs on Rankine cycle. The heat collected by trough is being transferred to water through thermic fluids[43] (HTF) for steam generation. Temperature of fluid goes up to 380°C and fluid indirectly heats water to generate steam. Thus, generated steam goes to the turbine for power generation.

41 World Bank-ESMAP: Paving the Way for a Transformational Future-Lessons from JNNSM Phase-I

42 Retrieved from SUN FOCUS: Oct-Dec 2016

43 The term is a combination of "thermo", referring to heat, and "fluids", which refers to liquids, gases and vapours

Table 17: Key features of GGEL CSP

Sl. No.	Particulars	Features
1.	Solar Field Aperture area	3,92,400 m^2
2.	No. of Loops	120
3.	No. of Solar Collector Assemblies (SCA)	480
4.	No. of SCAs per Loop	4
5.	No. of Modules per SCA	12
6.	SCA Aperture Area (m^2)	817
7.	SCA Length (m)	144
8.	Solar Field or Receiver Inlet Temperature	293^{0}C
9.	Solar Field or Receiver Outlet Temperature	390^{0}C
10.	Total Power Station Land Area (km^2)	1.5
11.	Power Cycle	Rankine

Source: NREL

Conclusion

Godawari plant is one of the finest examples of successful CSP technology in India. Being a first ever CSP plant in India, it created confidence among industries to adopt cleaner technology.

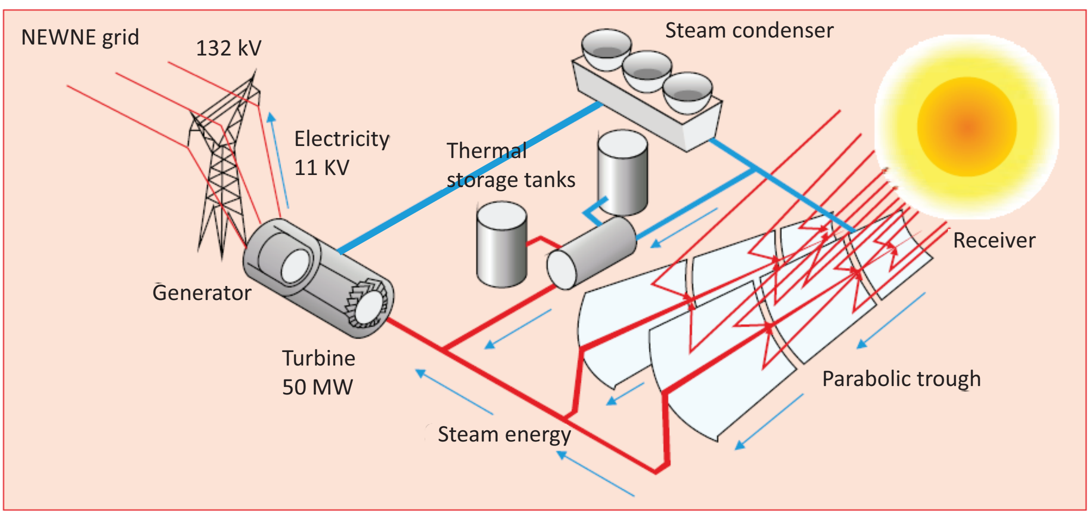

Figure 28: Technology and Project Boundary

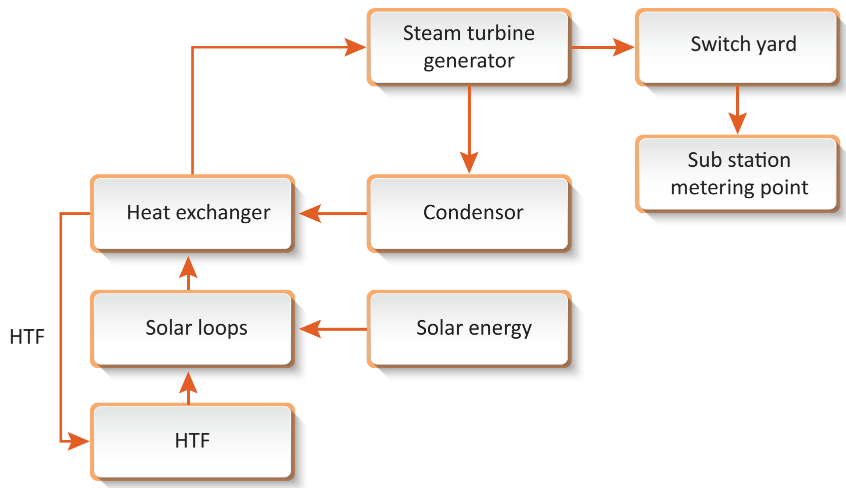

Figure 29: Schematic Diagram of CSP Project

5.3.2 Megha Solar Plant[44]

MEIL Green Power Limited (MGPL), a unit of Hyderabad-based Megha Engineering Infrastructure Limited (MEIL), commissioned a 50 MW CSP plant in November, 2014 at Nagalapuram village in Anantapur district of Andhra Pradesh.

Overview of the CSP plant

The 50 MW CSP is based on Parabolic Trough technology. The developer of the plant is Megha Engineering and Infrastructure, India and the EPC contractor is MEIL Green Power, India. The key features of the plant are shown in Table 18.

Table 18: Key features of Megha Solar Plant

Sl. No.	Particulars	Features
1.	Solar Field Aperture area	366,240 m^2
2.	No. of Loops	112
3.	No. of Solar Collector Assemblies (SCA)	448
4.	No. of SCAs per Loop	4
5.	No. of Modules per SCA	12
6.	SCA aperture area	817 m^2
7.	SCA Length	150 m
8.	Solar Field or Receiver Inlet Temperature	293^{0}C
9.	Solar Field or Receiver Outlet Temperature	393^{0}C
10.	Total Power Station Land Area	2.42 km^2
11.	Power Cycle	Rankine

Source: NREL

Megha Solar Plant signed a PPA with NVVN for sale of power at a tariff of Rs.11.31/kWh for 25 years.

44 https://solarpaces.nrel.gov/project/megha-solar-plant; https://www.business-standard.com/article/companies/meil-commissions-50mw-solar-plant-in-ap-114111301093_1.html

5.3.3 'India One' CSP Plant with Storage[45]

'India One' is a 1 MW CSP plant with 16 hours thermal energy storage allowing for round-the-clock operation. This captive power plant supplies power to Brahma Kumaris headquarters in Abu Road, Rajasthan with total capacity of 25,000 people.

The key features of the research and development achievements at the India One CSP plant are as follows:

» A total of 770 parabolic reflectors of 60 m^2 with unique static focus design, using special solar grade mirrors with 93% reflectivity and equipped with fully automatic dual axis tracking mechanism to adjust daily and seasonally, to the position of the sun.

» A total of 770 indigenously designed cast iron cavity receivers, generating directly superheated steam (up to 420°C temperature and 42 bar pressure). Due to the static design, receivers are cost-effective and last long with minimum required maintenance. The solid mass of 3 tonnes of cast iron acts as a medium to store thermal energy, due to its good properties of specific heat and density.

» The 60 m^2 parabolic reflector tracks the sun, concentrating the solar rays in the static cast iron receiver. Each receiver acts as a thermal energy storage system during the night or amid partial cloudy conditions. The cast iron core is surrounded by a steam coil, which acts as a steam generator by exchanging the heat from iron core to water. The high temperature steam runs through a turbine connected to a generator that produces electricity.

The 'India One' CSP Plant was successfully commissioned in the beginning of 2017. It is a good showcase for solar thermal power plants with storage and is also an example of the 'Make in India' initiative.

45 SUN FOCUS: Oct-Dec 2019

6. Development of Next Generation Technology Loop to Generate Clean Energy in India

Indian scientists have developed a super critical carbon dioxide (sCO_2) Brayton test loop facility that would help generate clean energy from future power plants including solar thermal. This next generation technology loop was developed indigenously by Indian Institute of Science, Bangalore.[46]

This is India's first test-bed for next generation, efficient, compact, waterless super critical carbon dioxide Brayton cycle test loop for power generation. The technology is perhaps the first test loop coupled with solar heat source in the world.

The new generation high efficiency power plants with closed cycle sCO_2 as the working fluid have the potential to replace steam based nuclear and thermal power plants, thus reducing the carbon foot print significantly.

This test loop is designed to generate the necessary data for future development of scaled up sCO_2 power plants, which would require overcoming several technological challenges–developing critical components such as the turbine, compressor and heat exchangers that can work at the desired pressure and temperature ranges and using materials that can withstand these conditions.

This effort has already been identified as a possible national initiative for the next generation of CSP plants. This gives India an opportunity to become a world leader in this technology, and fulfil a major objective of the National Solar Mission which emphasizes indigenous manufacturing.

Today's thermal power plants use steam to carry heat away from the source and turn a turbine to generate power. However, it could generate more power if, instead of steam, supercritical CO_2 (sCO_2) is used. The term "supercritical" describes the state of carbon dioxide above its critical temperature of 31.1°C and critical pressure of 73 atmospheres making it twice as dense as steam.

The efficiency of energy conversion could also be significantly increased by as much as 50 percent or more if sCO_2 is operated in a closed loop Brayton cycle. Besides increasing power generation and making the process more efficient, there are other advantages of using this new technology. Smaller turbines and power blocks can make the power plant cheaper, while higher efficiency would significantly reduce CO_2 emissions for fossil fuel-based plants. Moreover, if the power plant used solar or nuclear heat source, it would mean higher capacity at lower operating costs.

Need for new heat transfer media for next generation CSPs in India

New heat transfer media are already being developed globally. India too have developed supercritical CO_2 Brayton test loop facility that would help generate clean energy from future power plants including CSPs. This effort has already been identified as a possible national initiative for the next generation CSPs. This gives India an opportunity to fulfil a major objective of the National Solar Mission which emphasizes indigenous manufacturing.

Department of Science & Technology, under the Ministry of Science and Technology, may be identified by the Government of India to develop the next generation CSP based on newly developed supercritical CO_2 such that CSP of large capacity in the range between 100 MW and 200 MW can be developed in the country.

[46] PIB release ID: 1521432 dated 22nd February 2018

7. Challenges to the Growth of CSPs

Although the solar potential is quite significant, the current deployment of CSP technologies is quite insignificant (0.10% in RE capacity; 0.03% in total capacity as on 2023). This is largely due to the challenges which have affected realisation of actual potential, as a result of which the technology is still not widely adopted. The key challenges to the growth of CSP is summarised in Table 18.[47]

Table 19: Key challenges to CSP growth

Sl. No.	Challenges	Related issues	Proposed way to address the issues
1.	Solar radiation data	The capital cost of CSP project is dependent on the solar irradiation level at a particular location. Variation of solar irradiation level at different locations result in variation in electricity output, CUF and capital costs. The solar resources from different sources such as NREL, CIEMAT, Meteonorm, NASA etc., are available. The right DNI to be considered is a matter of concern for any developer setting up CSP in India.	Realistic estimation of DNI for CSP projects is needed, being site specific. Ten years on the ground measurements to be compared and correlated to satellite-based analysis will present a comprehensive understanding to the developers.
2.	Technology	Selection of CSP Technology: The type of CSP technology to be considered for setting up CSP plant in India is a concern for the developers. Out of the CSP plants set up under the JNNSM scheme, the CSP plants with Parabolic Trough are only operational. CSP with Power Tower & Linear Fresnel technology gradually became non-operational due to various reasons.	Lessons from the experience gathered from the CSP generating companies will help upcoming developers to set up CSP plants in future. International experience may also be gathered to further enhance developer's knowledge.

47 TERI compilation from "CERC Tariff Order for FY2014-15; ESMAP: Study on barriers for solar power development in India"

Table 19: Key challenges to CSP growth

Sl. No.	Challenges	Related issues	Proposed way to address the issues
3.	Infrastructure	Apart from the requisite solar radiation, below mentioned are the most important parameters in infrastructure required for developing CSP: a) Gradient: the land needs to be almost flat (horizontal); b) proximity to water resources; c) proximity to power evacuation; d) accessibility. Since the developers of solar PV projects under JNNSM scheme, were already allotted the required land and given the accessibility to both water resources & nearest substation, CSP developers needed more lead times for arranging the required infrastructure.	Need for a single window clearance for CSP, will help in obtaining land and water related approvals and other clearances related to evacuation of power under one roof.
4.	Financing	Unlike Solar PV, CSP have upfront costs for setting up plants. As detailed above, solar field constitute about 57.5% of the total cost of CSP, followed by HTF (23.9%), Turbine and inter-connecting piping (10.8%), BoP (6.5%), land and site development (1.3%). Excepting BoP, all components are required to be imported. The solar PV cost declined with fall in prices in PV module in international market and in addition, Govt. has also provided various incentive schemes like VGF while bidding for the solar PV projects. Financing is an issue for the developers to access funds from financial institutions and Govt. subsidy.	To encourage development of CSP, incentives to be provided to the prospective developers, opting for setting up CSP in the country. Financial institutions should disseminate knowledge on solar power so that they become more aware of the sector as a whole, including CSP. Only then financial institutions can lend money to CSP developers similar to Solar PV developers.

Table 19: Key challenges to CSP growth

Sl. No.	Challenges	Related issues	Proposed way to address the issues
5.	Bankable PPA	Developers need some sort of guarantees of payment with regard to electricity delivered by the CSP projects, as a risk mitigation measure.	There is a need of a Bankable PPA between CSP projects and buyers of the solar power with regard to guarantee of payment by the buyers of electricity from these projects. Project developers are required to acquire realistic ground measurement of DNI, in order to keep the performance of the plant at the level required as per the PPA. This will also satisfy the financial institutions.
6.	CSP component supply	The CSP components required to be imported have a bearing on foreign exchange, creating an uncertainty to CSP developers due to long duration between time of bidding for the project and time of procurement of components.	There is a need for domestic manufacturing of the CSP components under the Aatma Nirbhar Bharat scheme of the Govt. of India, with Govt. subsidies or incentives like PLI etc.

Source: TERI Compilation from: CERC Tariff Order for FY2014-15; ESMAP: Study on barriers for solar power development in India

8. Benefits of CSP

Concentrated Solar Power (CSP), as a renewable energy technology, is also an essential component of the transition to an energy system that is less damaging to the environment and health of the population, and that provides greater energy security. CSP uses a local, free energy source: the sun, for generating electricity, thereby reducing dependency on fossil-based fuel.

CSP offers various range of services and benefits that complement other generation options to meet growing demand for affordable, secure, and clean power while offering opportunities for domestic, industrial and social development. Some of the key benefits of CSP are presented below:

» CSP provides a relatively continuous source of electricity, particularly in comparison to solar photovoltaics (PV) and wind power, which provide intermittent supplies. The electricity generated is predictable and reliable, because CSP plants can store solar energy in the form of thermal energy storage, such as molten salts, etc.

» CSP can serve as a dispatchable energy source–providing power when it is most needed, such as during evening peaks–or even as a baseload power which offers stable power continuously. This is an extremely valuable attribute given the intermittency of solar PV (solar panels) and wind energy, which rely on the sun and wind to produce their energy.

  · CSP with thermal energy storage:

  · allow higher capacity factors, dispatchability, contribute to grid balancing, spinning reserve, and ancillary services.

  · is a flexible renewable resource that can quickly ramp up and down in response to demand and needs of the grid operator.

  · can increase the security of an energy system by operating flexibly and for longer load hours than solar photovoltaics.

» Losses in thermal storage cycles are much less as compared to other existing electricity storage technologies (including pumped hydro and batteries). This makes thermal storage available in CSP plants more effective and less costly.

» CSP can be integrated into existing steam-based power plants, like those running on fossil fuels. This type of hybrid system saves fossil fuel consumption.

» Despite higher capital investments than some other energy sources, CSP offers considerable long-term benefits as compared to thermal power plants, because of minimum fuel costs and lower O&M costs.

» An emerging field is the utilization of CSP thermal energy in heat-intensive industrial processes. CSP can help supplant fossil fuels in sectors such as cement and steelmaking, where fossil fuels are currently the dominant energy source.

9. Way Forward

The report articulates the various range of services and benefits of CSP that complement other generation options to meet growing demand for affordable, secure, and clean power while offering opportunities for domestic, industrial and social development.

The demand for CSP was created in the United States mainly due to the ability of CSP with thermal storage to provide solar power on demand and improve grid integration for renewables.

The 950 MW CSP-PV hybrid plant recently set up in Dubai provides solar power at $7.30 cents per kWh, a price competitive with fossil fuel-based power generation, on round-the-clock basis, thereby helping the grid shift away from dependency on fossil fuel. The energy stored can be used as needed, even multiple times a day, if necessary.

In view of above, the following recommendations would provide a roadmap for actions required to be taken for developing CSPs in the country:

» **Identification of new sites**

- **Solar irradiance data:**

  CSP projects being dependent on locational solar irradiation a satellite-based solar map providing realistic value of direct normal irradiance (DNI) on a Pan-India basis needs to be developed through any authorized agency like NREL, CIEMET, CIWET, NASA etc. Ground-based measurement would further facilitate in locating sites with optimum DNI suitable for setting up CSPs in India.

- **Developing of solar parks for setting up CSP Plants**

  Solar parks can be developed based on identified sites with optimum DNI based on satellite & ground-based measurement, as detailed above.

  The solar parks will provide contiguous parcels of land with all clearances, transmission system, water access, road connectivity, communication network, etc. The solar parks will facilitate and speed up installation of grid connected CSPs on a large scale in the range of 20 MW to 100 MW.

  Financial institutions such as PFC, IREDA etc., may provide the required finance to park developers for site selection, preparatory works, preparation of detailed project reports, and for obtaining environment and forest clearances, etc.

The solar parks are required to be developed in collaboration with State Governments and their agencies. Developing and maintaining the solar parks are required to be done by the state designated agencies.

- **Natural phenomena**

  Sites identified for CSP should avoid such areas with history of such natural phenomena such as earthquakes and storm as they generally have an impact on the costs of energy systems.

» **Bidding for CSP plants: Tariff based competitive bidding in a phased manner**

- **Bidding for smaller capacities**

  In order to promote CSP plants, the initial bidding may be carried out considering capacities in the range between 20 MW and 50 MW in the areas identified in solar parks. The selection of projects needs to be technology agnostic. Bidders may be invited with tariff based on capacity and number of hours of operation to deliver power.

  The timeline for bidding may be of the order of 180 days, to provide the potential bidders enough time to decide the technology, optimal capacity and select technology partner as well as EPC contractor. This will increase competition and result in lower price bids. This will also reduce the time for completion of the project after the award of the contract as the site being within the solar park and technology being agnostic, bidders would have finalized the technical details during the bid process.

  A Bankable PPA between CSP project developers and the buyers of solar power would provide guarantee payment to the project developers.

- **Bidding for larger capacities**

  The success of initial round of bidding for smaller capacities would build bidder's confidence and provide platform for larger capacities. The next round of bidding could include larger capacity in the range between 50 MW and 100 MW in the areas identified in solar parks. The bidding parameters and the bidding methodology would be same as detailed above for smaller capacities. Future capacities may be increased to 150 MW and above.

» **Reducing import dependency**

  With the maturity of CSP in India, import dependency can be reduced in a phased manner, and encourage domestic manufacturing of CSP components under the Aatma Nirbhar Bharat scheme of the Government of India, with Govt. subsidies or incentives like PLI scheme etc.

10. Conclusion

- Globally CSP plants are growing due to their ability to provide dispatchable renewable energy on demand. Large-scale CSP plants are being developed and constructed currently in China, Morocco, South Africa and the UAE. Declining cost and higher thermal storage hours provide opportunity for adoption of CSP technology.
- Compared to solar PV and wind power, CSP provides a relatively continuous source of electricity. CSP-PV hybrid plant in Dubai has proved that it is possible to provide round-the-clock power supply without depending on fossil fuels.
- Further, CSP plants can provide storage and generation of solar power for remote areas where other storage options such as pumped storage hydro plants are not possible to set up.
- Next generation systems currently in development are seeking to reduce costs, by incorporating new heat transfer media such as supercritical CO_2, particle-based energy storage, new molten salt technology for higher-temperature storage, liquid metal and other next generation technologies under development.
- India endowed with vast potential of solar resources, has the opportunity to adopt CSP technology considering the benefits and the global development of CSP. Competitive bidding in a phased manner as mentioned in previous section, would pave the way for lower tariff. With scaling up of CSP capacity in future, the need for new fossil fuel based thermal stations would reduce.
- Domestic manufacturing of CSP components can further bring down tariff of power from CSP plants comparable with conventional power tariff.

Annexure

Annexure-1: Details of CSP in Spain, USA and China

Table 20: Details of CSP plants in Spain

Sl. No.	Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/ year)	Solar field area (m²)	Solar field area (m²/ MW)	Status
1.	Andasol-1	50	2008	Parabolic Trough	2,260	5,10,120	10,202	Operational
2.	Andasol-2	50	2009	Parabolic Trough	2,260	5,10,129	10,203	Operational
3.	Andasol-3	50	2011	Parabolic Trough	2,260	5,10,120	10,202	Operational
4.	Arcosol-50	50	2011	Parabolic Trough	2,007	5,10,120	10,202	Operational
5.	Arenales	50	2013	Parabolic Trough	2,064	5,10,120	10,202	Operational
6.	Aste-1A	50	2012	Parabolic Trough	2,104	5,10,120	10,202	Operational
7.	Aste-1B	50	2012	Parabolic Trough	2,104	5,10,120	10,202	Operational
8.	Astexol II	50	2012	Parabolic Trough	2,055	5,10,120	10,202	Operational
9.	Borges Termosolar	22.5	2012	Parabolic Trough	1,878	1,83,120	8,139	Operational
10.	Casablanca	50	2013	Parabolic Trough	2,064	5,10,120	10,202	Operational
11.	CRS	5	2012	Parabolic Trough		10,560	2,112	Operational

Table 20: Details of CSP plants in Spain

Sl. No.	Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/ year)	Solar field area (m²)	Solar field area (m²/ MW)	Status
12.	Enerstar	50	2013	Parabolic Trough	1,992	3,39,506	6,790	Operational
13.	Extresol-1	50	2010	Parabolic Trough	2,096	5,10,120	10,202	Operational
14.	Extresol-2	50	2010	Parabolic Trough	2,096	5,10,120	10,202	Operational
15.	Extresol-3	50	2012	Parabolic Trough	2,096	5,10,120	10,202	Operational
16.	Gemasolar	20	2011	Power Tower	2,072	3,04,750	15,238	Operational
17.	Guzman	50	2012	Parabolic Trough	2,064	3,10,406	6,208	Operational
18.	Helioenergy-1	50	2011	Parabolic Trough	2,159	3,00,000	6,000	Operational
19.	Helioenergy-2	50	2012	Parabolic Trough	2,068	3,00,000	6,000	Operational
20.	Helios-I	50	2012	Parabolic Trough	2,092	3,00,000	6,000	Operational
21.	Helios-II	50	2012	Parabolic Trough	2,092	3,00,000	6,000	Operational
22.	Ibersol Ciudad Real	50	2009	Parabolic Trough	2,042	2,87,760	5,755	Operational
23.	La Africana	50	2012	Parabolic Trough	2,062	5,50,000	11,000	Operational
24.	La Dehesa	50	2011	Parabolic Trough	2,069	5,52,750	11,055	Operational
25.	La Florida	50	2010	Parabolic Trough	2,086	5,52,750	11,055	Operational
26.	La Risca	50	2009	Parabolic Trough	2,085	3,52,854	7,057	Operational

Table 20: Details of CSP plants in Spain

Sl. No.	Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/year)	Solar field area (m²)	Solar field area (m²/MW)	Status
27.	Lebrija-1	50	2011	Parabolic Trough	2,065	4,12,020	8,240	Operational
28.	Majadas-I	50	2010	Parabolic Trough	2,086	3,72,240	7,445	Operational
29.	Manchasol-1	50	2011	Parabolic Trough	2,107	5,10,120	10,202	Operational
30.	Manchasol-2	50	2011	Parabolic Trough	2,107	5,10,120	10,202	Operational
31.	Moron	50	2012	Parabolic Trough	2,068	3,80,000	7,600	Operational
32.	Olivenza-1	50	2012	Parabolic Trough	2,053	4,02,210	8,044	Operational
33.	Orellana	50	2012	Parabolic Trough	2,074	4,05,500	8,110	Operational
34.	Palma del Rio-I	50	2011	Parabolic Trough	2,064	3,72,240	7,445	Operational
35.	Palma del Rio-II	50	2010	Parabolic Trough	2,064	3,72,240	7,445	Operational
36.	Planta Solar 10	11	2007	Power Tower	2,076	75,000	6,818	Operational
37.	Planta Solar 20	20	2009	Power Tower	2,076	1,50,000	7,500	Operational
38.	Puerto Errado-1	1.4	2009	Linear Fresnel	1,996	48,562	34,687	Operational
39.	Puerto Errado-2	30	2012	Linear Fresnel	1,996	3,02,000	10,067	Operational
40.	Solaben-1	50	2013	Parabolic Trough	2,076	3,00,000	6,000	Operational
41.	Solaben-2	50	2012	Parabolic Trough	2,076	3,00,000	6,000	Operational

Table 20: Details of CSP plants in Spain

Sl. No.	Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m^2/year)	Solar field area (m^2)	Solar field area (m^2/MW)	Status
42.	Solaben-3	50	2012	Parabolic Trough	2,076	3,00,000	6,000	Operational
43.	Solaben-6	50	2013	Parabolic Trough	2,076	3,00,000	6,000	Operational
44.	Solacor-1	50	2012	Parabolic Trough	2,042	3,00,000	6,000	Operational
45.	Solacor-2	50	2012	Parabolic Trough	2,042	3,00,000	6,000	Operational
46.	Solnova-1	50	2009	Parabolic Trough	2,076	3,00,000	6,000	Operational
47.	Solnova-3	50	2009	Parabolic Trough	2,076	3,00,000	6,000	Operational
48.	Solnova-4	50	2009	Parabolic Trough	2,076	3,00,000	6,000	Operational
49.	Termesol-50	50	2011	Parabolic Trough	2,007	5,10,120	10,202	Operational
50.	Termesol-1	50	2013	Parabolic Trough	2,077	5,23,200	10,464	Operational
51.	Termosol-2	50	2013	Parabolic Trough	2,077	5,23,200	10,464	Operational
	Total capacity	**2309.9**						

Table 21: Details of CSP plants in USA

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/year)	Solar field area (m²)	Solar field area (m²/MW)	Status
Crescent Dunes	110	2015	Power Tower	2,734	11,97,148	10,883	operational
Genesis	250	2014	Parabolic Trough	2,676	19,28,320	7,713	operational
Holaniku	2	2009	Parabolic Trough	-	15,378	7,689	Non-operational
Ivanpah	377	2014	Power Tower	2,768	26,00,000	6,897	operational
Kimberlina	5	2008	Linear Fresnel	-	25,988	5,198	Non-operational
Maricopa	1.5	2010	Dish	-	-	-	Non-operational
Martin Next Generation	75	2010	Parabolic Trough	1,799	4,64,908	6,199	operational
Mojave	280	2014	Parabolic Trough	2,888	15,59,347	5,569	operational
National Solar Thermal Test Facility	5	1976	Power Tower	-	-	-	operational
Nevada Solar One	72	2007	Parabolic Trough	2,625	3,57,200	4,961	operational
Saguaro	1	2006	Parabolic Trough	-	10,340	10,340	Non-operational
Sierra Sun Tower	5		Power Tower	-	27,670	5,534	Non-operational
Solana	250	2013	Parabolic Trough	2,784	22,00,000	8,800	operational
Solar Electric Generating Station-I	13.8	1984	Parabolic Trough	2,885	82,960	6,012	Decommissioned

Table 21: Details of CSP plants in USA

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m^2/ year)	Solar field area (m^2)	Solar field area (m^2/ MW)	Status
Solar Electric Generating Station-II	30	1985	Parabolic Trough	2,885	1,90,338	6,345	Decommissioned
Solar Electric Generating Station-III	30	1985	Parabolic Trough	2,987	2,30,300	7,677	Decommissioned
Solar Electric Generating Station-IV	30	1985	Parabolic Trough	2,987	2,30,300	7,677	Decommissioned
Solar Electric Generating Station-IX	80	1990	Parabolic Trough	2,893	4,83,960	6,050	operational
Solar Electric Generating Station-V	30	1989	Parabolic Trough	2,987	2,50,500	8,350	Decommissioned
Solar Electric Generating Station-VI	30	1989	Parabolic Trough	2,987	1,88,000	6,267	Decommissioned
Solar Electric Generating Station-VII	30	1989	Parabolic Trough	2,987	1,94,280	6,476	Decommissioned
Solar Electric Generating Station-VIII	80	1989	Parabolic Trough	2,893	4,64,340	5,804	Decommissioned

Table 21: Details of CSP plants in USA

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/year)	Solar field area (m²)	Solar field area (m²/MW)	Status
Solar One	10	1982	Power Tower	2,885	72,650	7,265	Decommissioned
Solar Two	10	1995	Power Tower	2,885	-	-	Decommissioned
Stillwater GeoSolar	2	2015	Parabolic Trough	-	-	-	operational
Tooele Army Depot	1.5		Dish	-	-	-	Non- operational
Total capacity	1810.8						
Operational capacity	1501						

Table 22: Details of CSP plants in China

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/year)	Solar field area (m²)	Solar field area (m²/MW)	Status
Badaling Dahan	1	2012	Parabolic Trough	1,290	10,000	10,000	Operational
CEEC Hami	50	2019	Power Tower	1,789	6,96,751	13,935	Operational
CEIC Dunhuang	100	2023	Linear Fresnel	1,649	-	-	Under Construction
CGN Delingha	50	2018	Parabolic Trough	1,950	6,20,000	12,400	Operational

Table 22: Details of CSP plants in China

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m²/year)	Solar field area (m²)	Solar field area (m²/MW)	Status
CSNP Urat	100	2020	Parabolic Trough	2,170	11,50,000	11,500	Operational
Huaqiang TeraSolar	15	2018	Linear Fresnel	-	1,70,000	11,333	Operational
Huidong New Energy Akesai	110	2023	Beam-Down Tower	-	-	-	Under Construction
Jinta Zhongguang	100	2023	Power Tower	-	-	-	Under Construction
Lanzhou Dacheng Dunhuang-1	10	2016	Linear Fresnel	1,786	-	-	Operational
Lanzhou Dacheng Dunhuang-2	50	2019	Linear Fresnel	1,649	12,70,000	25,400	Operational
LuNeng Haixi	50	2019	Power Tower	1,945	6,10,000	12,200	Operational
Power China Qinghai Gonghe	50	2020	Power Tower	1,883	5,16,000	10,320	Operational
Shouhang Dunhuang Phase-I	10	2016	Power Tower	1,777	1,75,375	17,538	Operational
Shouhang Dunhuang Phase-II	100	2018	Power Tower	1,777	14,00,000	14,000	Operational
SUPCON Delingha-I	10	2013	Power Tower	2,043	63,000	6,300	Operational

Table 22: Details of CSP plants in China

Power plant	Capacity (MW)	Start year	Technology	Solar irradiation (kWh/m^2/year)	Solar field area (m^2)	Solar field area (m^2/MW)	Status
SUPCON Delingha-II	50	2018	Power Tower	2,043	5,42,700	10,854	Operational
Yumen Xinneng/ Xinchen	50	2021	Beam-Down Tower	1,641	2,08,240	4,165	Operational
Total capacity	906						
Operational capacity	596						

Annexure-2: Rankine Cycle

The Rankine cycle is a thermodynamic cycle involving a constant pressure heat engine which converts heat into mechanical work. The heat is supplied externally in this cycle in a closed loop, which uses either water or any other organic fluids as a working fluid. The Rankine cycle is the process widely used by power plants such as coal-fired power plants or nuclear reactors.

Working Principle of Rankine Cycle

A Rankine cycle has four thermodynamic processes which are explained below referring to the diagram.

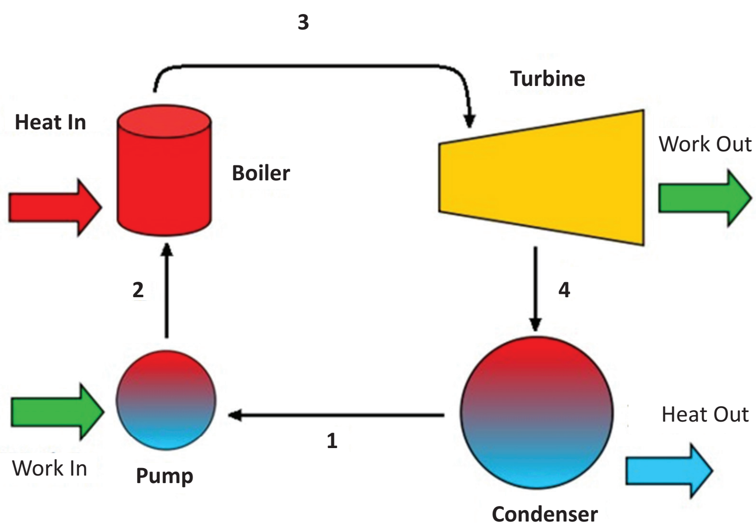

Figure 30: Schematic of Rankine Cycle

» Process 1-2: The working fluid (saturated liquid) entering the pump, is pumped from a low to high pressure. This is also known as isentropic compression. The input energy is needed at this stage.

» Process 2-3: Liquid at a high pressure entering the boiler is heated by an external heat source at a constant pressure. The liquid is converted to dry saturated steam by constant pressure heat addition in the boiler.

» Process 3-4: The dry saturated steam from the boiler expands as it enters the turbine. It is also known as isentropic expansion. Due to this, the temperature and pressure of the steam decreases.

- Process 4-1: The wet vapour entering the condenser at this stage is condensed at a constant pressure. It is then converted to saturated liquid. This process is also known as constant pressure heat rejection in the condenser (isobaric heat rejection). This saturated liquid is again circulated back to the pump, and the cycle continues. The heat rejected or the exhaust heat after the final stage is represented as Heat out.

A simple illustration of Rankine cycle in a nuclear power plant is shown below.

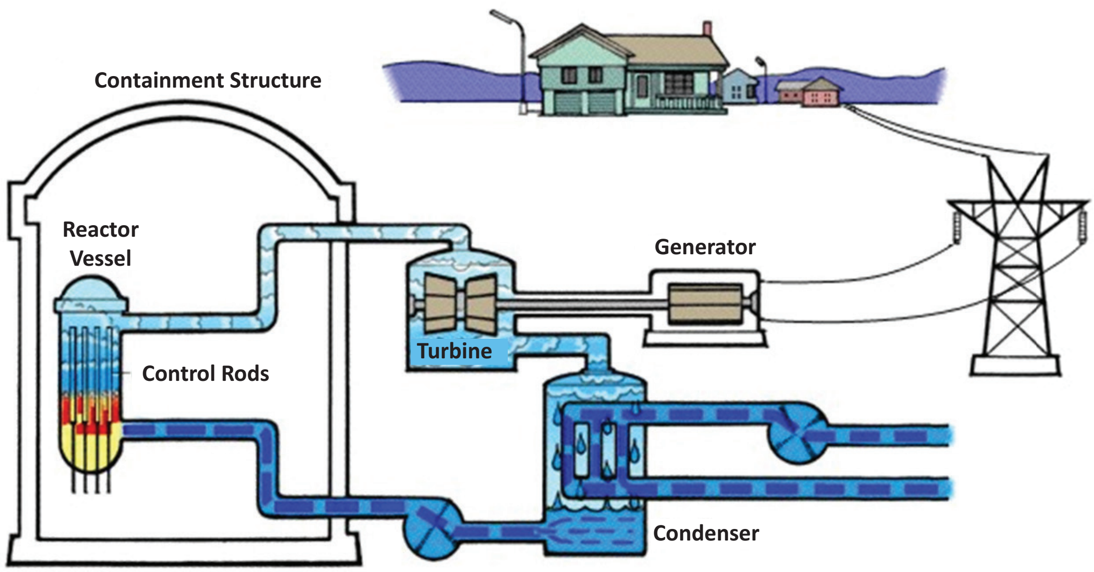

Figure 31: Rankine cycle in a nuclear plant

Source:https://testbook.com/mechanical-engineering/rankine-cycle-process-diagram-and-applications#:~:text=The%20Rankine%20cycle%20is%20the,continuous%20cycle%20of%20evaporation%20%26%20condensation;https://energyeducation.ca/encyclopedia/Rankine_cycle;https://www.theengineeringconcepts.com/thermodynamic-cycle-2/)

Annexure-3: Brayton cycle

The Brayton Cycle is a thermodynamic cycle used in gas turbine engines and power plants to convert heat energy into mechanical work. The Brayton Cycle operates on the principle of **constant pressure heat addition** and **constant pressure heat rejection**. The sequence of operation for Brayton cycle is:

» Process 1-2: Adiabatic (compression)

» Process 2-3: Isobaric (heat addition)

» Process 3-4: Adiabatic (expansion)

» Process 4-1: Isobaric (heat rejection)

The Brayton cycle consists of a compression stage (process 1–2) which takes place adiabatically followed by a second stage (process 2–3)–the heat addition process–which occurs isobarically. The third stage (process 3–4) is an expansion process which occurs adiabatically and the final stage (process 4–1), heat rejection, occurs isobarically, as shown in the figure below.

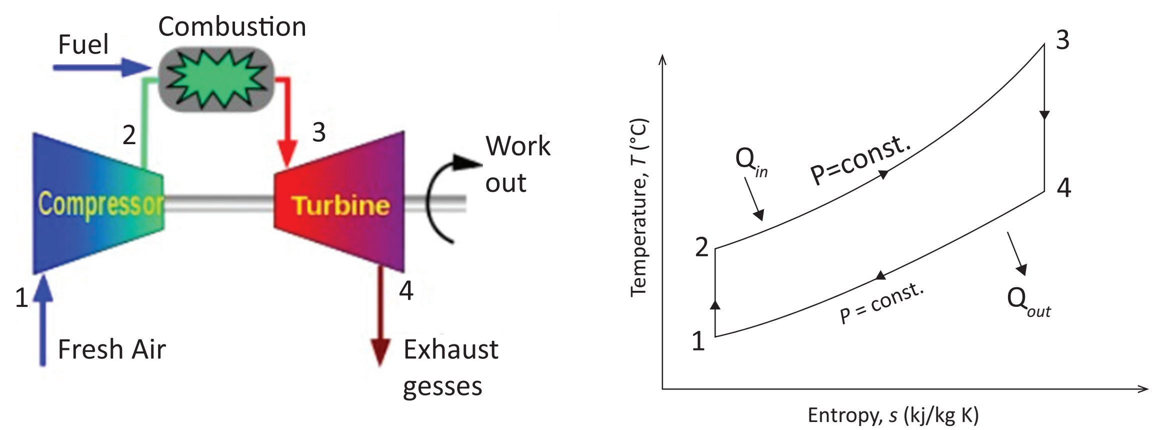

Figure 32: Brayton cycle operation and temperature entropy graph for a Brayton cycle

Source: https://www.theengineeringconcepts.com/thermodynamic-cycle-2/

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