Concentrated solar power in India: current status, challenges and future outlook

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India is blessed with good solar resources and many regions of the country receive above-average sunshine compared to other regions of the world. The primary technology used for harnessing and converting solar energy into electrical energy in India is based on photovoltaic (PV) cells. Concentrated solar power (CSP) has hardly contributed to the overall installed solar power capacity in the country. In this article, some of the challenges that have inhibited the growth of CSP are identified and possible solutions suggested. The critical challenges for CSP are related to the lack of reliable direct normal irradiance database, indigenous manufacturing and competition from PV. The results of a case study carried out to assess the impact of indigenous manufacturing and economies of scale on capital costs and levelized cost of electricity are presented. This study shows that even with indigenous manufacturing and considering economies of scale, the capital cost per MW (Megawatt) of installed capacity is higher than the Central Electricity Regulatory Commission benchmark costs. To initiate larger adoption of CSP in India, we may have to consider alternative configurations, such as coupling desalination or thermal cooling systems to a CSP power plant. The merits of such configurations, called poly-generation plants, are presented for the Indian scenario.

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ALL forms of energy that are driving our economic progress can be traced back to the sun. For centuries mankind has been harnessing energy from the sun, directly or indirectly. The indirect mode of using solar energy is by fossil fuel. As a consequence of exponential economic growth, fossil fuels have been excessively used and has resulted in global climate changes[1]. In recent years, interest in harnessing renewable energies, especially solar energy, has increased. This is quite obvious as the earth's surface receives enormous amounts of solar energy, totaling to about 885 million TWh per annum. This is several times more than the energy consumption of the world[2]. However, solar energy is intermittent in nature and is difficult to harness completely.

The solar energy falling on a horizontal surface on the earth has two major components to it, namely the direct normal irradiance (DNI) and diffused horizontal irradiance (DHI). DNI is the direct portion of the solar irradiance which strikes the surface normal to the sun's beam and DHI is the scattered portion of the solar irradiance due to earth's atmosphere.

Solar energy is harnessed by either using photovoltaic (PV) cells or solar thermal collectors. PV cells are made of silicon semiconductors which directly convert photons in the solar radiation into electrical energy.

Polycrystalline silicon is the most widely used semiconductor material in the manufacture of solar panels. The typical efficiency of such panels ranges from 17% to 21% (ref. 3). There are other semiconductor materials such as gallium arsenide, which have an efficiency of around 28% (ref. 4). Unlike PV cells, a solar thermal collector absorbs solar radiation and converts it to thermal energy or heat. The thermal energy from these collectors can then be used for process heating applications or for generating steam to run turbines. There are two types of solar thermal collectors: concentrating type which uses reflectors (mirrors or lens) to increase the energy density falling on the absorbing surface of a collector, and non-concentrating type which does not use any form of reflectors and simply absorbs the incident solar radiation.

The concentrating collectors, typically referred to as concentrated solar power (CSP) system, operate by harnessing the DNI component of solar irradiance. A CSP system mainly consists of a series of reflectors which are used for concentrating the solar radiation onto a receiver, which absorbs and converts the concentrated solar radiation to thermal energy. A heat transfer fluid (HTF) is circulated in the receiver, where it absorbs and transfers the thermal energy gained to either a thermal energy storage (TES) or a heat exchanger to produce steam. Thus,

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the generated steam will be either used for process heating or for power generation. As mentioned earlier, beam radiation is required for CSP systems to generate energy and to ensure this, a tracking device which is attached to the reflectors constantly tracks the strong motion of the sun. A typical CSP plant is shown in the Figure 1, which consists of collector assemblies, TES, solar field heat exchanger and power block. The land area where the solar harnessing components are installed is called the solar field. The solar-to-electric efficiencies of CSP systems depend on the temperature at which they operate and generally range from 12% to 26% (ref. 5).

The current worldwide capacity for CSP is around 5.2 GW (ref. 6). CSP technologies are broadly classified as either line focusing or point focusing. The point focusing concentrators are used for high-temperature applications (400–750°C)[7,8], whereas the line focusing concentrations are used for low- to medium-temperature applications (100–550°C)[9,10]. Four types of CSP technologies are currently being installed. These are the line focusing parabolic trough collector (PTC), linear Fresnel reflector (LFR), point focusing solar tower (ST) and parabolic dish.

PTC consists of a parabolic-shaped reflector which collects DNI and reflects it onto a receiver placed at the focus of the parabolic mirror. To maintain focus, the PTC continuously tracks the sun and the receiver converts the solar radiation into thermal energy. PTC can operate up to a maximum temperature of 550°C (ref. 11) and use either synthetic oils or molten salts (depending on the maximum operating temperature) as HTF. LFR technology consists of a series of linear strips of mirrors which reflect the solar radiation onto a linear reflector. Like PTC, LFR can operate at a maximum temperature of about 550°C (ref. 9) and has a slightly lower capital cost as compared to PTC (ref. 12). However, the cost of electricity generation for LFR is higher compared to PTC because of lower concentration ratios and higher cosine effects. ST technology consists of a central receiver (volumetric or cavity type) mounted on a tall tower surrounded by an array of mirrors (flat or slightly curved) called heliostats, reflecting the solar radiation onto the central receiver. Heliostats have trackers which ensure that the solar radiation being reflected always falls on the receiver. ST has an operating temperature of around 550°C and hence has higher efficiency compared to PTC. Parabolic dish collector, a fledging CSP technology can be used for small-scale power generation, e.g. as a replacement for diesel generators. To generate electricity, a Stirling engine is used which is placed at the focus of the parabolic dish reflector. Parabolic dishes can also be used for domestic and industrial process heating applications such as in textile and paper industries, cooking, etc.

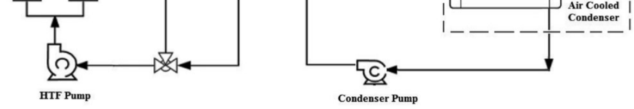

Figure 1. A schematic of a typical concentrated solar power plant with thermal storage system[24].

The minimum required DNI above which power generation would become feasible is around 200 W/m^2 (ref. 13), whereas the average annual DNI for India is around 600 W/m^2 (ref. 14). Also, CSP plants can run economically only when the annual insolation is greater than 1800 kWh/m^2/year (ref. 15), which is the annual average insolation for India. Therefore, there is high potential for widespread adoption of CSP technologies in the country.

Current status of CSP in India

The PTC technology is the most mature amongst the CSP technologies contributing almost 4.4 GW of the worldwide installed capacity of 5.2 GW (ref. 6). ST technology contributes approximately 0.6 GW and the other two technologies hardly contribute 0.2 GW towards the total installed global capacity[6]. The total installed CSP capacity in India is around 228.5 MW, with major contribution coming from LFR which is around 125 MW, whereas parabolic trough contributes close to 101 MW and ST nearly 2.5 MW (ref. 12). Parabolic dishes have been primarily restricted to demonstration plants based on Stirling engine and are set up by the Ministry of New and Renewable Energy (MNRE), Government of India in collaboration with Oil and Natural Gas Corporation (ONGC). The upcoming CSP plants in India are all PTC-based with the total capacity adding to 275 MW. This shows that PTC technology will be preferred in India due to its well established supply chain[12]. Table 1 shows the CSP plants which are both operational and under construction.

It is clear from Table 1 that CSP technologies have not yet been adopted widely throughout the country. India lags behind other global leaders such as Spain and the Unites States. The challenges impeding the growth of CSP in India are identified and discussed below.

Challenges for CSP in India

As mentioned earlier, CSP technologies have not yet been adopted widely throughout India compared to PV technology. Some of the challenges observed during the

Table 1. Location, technology type, capacity and current status of various CSP plants in India[12]

Project	Technology type	Capacity (MW)	Current status
Dhursar	Fresnel reflector	125	Operational
Godawari Solar Project	Parabolic trough	50	Operational
Megha Solar Plant	Parabolic trough	50	Operational
ACME Solar Tower	Solar tower	2.5	Operational
National Solar Thermal Power Facility	Parabolic trough	1	Operational
Diwakar	Parabolic trough	100	Under construction
KVK Energy Solar Project	Parabolic trough	100	Under construction
Abhijeet Solar Project	Parabolic trough	50	Under construction
Gujarat Solar One	Parabolic trough	25	Under construction
Dadri ISCC Plant	Fresnel reflector	14	Under Construction
Rajasthan Solar One	Parabolic trough	10	Under construction

first phase of the solar mission were low investor confidence, lack of indigenous manufacturing, unreliable solar data, etc. We will examine in detail these challenges and provide probable solutions.

Low investor confidence

For any technology to be successful in the market, investments play a pivotal role. One of the major reasons for the limited adoption of CSP technologies in India can be attributed to the lack of investor confidence in these technologies. This could be because of fewer demonstration plants for each of the CSP technologies in the country. For example, during implementation of the Jawaharlal Nehru National Solar Mission (JNSSM) Phase-1, there were no demo plants for testing the techno-economic feasibility. Some of the operational pilot plants in India did not provide reliable data for the investors to confidently invest in CSP technologies. Lack of investments in research and development (R&D) and policy guidelines could be some of the reasons for fewer pilot plants as there were supply chain constraints due to limited indigenous manufacturers. R&D plays an important role in improving the performance of the system and in bringing down the capital cost by improving the indigenous manufacturing ecosystem.

Lack of indigenous manufacturing

In India, most of the components of a CSP plant, especially the solar field components are currently imported. This is because the country does not have any indigenous manufacturing units to cater to the demand of critical components such as mirrors, absorber tubes, etc. Also, a report by the World Bank indicates that importing would have an additional cost on the solar field components[16]. Indigenous manufacturing of some of the key components can bring down the capital cost as India can provide the required labour force at a low cost. A study jointly conducted by the World Bank and Energy Sector Management Assessment Program (ESMAP) reported cost reduction potential of 30% for receiver tubes, 28% for reflectors and 40% for support structures[17]. A further reduction in the cost of energy generation for CSP can be achieved by integrating thermal energy storage into the CSP plants[18], which would increase the capacity utilization factor of the plant[19].

Low availability of skilled labour

Skilled manpower is important for successfully completing and commissioning CSP plants on time. During the JNNSM Phase-1, some of the projects were delayed due to lack of experience in handling and installing the solar field components. Therefore, for CSP to have large-scale adoption, the development of required skilled human resource is mandatory. Government institutions like the National Institute of Solar Energy (NISE) could conduct workshops and training programmes on solar power equipment handling and installation, which may result in enhancing the skills of the workforce.

Unreliable solar data

The other challenge for CSP in India are the unreliable DNI data for any location in the country. Generally, National Renewable Energy Laboratory (NREL) data, Centre for Energy, Environment and Technology (CIEMAT) data and National Institute of Wind Solar Radiation data have been used by solar plant designers to calculate the land and mirror area requirements. The solar power plants which were designed based on DNI data from these organizations have generally underperformed. For example, the Godavari Green project used the wrong DNI value to calculate the number of loops required (around 80), which was less than the actual loops required (around 120)[20]. A possible solution would be to use satellite-based data as against the unreliable ground-based data.

Table 2. Current solar field component cost used for simulating cases 1–3

Case	Cost of mirror (Rs/m^2)	Cost of absorber tube (Rs./m)	Cost of HTF (Rs/litre)	Cost of support structure (Rs/m^2)	Cost of thermal energy storage (Rs kWh)	Cost of hydraulic tracking system (Rs/unit)	Cost of swivel joint (Rs/unit)
1	2,450	14,250	200	2,850	1,710	130,000	70,000
2	1,764	9,975	140	1,710	1,197	91,000	49,000
3	1,470	8,550	120	1,425	1,026	78,000	42,000

Availability of water

Another critical resource that is required for successfully running a CSP plant is water. The International Energy Agency has estimated that PTC plant requires close to 3 m^3/MWh and the ST plant requires less than 2 m^3/MWh. Unfortunately, areas of high DNI, where CSP plants are economically feasible, suffer from acute water shortage. A possible solution to the problem is using dry cooling, but the performance of the plant decreases by 7% and the cost of generation increases by 10% (ref. 20).

High cost compared to PV

Finally, the major challenge for widespread adoption of CSP technologies is from the competitive PV. For utility-scale plants, the capital cost per MW required to setup a CSP plant is around Rs 12 crores (ref. 21), whereas the cost to setup an equivalent capacity PV plant would be around Rs 5 crores. The low investment cost for PV will result in a lower cost of electricity generation compared to CSP (2.5 times lower). Also, the CSP plants are much more difficult to maintain and operate compared to PV plants. This makes CSP unattractive and capital-intensive for the investors.

Next, we will look at the possible avenues for cost reduction, which could bring in a turnaround in the current CSP adoption trends.

Impact of indigenous manufacturing and economies of scale on LCOE: a case study

India has the potential to become a truly global major in CSP technologies, provided some, if not all, of the challenges mentioned above are addressed. The challenges that have to be addressed immediately pertain to building demonstration CSP plants, creating reliable DNI database and manufacturing sub-components locally.

As mentioned earlier, one of the major issues plaguing large-scale CSP adoption is the relatively high capital and energy generation cost. Economies of scale and indigenous manufacturing are factors which could lead to cost reduction in CSP. These two factors will play an important role when Gigawatts (GW)-scale plants are being set up. To better understand the impact of indigenous manufacturing and economies of scale on the capital cost and on levelized cost of electricity (LCOE), a techno-economic case study is presented for a DNI-rich location such as Jodhpur in Rajasthan. A techno-economic analysis tool called CSTEM-PT was used (for more details, see http://www.cstep.in/expertise/tools-and-models). This tool takes in various technical and cost inputs for each of the sub-components of the solar field and power block and then calculates as outputs, the technical metrics such as land and mirror area required, gross electrical energy generated, etc., and financial metrics such as total capital cost, LCOE, rate of returns, etc. Suresh *et al.*[22], discussed the methodology used and validation of the CSTEM-PT tool. For the first case, the current market cost values were used for simulation using the CSTEM-PT tool. These cost values have been used based on discussion with industry sources. The second case is based on a scenario where indigenous manufacturing could bring down the cost of sub-components by 30–40% (based on World Bank estimates). The third and final case is based on another scenario where indigenous manufacturing and economies of scale could result in a further cost reduction of 40–50% absolute (from industry sources). Table 2 gives some of the important cost values input into CSTEM-PT for the above three cases.

With the above cost inputs, the CSTEM tool was run for a capacity of 30 MW and thermal energy storage of 6 h. Figure 2 *a*, *b* and *c* shows the variations in primary financial metrics such as total capital cost, LCOE and internal rate of returns (IRR) for all three cases respectively. We can observe that with indigenous manufacturing LCOE reduces by 20%, and it would further reduce by about 26% if indigenous manufacturing and economies of scale are considered. This exercise shows that the effect of indigenous manufacturing has more impact on LCOE compared to the effect of economies of scale. The capital cost reduces to Rs 19.5 crores/MW with indigenous manufacturing of sub-components and further reduces to Rs 17.83 crores/MW with indigenous manufacturing and economies of scale. This is still high compared to the CERC benchmark value of Rs 12 crores/MW (ref. 21).

Future outlook for CSP in India

For CSP to become competitive, the thermal energy from the solar field should be utilized much more efficiently than it is at present. One observation in the current CSP plant is that a fairly large portion of the input thermal

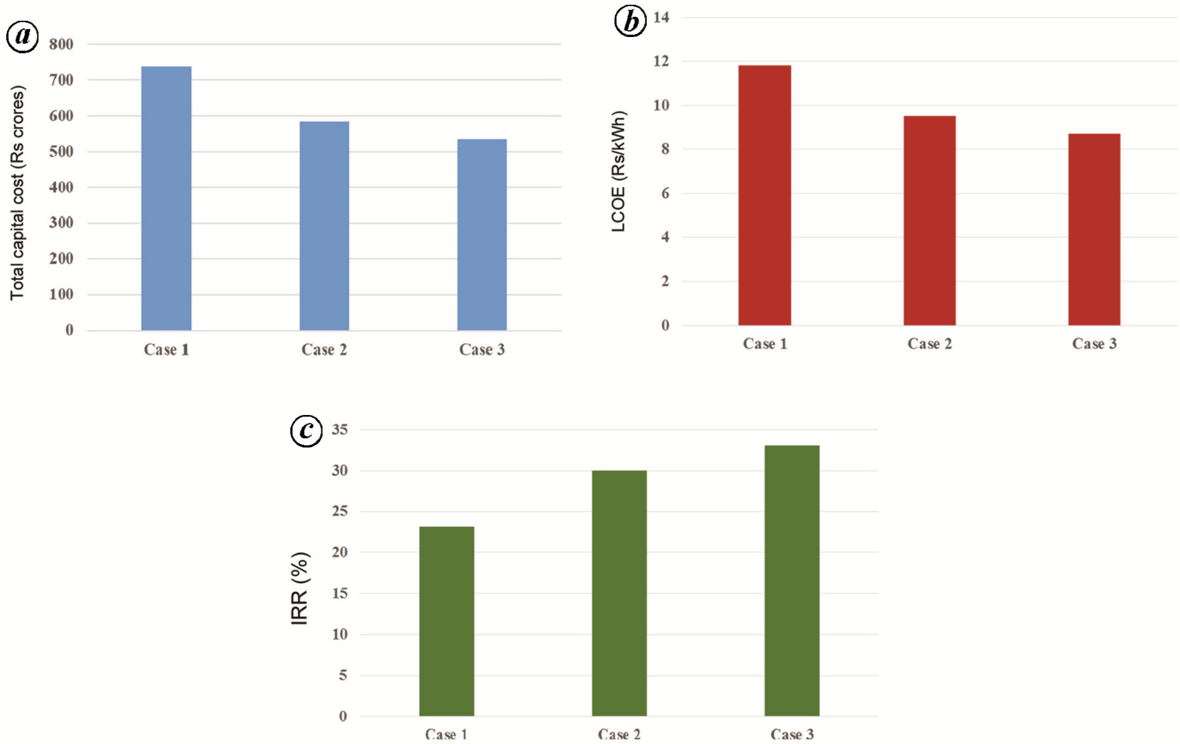

Figure 2. ***a***, Total capital costs obtained for cases 1–3. ***b***, Cost of electricity generation (LCOE) obtained for cases 1–3. ***c***, Internal rate of returns obtained for cases 1–3.

energy has to be rejected in a condenser. If this rejected energy can be utilized to run some other useful process, then the high investment cost of CSP could be justified.

One such process where the condenser-rejected thermal energy could be utilized is in multi-effect distillation (MED). This system requires steam at 70°C (absolute pressure at 0.3 bar), which is well within the operating range of most of the steam turbine exit temperatures. The steam exiting the turbine can then be utilized to generate pure distilled water from sea or brackish water. Thus, by replacing the condenser with the MED system, investment in CSP could be justified. In future, India may face water scarcity. Thus coupling MED systems with CSP could be an attractive solution to alleviate water demands in the country.

Also, cooling systems which require thermal energy input to operate, such as vapour absorption machine (VAM), can also be integrated to CSP with MED plants. There is need for cold storages in India, as most of the agricultural produce goes waste due to lack of storage facilities. These plants (CSP integrated with MED and VAM), commonly called poly-generation plants, are the most efficient CSP-based plants as thermal energy from solar field is utilized in the most efficient manner.

Integrating MED and VAM to a CSP plant will offer triple benefits, i.e. generate power and distilled water, and at the same time provide thermal energy to power cold-storage units. This process of multiple energy generation technique has the potential to reduce cost of energy generation. Sahoo *et al.*[23] showed that a poly-generation plant can save up to 15.3% of primary energy and the net equivalent power from the plant increases by 18.3% compared to a simple CSP plant. The initial investment for a poly-generation plant will be slightly higher compared to a simple power plant, but in the long run it should prove economical[23]. From the above outlined benefits, poly-generation plants could be the future in India and elsewhere in the world.

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