Challenges and Opportunities for Solar Tower Technology in India

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Abstract

Solar Tower technology has gained considerable momentum over the past decade. Unlike the parabolic trough, Solar Tower has a lot of variants in terms of type of receivers, working fluids, power cycles, size of heliostats, etc. Most of the literature available on this technology does not address in great depths, details of various parameters associated with tower technology. A detailed examination of plant parameters is required in order to perform a potential assessment, design basis or feasibility analysis. This paper aims to assess the principal parameters of existing plants, namely, solar to electric conversion efficiency, mirror and land area per MW_e of equivalent capacity, packing density, field layout configuration, receiver size, tower height and gross costs of plants, wherever data is available. Based on this global review of existing plants, it is observed that, the annual solar to electric conversion efficiencies has an average value of 16% and an average packing density of about 20%. Since most of the existing plants have been constructed for demonstration purposes, the true potential of this technology has not yet been realised. Using this assessment as a basis, the technical, financial and policy drivers and barriers for adopting tower technology in India are discussed. It is seen that based on indigenisation prospects, tower technology with external cylindrical or cavity receivers with storage could be adopted. The role and significance of this technology is brought out in the context of the Jawaharlal Nehru National Solar Mission (JNNSM) in order to achieve grid-connected solar power. It is estimated that around 1800 MW of grid connected Solar Tower plants could come up under this mission by 2022.

Keywords: Solar Tower; Global Review; Operational; Under Construction; India; JNNSM;

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1. Introduction

Solar Tower (ST) technology, which is also referred as Central Receiver Technology, uses a large number of heliostats having a dual axis control system (one about the elevation axis and the other about the azimuthal axis). These heliostats reflect direct beam solar radiation (impinging on their surface) to a stationary receiver located at the top of a tower. In the receiver, Heat Transfer Fluid (HTF) gains heat and transfers this thermal energy to the power block to generate electric power. This technology has evolved over the past 20 years. Even though it dates back to the late 1980s, over the past decade, a considerable increase in the number of operational ST plants has been observed. The capacity of plants under construction indicates that the growth of ST technology is on par with that of Parabolic Trough (PT) technology [1].

This paper presents an analysis of the challenges, opportunities and potential of ST technology for Indian conditions, based on a gross assessment of certain parameters of existing plants worldwide. Based on available information, solar to electric conversion ratio, mirror and land area variations with equivalent capacity, field layout configurations, working fluids employed, receiver size estimation, tower height, and gross costs of plants have been examined. Furthermore, an assessment of available solar and land resources in India, technological expertise in terms of engineering, design and manufacturing have also been discussed. Based on this assessment, the potential of ST technology for Indian conditions is estimated.

Most of the literature available on the existing ST plants discuss the overview, plant construction and characteristics [2],[3],[4],[5]. Studies have also been conducted on operation evaluation, modelling and simulation of specific components of plants [6],[7]. A design of reference plants using particular heliostats have been proposed [8]. Also, specific reviews of ST plants [9] as well as reviews of all the Concentrated Solar Power (CSP) technologies (which includes ST) have been performed [10],[11].

While most of the literature identified, discuss in depth, the performance characterisation of components of particular plants, they do not present a methodological assessment of ST parameters. In this paper, a detailed assessment of various parameters of existing ST plants is presented. This is used to infer the challenges and opportunities for employing ST technology in the Indian context.

The total installed capacity of ST plants worldwide is shown in Table 1. It has been compared with PT technology to identify the growth potential of ST in the next few years.

In India, the experience with ST is very limited and is yet to gain momentum. The Jawaharlal Nehru National Solar Mission (JNNSM), one of the eight missions under the Prime Minister's National Action Plan for Climate Change (NAPCC), was released in 2010. The objective of this mission is to achieve 20 GW of grid-connected solar power and 2 GW of off-grid solar power by 2022. The targets set by JNNSM on capacity addition, is shown in Table 2. Planning supported by technology improvement and policy support can lead to high level of solar additions in India.

Section 2 of this paper discusses the assessment of existing plants based on various parameters like solar to electric conversion efficiencies, mirror & land area used for various ST technologies, field layout, tower height etc. Section 3 discusses the challenges and opportunities for ST in India based on technical, financial and policy perspectives for critical parameters. This is done in terms of resource availability (solar and land) and technological expertise (engineering, design and manufacture).

2. Assessment of Existing Plants

Tables 3 and 4, provide information on certain parameters of existing plants, both in operation and under construction. Based on the information available, assessment of the ST plants was carried out, and is discussed in this section.

2.1. Overall Efficiency of Conversion of Solar to Electric Energy

The solar to electric conversion efficiency of any plant is defined using Eq. (1).

$$\eta_{s-e} = \frac{\text{Annual Electricity Generation (MWh)}}{\text{Annual Solar Resource (MWh/m}^2\text{)} \times \text{Heliostat Field Area (m}^2\text{)}} \quad (1)$$

The values of conversion efficiency for various existing plants are calculated and shown in Table 5. In this table, the last column contains calculated values while the other columns contain collated data [13]. It is broadly segregated based on the type of receiver being employed for operational plants and plants under construction. From the table, it is seen that η_{s-e} lies in the range of 15.51% to 17.30%. The Jülich plant has a very low conversion efficiency of 6.16%. This is because air is used as the HTF, which transfers its thermal energy to water. The steam generated in the process drives a Rankine cycle. This is an inept process as the efficiency of heat transfer from air to water/steam is quite low. The average value of η_{s-e} , from Table 5 is found to be about 16%.

2.2. Comparison of Heliostat Field Area and Land Area with respect to Equivalent Capacity

The mirror area and land area per MW_e of rated capacity varies due to the number of thermal storage hours employed. Hence there is a necessity to normalise the mirror and land area taking into consideration the number of hours of thermal storage. In order to do this, it is assumed that with no thermal storage, a typical plant can operate for around nine hours [14],[15],[16]. If x hours of thermal storage are incorporated, then the capacity increases by $(9+x)/9$ times as compared to a similar plant with no thermal storage. We define this as the equivalent capacity (in MW_e) of the plant, given by Eq. (2).

$$\text{Equivalent Capacity} = \text{Rated Capacity} \times \left(\frac{9+x}{9} \right) \quad (2)$$

where, x is the number of hours of thermal storage.

Mirror and land area were compared with rated and equivalent capacity for existing plants, separately, for each type of receiver used.

2.2.1. Mirror Area

Table 6 gives the values of the mirror area per MW_e of rated and equivalent capacity.

It can be seen from the table that the mirror area per MW_e of equivalent capacity (m^2/MW_e) of plants using cavity receivers ranges from about 6000 to 6750 and for plants using external receivers ranges from about 3800 to 6650. It can also be seen that both Rice Solar and Crescent Dunes plants have lesser mirror area/ MW_e compared to other plants. This is because these two sites have higher solar resource (see Table 5). Even though the Ivanpah plant has the highest solar resource, its mirror area/ MW_e is also high since it employs the Direct Steam Generation (DSG) mode for attaining temperatures of the order of 565°C .

A plot of mirror area vs. equivalent capacity is shown in Fig. 1 for operational plants and the curve obtained was found to resemble a linear pattern.

2.2.2. *Land Area*

Table 7 shows the utilisation of land area per MW_e of rated and equivalent capacity.

The land area per equivalent capacity (hectares/ MW_e) for plants with cavity receivers ranges from 1.3 to 4.5 and for plants with external receivers ranges from 2 to 3.7. Here, the variation could be due to the type of receiver employed, height of the tower, sizes of heliostats used, and further, due to the variations in packing density.

A similar plot (as presented in Fig. 1) showing variation of land area with equivalent capacity is given in Fig. 2, which also indicates a linear variation.

2.2.3. *Packing Density*

The packing density of a plant is defined as the ratio of mirror area to land area. It gives an indication of the extent of utilisation of land. Packing density percentage is defined in Eq. (3).

$$\text{Packing density percentage} = \frac{\text{Mirror Area}}{\text{Land Area}} \times 100 \quad (3)$$

In Table 8, the packing density of existing plants (segregated based on type of field configuration) has been calculated and presented. It can be observed that the average value of packing density for operating plants is about 20%.

2.3. **Field Layout Configuration**

There are some standard layout patterns which have been observed for the heliostat field design of existing plants. These are: radial staggered and cornfield patterns.

2.3.1. *Radial staggered*

In this configuration, heliostats are arranged in a circular manner around the tower. This can be seen in Fig. 3, which is the heliostat field of the Gemasolar plant. In Fig. 4, the field for PS 10 and PS 20 towers have been shown. As seen in the radial staggered configuration, the arrangement is such that no two heliostats in adjacent rings are on the same radial line. Consecutive circular rings position heliostats in a staggered formation of this kind. They are typically employed for plants using external cylindrical receivers with surround field layouts or cavity receivers with northern fields.

2.3.2. *Cornfield*

A cornfield layout, as the name suggests, refers to a configuration where the heliostats are arranged in straight rows, one behind the other. This is shown in Fig. 5 (the Sierra Sun Tower) and Fig. 6 (the Jülich tower). In Fig. 6, a single-side field is used, since the Jülich tower uses a cavity receiver with a single-side aperture.

2.3.3. *Observations on field layouts of existing plants*

From Figs. 3 to 6, one can infer that the layout of heliostats does not follow any particular norm. Depending on the plant capacity, type of receiver used, as well as the latitude of the plant, the

heliostat field layout changes. It is interesting to note that all these plants (except Dahan and Jülich) are located in the latitude range of 28°11' N to 38°14' N. However, their layouts are different because different types of receivers are used. At these latitudes, the sun is due south throughout the year. Therefore in the PS 10, PS 20, ACME, Dahan and Solugas plants, using single cavity receivers, it is appropriate to locate all heliostats to the north of the tower. The Gemasolar plant uses an external cylindrical receiver and consequently the heliostats are located all around the tower (surround field), but a greater number of heliostats are on the northern side.

The ratio of the radial distance of the farthest heliostat (r) and the height of the tower (h) is shown in Table 8. The r values were estimated from the Google Maps and Wikimapia images [17], [18], [19], [20] and the h values were taken from the NREL database [13]. The r/h ratio for the Gemasolar plant on the north side of the field is 6.1 whereas on the south side it is 4.3. Sierra SunTower has two units, one uses an external cylindrical receiver and the other uses a dual cavity receiver [13]. The maximum r/h ratio seen in both cases is 2.3. Thus, the heliostat field layout is closely linked with the choice of the receiver and other design considerations.

The size of the heliostat also plays a key role in determining the field layout. It can be seen that the Sierra Sun Tower heliostats with cornfield pattern are more closely packed (leading to a high packing density, See Table 8). The Jülich plant also has a cornfield pattern and relatively high packing density. It can be seen from Table 8, that plants with cornfield pattern have better land utilisation compared to plants with radial patterns.

For plants with radial staggered configurations (surround/north fields) and large heliostats, for example, PS 10, PS 20 and the Gemasolar plant, the packing densities are smaller. When the heliostat size increases, the shadowing and blocking effects increase. If these have to be minimised, the mirrors will have to be placed at large distances from each other, thereby reducing the packing density.

2.4. Working Fluid Employed

Different types of HTFs can be used in an ST plant based on the type of receiver and power cycle employed in the system. HTFs that have been used in existing operational ST plants are water, molten salt and air.

2.4.1. Water

When water is used as HTF, the solar field generates steam directly and the Rankine steam cycle is used for power generation. Since in this case, water is used both as HTF and working fluid, it eliminates the need for a heat exchanger. The maximum possible temperature that has been achieved with water is 566°C [13]. Plants using water as HTF are PS 10, PS 20, Dahan, Sierra Sun Tower and Ivanpah.

2.4.2. Molten Salt

In the case of molten salt as HTF, a heat exchanger is used to transfer thermal energy from the HTF to water in order to generate steam. Steam Rankine cycle is used for power generation. One of the advantages of using this as the working fluid is that the HTF used is same as the storage media. When the plant is not in operation, HTF from the receiver has to be drained out as the freezing temperature of molten salt is relatively high, its value being around 238°C [21]. Gemasolar plant uses molten salt as its HTF. This is also because it employs 15 hours of thermal storage.

2.4.3. Air

Air is used as the HTF when a volumetric receiver is used. The receiver design is rather complex with one disadvantage being that air has poor heat transfer properties. Therefore, the efficiency of heat transfer to the power block is not very high. Compressed air has better heat transfer properties as it is denser. Air at high temperatures of the order of 1000°C gives rise to better heat transfer properties but the material constraints of the HTF carrying pipes will have to be considered. Also air does not require cooling water and hence is advantageous especially in locations where water availability is a problem. Jülich tower in Germany uses a volumetric receiver, with air as HTF and water as working fluid. This plant employs a steam Rankine power cycle. Since the advantage of air reaching high temperatures is not completely utilised, low power block efficiencies are observed in this case.

The advantages and limitations of the working fluids mentioned in this Section are shown in Table 9.

2.5. Estimation of Receiver Size

It is observed from the literature review that a basis for sizing the receiver and arriving at an optimum size of the receiver was not explicitly available. In this section, a methodology has been arrived at, for a first order estimation of receiver size. This is based on the equivalent capacity of a plant, the type of HTF used, and operating temperatures. The actual receiver size is higher than the estimated one as it accounts for spillages, varying flux distributions, thermal losses, etc. Based on the actual receiver size (from existing plant data), the factor by which it is higher than the estimated area has been arrived at (see Eq. (7)). Table 10 presents the estimation of receiver size. The values assumed for the power block efficiency are shown in this table. From this, the power input to the power block (MW_{th}) is estimated as shown in Eq. (4).

$$\text{Thermal power input to the power block } (P_{input,PB}) = \frac{\text{Equivalent Capacity}}{\eta_{PB}} \times 100 \quad (4)$$

where, *Equivalent Capacity* is in MW, $P_{input,PB}$ is in MW_{th} and η_{PB} is the power block efficiency percentage.

The receiver efficiency is in the range of 80% to 90%. For this study, it is assumed to be 85% [23] and therefore, the thermal power input to the receiver from the solar field (MW_{th}) is given in Eq. (5).

$$\text{Thermal power input to the receiver } (P_{input,receiver}) = \frac{P_{input,PB}}{85} \times 100 \quad (5)$$

where, $P_{input,receiver}$ is in MW_{th} .

Depending on the type of HTF used, the maximum allowable flux density on the receiver is fixed. For safety conditions, it has been assumed that approximately 85% of this maximum allowable flux is incident on the receiver. The calculated receiver area is obtained from Eq. (6).

$$\text{Calculated Receiver Area} = \frac{P_{input,receiver}}{\text{Flux on receiver}} \times 1000 \quad (6)$$

where, *Flux on receiver* is in kW/m^2 .

This calculated receiver area is compared with the actual receiver area of various plants - Jülich, PS10, Solar Two and Gemasolar [24], Dahan [7], Solugas [25], which is available in the literature.

There is a limitation on the maximum allowable flux density for various HTFs. For molten salt, it is 1000 kW/m^2 [26], for water it is 350 kW/m^2 [23] and for air it is assumed to be 1200 kW/m^2 .

The ratio of actual receiver size and calculated receiver size is given in Eq. (7) is computed.

$$\text{Ratio} = \text{Actual Receiver Area} / \text{Calculated Receiver Area} \quad (7)$$

This ratio varies from 1.47 to 2.31 for plants using molten salt, 0.96 to 1.57 for plants with water and 2.86 and 5.10 for plants with air as HTF as shown in Table 10. It can be seen that this ratio is high for receivers using air as HTF. These receivers can attain temperatures of 1000°C. Due to the lower heat capacity of air, these plants require receivers with bigger surface area compared to receivers using water as HTF.

2.6. Tower Height

Table 11 lists the tower heights (h) of ST plants. Fig. 7 shows the variation of tower height with equivalent capacity, with the numbers indicating the serial number of the plant given in Table 11. It is observed that no direct correlation is evident between the tower height and the equivalent capacity of a plant.

Once the capacity of a plant, its thermal storage and solar resource are known, the land and mirror areas can be determined. Based on the type of receiver and design of a plant, the heliostat field can be designed. However, the basis on which the height of the tower is arrived at is not clear. From Table 8, it can be seen that the ratio of the farthest distance of the heliostat to the tower height (r/h) is between 5.7 and 6.8 for most of the plants. However, for the Ivanpah plant, it is higher (of the order of 10), while for the Sierra Sun tower plant and the Jülich plant, it is a much smaller value, 2.3.

2.7. Gross Cost of Existing Plants

The data available on the gross costs for existing tower plants is limited. The gross cost of the PS 10 plant (cavity receiver) is about Rs 19 crores per MW_e (35 million Euros [27]). The gross cost for the Dahan plant (cavity receiver) is approximately Rs 20 crores per MW_e (32 million CNY [28]). The overall cost of the Gemasolar plant (external cylindrical receiver) is approximately Rs 36 crores per MW_e (419 million USD [29]). This data is depicted in Table 12. Data for most of the other existing plants was not available.

3. Challenges and Opportunities for ST Deployment in India

This section discusses the challenges and opportunities for deployment of ST technology in India. This is analysed with respect to technical, financial and policy aspects for the following parameters, as applicable.

3.1. Solar Resource

3.1.1. Technical

Challenges: Solar resource data is available either through satellite or ground based measurements. At present, for India, ground-based measurements are available for 119 stations [30]. On the other hand, satellite data is available for India from various sources [31],[32],[33],[34]. However, satellite data is not as accurate as solar resource data obtained from ground-mounted sensors. Satellite-based models cannot provide accurate instantaneous values like the ground-based measurements. They also provide data with lower frequency of measurement [35]. Therefore, ground-based data is required for many more stations in India, such that accurate pre-feasibility analyses can be carried out to identify the potential locations for installations of ST technology.

As seen, in Table 8, the r/h ratios are such that the farthest heliostat can be as much as a km away from the tower. When a sun ray is reflected from such a large distance, it is bound to undergo attenuation losses. These losses occur due to the scattering and diffusion of reflected solar radiation by aerosols, moisture content and dust in the atmosphere. As the particulate matter content of the atmosphere increases, so does the attenuation loss. [36].

Most areas in India which have abundant solar irradiation (for example, Gujarat and Rajasthan) are also areas which are prone to very high dust factors. Dust in the atmosphere, not only causes attenuation losses but also settles on the heliostats, thereby reducing their life and efficiency. In these cases, maintenance of each heliostat (mirror cleaning) is of prime importance and this is not an easy task in a field with thousands of mirrors.

Opportunities: Most parts of India receive high solar resource, i.e., Direct Normal Irradiance (DNI) almost throughout the year, which has the potential to be tapped. The best sites in India receive around 2100 kWh/m²/annum. [14]. As noted from the assessment, this is on par with all the existing plants that are producing grid connected power. These sites have solar resources of the same order, the average being around 2230 kWh/m²/annum (See Table 5). This sets the benchmark for commercial viability of this technology under Indian conditions.

As can be seen from Section 2, the geographical location of a plant has a bearing on the type of receiver and heliostat field configuration used. The position and path of the sun depend on the latitude of the given location.

India is situated approximately between 8°N & 34°N latitude and 70°E & 96°E longitude. Two nomograms have been prepared considering the extreme latitudes of 8°N and 34°N to illustrate the path of the sun over the year. These nomograms are shown in Fig. 8 for days of Mar 21, July 21 and Dec 21. The radial lines indicate the azimuth position of the sun whereas the concentric circles

represent the altitude angle of the sun. From these nomograms, it can be seen that the sun stays predominantly due south for most of the year. Considering all these facts, cavity receiver with northern field could be ideal for smaller plant capacities (<20 MW). This is also evident from assessment in Section 2 (see Table 3). Similarly, external cylindrical receivers with surround heliostat field and dual cavity receivers are suitable for higher capacity plants (>20 MW).

India receives around 300 sunny days in a year [14], thus enabling harnessing of solar energy for the setting up of power plants. Fig. 9 shows the DNI Map of India. It can be seen from this map, that most parts of India enjoy a daily solar radiation of 4.5 - 5 kWh/m²/day. Out of the 3.28 million km² of land area that India spans, around 18% receives solar radiation of 5.5 - 6 kWh/m²/day which is suitable for solar thermal power generation. This land area might include forests, agricultural land, waste land, built up area, water bodies etc.

3.2. Land Resource

3.2.1. Technical

Challenges: Micro-siting of wastelands has not been conducted for all states in India. This needs to be performed in order to estimate the potential or possibility of ST technology by assessing terrain, soil, wind conditions etc. The proximity of wastelands from the load centers is not explicitly available. The wasteland locations have to be coupled with matrices like sub-stations, water availability and road connectivity in order to identify suitable wastelands for ST installations.

Opportunities: Approximately 0.4 million km² of wasteland is available in India [38]. From the assessment (see Table 7), it is seen that for existing ST plants with grid connected power, the average land requirement per MW_e is 3.8 hectares (0.038 km²). Even if 1% of this wasteland is utilized, the potential for ST technology is around 105 GW_e. Therefore, land should not pose as a constraint for ST deployment.

3.2.2. Financial

Challenges: Even though wastelands are available, acquisition challenges in terms of obtaining clearances, time for sanctioning land etc. are not very easy to obtain and these add to the total pre-operative costs. If the terrain has a slope greater than 5°, then considerable earthwork would be required to be performed. This would lead to an increase in the construction time and the installation (set-up) cost.

Opportunities: Costs of wasteland are relatively cheap in India and would be of the order of about 1-2% of the total capital costs. [22].

3.2.3. Policy

Challenges: For zones which receive high DNI in India, land banks have not yet been identified. The Government needs to take initiative in earmarking land banks which have proximity to water resource and power evacuation facilities which are quintessential to large scale ST plants. There is a void in the policy support towards this which needs to be addressed.

3.3. Technology

3.3.1. Technical

Challenges: The maturity of ST technology is not very high in India. It is still in the nascent stages where R&D work needs to be carried out. India has limited experience in the development of power tower systems. Apart from a couple of small-scale demonstration plants, there are no plants in the pipeline. ACME company in India partnered with eSolar company, USA, to develop a 2.5 MW_e tower plant in Bikaner, Rajasthan. The heliostat field for this plant set-up utilises 1.16 m² small size flat mirrors [13]. The advantage of small size heliostats is that they are easy to handle and install, but a major disadvantage is that they require more number of controllers for tracking. Even though the plant, was commissioned in 2010, it has been running at reduced capacity [39]. Some of the possible problems that can be envisaged include lack of sufficient DNI, difficulties in tracking, and accumulation of dust on the mirrors.

SunBorne Energy is setting up a 1 MW_{th} solar power tower system with the support of the Ministry of New and Renewable Energy (MNRE), Government of India at the National Institute of Solar Energy (NISE), Gurgaon. The primary aim of this demonstration plant is to devise a method to optimise the heliostat field (using Titan tracker heliostats) using a volumetric air receiver while simultaneously having a provision for thermal storage. This plant is planned to be set-up using regional indigenous resources for most of the system components [40].

Detailed studies need to be carried out to understand the suitable ST technology variants that are ideal for Indian conditions. The ground work required to make this technology more acceptable to the market has to be performed. Many of the existing plants that have been collated in this study are demonstration plants. Currently, only four plants are commercial plants, producing grid connected power.

Opportunities: In terms of technology that can be used for Indian conditions, the initial assessment (See Section 3.1.1) suggests that for India, plants with an external cylindrical receiver (with surround field) or cavity receiver (with north side field). Since plants employing these receivers have been commercially proven, these two technologies can be adopted for Indian conditions. High temperatures in the range of 300 to 1000°C are possible with the use of suitable HTFs leading to higher power cycle efficiencies.

Due to availability of biomass resource in India, hybridisation with biomass can be achieved in order to increase the Plant Load Factor (PLF) of the plants.

3.3.2. Financial and Policy

Challenges: Since ST technology is a new entrant in the power sector, and only a few demonstration plants have been built, the actual costs are not known. Bankability of this technology is also an issue in the Indian market. Hence, getting financial closure would be difficult in this case. Furthermore, there is a void in the policy framework for tariff support for implementation of power plants with storage and hybridisation. This is a deterrent to the growth of ST plants in India.

3.4. Engineering & Design

3.4.1. Technical Expertise in India

Challenges: Companies specialising in design, implementation and construction of ST plants are currently not present in India and very few companies exist worldwide. The lack of domestic industry participation also hampers the investment that can be made in this technology. Not enough pilot projects have come up, in India, in order to gain a better understanding of the ST technology.

Opportunities: India could have a head start in the designing and manufacturing of various components and further improvement through R&D facilities. A gradual market can be built up. Meanwhile the advantages in importing various components of this technology can be examined.

3.4.2. Manufacturing, Supply Chain & Materials

Challenges: Absence of an established supply chain for the main ST components is a major challenge. One of the most important components of ST technology, namely, the receiver, does not have even a single indigenous manufacturing unit in India. At the international level as well, there are only a handful of manufacturers, resulting in expensive receivers.

For the HTF, there are only three suppliers of molten salt globally, namely, SQM (Chile), Haifa Chemicals (Israel), and Duferrit Salts and Auxiliary Products (Germany). Lack of domestic suppliers for molten salt is a barrier in implementing ST plants with storage (as molten salt storage is the most efficient presently). This is due to the fact that molten salt is a major cost contributor of a storage system.

Unlike PT, which has a well-established supply chain, ST has limited suppliers as well as standards due to the large number of variants in technology. Furthermore there is no benchmarking for reliability testing of ST components. Due to this, market acceptability of in-house manufactured components is low. We can see that due to the lack of demand for components such as heliostats, receivers etc. for which a domestic market can be set up, the question of sustainability looms at large.

Opportunities: The manufacture of low cost heliostats is possible as there is considerable availability of low iron content glass in India, which is necessary for the fabrication of heliostats. The structural designing of the tower and manufacturing of heliostat support structures (requisite drive mechanisms) can be accomplished in India, at lower costs.

The establishment of an indigenous market for receiver technology (external cylindrical and cavity receivers) can be done as, once the specifications are known. Since India has a good engineering base, the manufacturing and fabrication process can be achieved.

4. Conclusion

The total capacity of grid-connected solar projects in India currently stands at 2632 MW as on March 31, 2014 [41]. The contribution from CSP in Phase-I has been very less compared to the contribution of photovoltaic systems. Some of the reasons for the slow deployment of CSP in India are: availability of solar resource data, delay in importing key components of the plant (mirrors, HTF, etc.), obtaining financial closure, etc. However, CSP is expected to play a significant role in the coming phases of JNNSM, given the mandate of 30% capacity addition from CSP [12]. Assuming that 30% of the target could be tapped from solar thermal technologies, the share of CSP will be around 6000 MW. Based on present maturity levels of ST technology, it is assumed that it can contribute around 30% of the CSP share, resulting in approximately 1800 MW of installed capacity by 2022.

As seen from the existing plants, most of the tower plants employ either the external cylindrical or the cavity type receiver. By using molten salt, one can achieve higher temperatures along with thermal storage for a long duration. The main advantage of using molten salt is that it can be used both as the HTF and as well as the storage medium.

Given the considerations mentioned above, the system configuration that could be ideal for Indian conditions are:

- Molten salt as both HTF and storage medium
- External cylindrical receivers with a larger north-side field, or cavity receivers with a north-side field
- Thermal storage for utility scale plants as it can provide reliable and dispatchable power, and further help in meeting peak-time demands
- Biomass hybridisation

As discussed earlier, based on reasonable assumption, the share of ST technology deployment in India, is about 1800MW (of grid-connected power), which is to be achieved by 2022. The assessment study concludes that this is an achievable target. Given the challenges with conventional methods of power generation, the use of tower technology in harnessing solar power will play a pivotal role in meeting India's future energy demands.

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Fig. 1: Mirror Area vs. Equivalent Capacity for Operational Plants

Fig. 2: Land Area vs. Equivalent Capacity for Existing Plants

Fig. 3: Helio-stat Field at the Gemasolar Plant, Spain [17]

Fig. 4: The Heliostat Field for PS 10 and PS 20, Spain [18]

Fig. 5: Heliostat Field at the Sierra Sun Tower, USA [19]

Fig. 6: Heliostat Field of the Jülich plant, Germany [20]

Fig. 7: Variation of Tower Height with Equivalent Capacity

Fig. 8: Nomogram Showing the Path of the Sun

Fig. 9: Annual DNI Map for India [37]

Table 1: Global Status of ST and PT CSP plants [1]

Technology	Solar Tower	Parabolic Trough
Operating Plants Capacity (MW)	457	1168
Under Construction Capacity (MW)	1197	1377

Table 2: JNNSM Capacity Addition Targets [12]

JNNSM Policy Targets (Cumulative)/Year	Phase 1 (2010-13)	Phase 2 (2013-17)	Phase 3 (2017-22)
Utility Grid Power (MW)	1100	10000	20000
Off-Grid Solar Application (MW)	200	1000	2000

Table 3: Information on Operational Plants [13]

Plant Name	Country	Capacity (MW)	Storage (hours)	Land Area (hectares)	Number of Heliostats	Heliostat Aperture Area (m ²)	Solar Field Aperture Area (m ²)	Tower Height (m)	Receiver type	HTF	Year of Start of Operation
PS 10	Spain	10	1	55	624	120	75000	115	Cavity	Water	2007
Jülich	Germany	1.5	1.5	8	2153	8	18000	60	Volumetric	Air	2008
PS 20	Spain	20	1	80	1255	120	150000	165	Cavity	Water	2009
Sierra Suntower	USA	5	0	8.1	24360	1.14	27670	55	Dual Cavity and External Rectangular	Water	2009
Gemasolar Thermosolar	Spain	20	15	195	2650	120	318000	140	External Cylindrical	Molten Salt	2011
ACME	India	2.5	0	4.8	14280	1.14	16222	46	Cavity	Water	2011
Dahan	China	1.5	1	5.2	100	100	10000	118	Cavity	Water	2013
Solugas	Spain	4.6	0	6	69	121	8349	75	Cavity	Air	2012
Ivanpah Solar Tower	USA	392	0	1417	173500	14.08	2295960	140	External Rectangular	Water	2013

Table 4: Information on Plants Under Construction [13]

Plant Name	Country	Capacity (MW)	Storage (hours)	Land Area (hectares)	Number of Heliostats	Heliostat Aperture Area (m ²)	Heliostat solar Field Aperture Area (m ²)	Tower Height (m)	Receiver type	HTF	Expected year of start of operation
Crescent Dunes	USA	110	10	648	17170	62.4	1000000	165	External Cylindrical	Molten Salt	2014
Rice Solar	USA	150	8	571	17170	62.4	1000000	165	External Cylindrical	Molten Salt	2016
Khi Solar	South Africa	50	2	140	4120	140	576800	200	Cavity	Water	2014
Supcon	China	50	2.5	330	217440	2	434880	80	To Be Decided	Molten Salt	2016

Table 5: Solar to Electric Conversion Efficiency for Existing Plants [13]

Plant Name	Rated Capacity (MW _e)	Annual Expected Electricity Generation (MWh/year)	Solar Resource (kWh/m ² /year)	Heliostat Aperture Area (m ²)	Solar to Electric Conversion Efficiency (%)
OPERATIONAL					
Receiver Type : Cavity					
PS 10	11.02	23400	2012	75000	15.51
PS 20	20	48000	2012	150000	15.9
Dahan	1.5	1950	1290	10000	15.11
Receiver Type : External Tubular					
Gemasolar	19.9	110000	2172	318000	15.93
Ivahpah SEGS	392	1079232	2717	2295960	17.30
Receiver Type : Volumetric					
Jülich	1.5	1000	902	18000	6.16
UNDER CONSTRUCTION					
Receiver Type : External Cylindrical					
Rice Solar	150	450000	2598	1071361	16.17
Crescent Dunes	110	485000	2685	1071361	16.86

Table 6: Mirror Area Based on Capacity [13]

Plant Name	Capacity (MW _e)	Storage (hours)	Equivalent Capacity (MW _e)	Mirror Area (m ²)	Mirror Area (m ²) per MW _e of	
					Rated Capacity	Equivalent Capacity
Operational						
Receiver Type : Cavity						
PS-10	11.02	1	12.24	75000	6806	6125
PS-20	20	1	22.22	150000	7500	6750
ACME	2.5	0	2.5	16279	6512	6512
Dahan	1.5	1	1.667	10000	6667	5999
Solugas	4.6	0	4.6	8349	1815	1815
Receiver Type : External Tubular						
Gemasolar	19.9	15	53.07	318000	15980	5992
Ivanpah	392	0	392	2600000	6633	6633
Receiver Type : External Cylindrical and Dual Cavity						
Sierra	5	0	5	27670	5534	5534
Receiver Type : Volumetric						
Jülich	1.5	1.5	1.75	18000	12000	10286
Under Construction						
Receiver Type : External Cylindrical						
Rice Solar	150	8	283.33	1071361	7142	3781
Crescent Dunes	110	10	232.22	1071361	9740	4614
Receiver Type : Cavity						
Khi Solar One	50	2	61	58000	1160	951

Table 7: Land Area Based on Capacity [13]

Plant Name	Capacity (MW _e)	Storage (hours)	Equivalent Capacity (MW _e)	Land Area (hectares)	Land Area (hectares) per MW _e	
					Rated Capacity	Equivalent Capacity
Operational						
Receiver Type : Cavity						
PS-10	11.02	1	12.24	55	5	4.5
PS-20	20	1	22.22	80	4	3.6
ACME	2.5	0	2.5	4.85	2.8	1.9
Dahan	1.5	1	1.667	5.2	3.4	3.1
Solugas	4.6	0	4.6	6	1.3	1.3
Receiver Type : External						
Gemasolar	19.9	15	53.07	195	9.7	3.7
Ivanpah	392	0	392.0	1417	3.6	3.6
Receiver Type : External Cylindrical and Dual Cavity						
Sierra	5	0	5.0	8.1	1.6	1.6
Receiver Type : Volumetric						
Jülich	1.5	1.5	1.75	8	5.3	4.6
Under Construction						
Receiver Type : External Cylindrical						
Rice Solar	150	8	283.33	571	3.8	2
Crescent	110	10	232.22	648	5.9	2.8
Receiver Type : Cavity						
Khi Solar One	50	2	61	140	2.8	2.3
Receiver Type : To be Decided						
Supcon Tower	50	2.5	50	330	6.6	6.6

Table 8: Packing Density of ST plants

Plant Name	Packing Density Percentage (%)	r/h
Field Configuration: Surround field (Radial)		
Gemasolar	16.3	6.2
Crescent Dunes	16.5	9.7
ISEGS	16.4	10.4
Field Configuration: Single side field		
PS 10	13.6	6.5
PS 20	18.8	5.6
Field Configuration: Cornfield		
Sierra Suntower	34.2	2.3
Jülich	22.5	2.3

Table 9: Advantages and Limitations of HTFs

HTF	Advantages	Limitations
Water	<ul style="list-style-type: none">-For steam Rankine cycle, water being the working fluid, the need for heat exchanger is eliminated-Eliminates the costs associated with the salt or oil based HTFs	<ul style="list-style-type: none">-Dissimilar heat transfer coefficients in liquid, saturated vapour and superheated gas phases-Consequent problems with temperature gradient and thermal stress-Flow control problems with varying solar flux-Difficult for long thermal storage hours
Molten Salt	<ul style="list-style-type: none">-Stable, non-toxic and environmentally benign-High thermal conductivity and thermal capacity-Operating temperatures can go up to 560°C	<ul style="list-style-type: none">-High melting point (~222°C); Needs auxiliary heating to prevent solidification-Highly corrosive at elevated temperatures
Air	<ul style="list-style-type: none">-High temperatures of the order of 1000°C can be utilized	<ul style="list-style-type: none">-Poor heat transfer properties (conductivity, film coefficient etc.) compared to other fluids-Complex receiver design

Table 10: Receiver Size Estimation

Plant Name	Equivalent Capacity (MW)	Power Block Inlet Temp (°C)	Power Block Efficiency ^a (%)	Power input to Power Block (MW _{th})	Power input to Receiver (MW _{th})	HTF	Max. Allowable Flux Density for HTF (kW/m ²)	Flux on Receiver (kW/m ²)	Calculated Receiver Area (m ²)	Actual Receiver Area (m ²)	Actual Area/ Calculated Area
Solar Two	13.33	565	43	31.01	36.47	Molten Salt	1000	850	42.91	99.30	2.31
Gemasolar	53.07	565	43	123.41	145.20	Molten Salt	1000	850	170.82	251.33	1.47
PS-10	12.24	250	27	45.33	53.33	Water	350	300	177.78	279.54	1.57
Dahan	1.67	400	25	6.68	7.86	Water	350	300	26.20	25	0.95
Jülich Solar Tower	1.8	680	25	7.2	8.47	Air	1200	1020	8.30	22	2.65
Solugas	4.6	850	30	15.33	18.04	Air	1200	1020	17.69	90.25	5.10

^aThese are assumed values [22]

Table 11: Tower Height and Distance of the Farthest Heliostat from the Tower

Sl. No.	Plant	Capacity (MW _e)	TES (hours)	Equivalent Capacity (MW _e)	Tower Height (m)
Operational					
Receiver Type : Cavity					
1	PS 10	11	1	12.2	115
2	PS 20	20	1	22.2	165
3	ACME	2.5	0	2.5	46
4	Dahan	1.5	1	1.667	118
Receiver Type : External Tubular					
5	Gemasolar	19.9	15	53.1	140
6	ISEGS	130	0	130	140
Receiver Type : External Cylindrical and Dual Cavity					
7	Sierra	5	0	5	55
Receiver Type : Volumetric					
8	Jülich	1.5	1.5	1.8	60
Under Construction					
Receiver Type : External Cylindrical					
9	Rice Solar	150	8	283.3	165
10	Crescent dunes	110	10	232.2	165
Receiver Type : Cavity					
11	Khi Solar One	50	2	61.1	200
Receiver Type : To be Decided					
12	Supcon	50	2.5	5	80

Table 12: Available Gross Costs of Plants

Plant	Capacity	TES (hours)	Equivalent Capacity (MW)	Cost/ Capacity (Rs. crore/MW)
Dahan	1.5	1	1.67	19.76
PS 10	11.02	1	12.2	18.62
Gemasolar	20	15	53.3	36.44