Global Review of Solar Tower Technology

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Global Review of Solar Tower Technology

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1 Introduction

This report aims to give a global overview on the various solar towers that are operating and under construction. First an outline of the Solar Tower (ST) technology and the different components that make up a tower plant, namely, the heliostats, receivers, Heat Transfer Fluid (HTF), and power cycles employed, is discussed. A list of the available literature on the various operational plants is also presented.

This is followed by a brief description of existing ST plants (operational and under construction) and a subsequent overall assessment of certain parameters of the plants. In the CSTEP report "Engineering Economic Policy Assessment of Concentrated Solar Thermal Power Technologies for India" published in 2012, a brief idea was given about the ST technology, its components, some brief assessment of parameters for the existing plants worldwide as well as a techno-economic viability study of ST technology in India. The present report is an extension to the review portion of the aforementioned report after carrying out a more detailed study of available literature and also updating the various data in the current (2014) scenario.

The receiver (which is located at the top of the tower) is one of the most crucial components of a tower plant. The type of receiver used will be the key to deciding many parameters which are chosen while modelling a plant, for example, the type of heliostat field, its layout, the heat transfer fluid to be used etc. Therefore, an assessment of existing power plants is made depending upon the type of receiver being used. The gross costs of the plants per MW_e (of equivalent capacity) is discussed subsequently.

The conclusion discusses the challenges and opportunities with respect to this technology in the Indian scenario. The global review on ST technology is carried out in this study to provide a bench mark for the design studies under Indian conditions.

2 Solar Tower and its Components

ST which is also referred to as Central Receiver uses a large number of heliostats, having dual axis control system (one about the vertical axis and the other about the horizontal axis). These heliostats reflect the solar radiation (impinging on their surface) to a stationary receiver located at the top of a tower. This concentrated solar energy incident on the receiver is converted to thermal energy, which is carried by the HTF passing through the receiver. The thermal energy of the HTF is transferred to the working fluid of the power cycle, thereby generating electricity.

The advantage of ST is that a high geometrical concentration ratio ranging from 200 to 1000 can be achieved. Consequently, temperatures of the order of 1000°C can be reached with suitable HTFs. The high temperature leads to an increase in the power cycle efficiency. As a result of this, potentially, an overall solar to electric conversion efficiency of around 28% can be achieved. (1)

Thermal energy storage and hybridisation can also be incorporated similar to the parabolic trough case. Further, molten salt can be used both as HTF and thermal storage medium. Given the potential of higher efficiency, ST with molten salt/water/air as HTF has gained momentum in recent years. However, there are a lot of variations in the design of heliostats, receivers, HTF and also in the power block. Hence, a common description for all the power plants is not possible. It must be pointed out that many details of the components were not available in open literature. A typical ST plant (Gemasolar) is shown in Figure 1(Source: http://solarpower.com/blog/concentrated-solar-power-plant/).

Figure 1: Gemasolar Power Plant

The major components involved in the ST system are explained below.

2.1 Heliostats

Heliostats are conventionally flat or slightly curved mirrors mounted on a backup steel structure, which can be controlled or tracked about two axes, one horizontal and other vertical, so as to tilt the heliostats to reflect the solar rays to a fixed receiver on top of a tower. The aperture areas of the heliostats that have been used in various plants vary considerably from 1 m^2 to 120 m^2, but all heliostats within a plant have the same aperture area.

Some developers (for example, eSolar) use small heliostats and claim that the advantages are mass production, easy handling & installation, smaller wind loads because of size and proximity to ground. Heliostats of 1 m^2 have a single flat mirror. However, if such small mirrors are used, the number of heliostats and controllers will increase.

Heliostats of 120 m^2 area (2; 3) have 28 curved facets (seven rows & four columns). While using such large heliostats, each facet has to be canted properly, so that the receiver could be made as small as possible thereby increasing the concentration ratio. As a result of using large heliostats, the number of heliostats and controls reduces. However, in these cases, the structure of the heliostat has to withstand large wind loads and the control system has to be more powerful. New concepts such as target aligned heliostats have also been explored. These heliostats use a tracking mechanism and are mounted and aligned to the receiver (target). This method can also be used to track asymmetrical heliostats. (4)

2.2 Receivers

The receiver is one of the most important parts of tower plants.

There are two types of receivers: tubular and volumetric. Tubular receivers are used for liquid HTF such as water, molten salt, thermic oil, liquid sodium and Hitec salt, and volumetric receivers use air or supercritical CO_2 as HTF. The type of receiver depends on the type of HTF and power cycle (Rankine or Brayton) used in the system. A brief description of the receivers is discussed in the following section.

2.2.1 Tubular Receivers

In tubular receivers, the HTF passes through a number of vertical tubes and gets heated by the radiant flux reflected from the heliostats. There are two types of tubular receivers: External cylindrical receivers and cavity receivers.

- External Cylindrical Receivers

In external cylindrical receivers vertical tubes are arranged side by side, in a cylindrical fashion and the radiant flux from the heliostats impinges from all directions. This is shown in Figure 2 (Source: http://www.solarreserve.com/newsroom/photo-video-library/). Since the receiver is exposed to atmosphere, it is subjected to higher convection losses.

Figure 2: External Cylindrical Receiver used in Crescent Dunes Power Tower

- Cavity Receivers

The cavity receiver consists of welded tubes kept inside a cavity in order to reduce convection losses. The heliostat field is arranged within the range of possible incident angles onto the receiver. Cavity receiver can be either be a single or dual cavity type. A single cavity receiver will have solar field on one side of the receiver while the dual cavity receivers will have solar field on either sides of the receiver. Figure 3 (Source: http://www.solarpaces.org/Tasks/Task1/ps10.htm) and Figure 4 (Source: http://www.victoryenergy.com/index.cfm?id=16) show the single cavity receiver and dual cavity used in the PS 10 and Sierra sun tower plants respectively.

Figure 3: Cavity Receiver used in PS-10

Figure 4: Dual Cavity Receiver used in Sierra Sun Tower

2.2.2 Volumetric Receivers

Receivers which use air as HTF are made of porous wire mesh or metallic/ceramic foams. The solar radiation impinging on the volumetric receivers is absorbed by the whole receiver. Volumetric receivers are of two types: open volumetric and closed/pressurised volumetric. Figure 5 and Figure 6 give a schematic representation of them.

- Open Volumetric Receivers

In open volumetric receivers, ambient air is sucked through the porous receiver where air gets heated up by concentrated solar energy. The outer surface of the receiver will have a lower temperature than inside the receiver because the incoming air from the ambient cools the surface and avoids damage to the material. Jülich tower plant uses a porous silicon carbide absorber module as receiver. The air gets heated up to about 700°C and is used to generate steam at 485°C, 27 bar in the boiler to run the turbine. The schematic representation of the open volumetric receiver used in Jülich Plant is shown in Figure 5 (Source: Report Article: The Solar Tower Julich - A research and demonstration plant for central receiver systems).

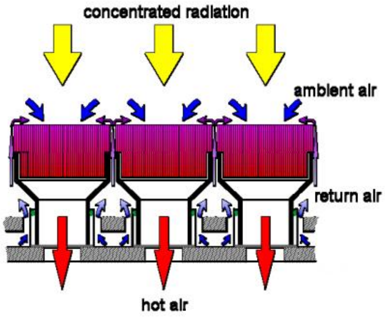

Figure 5: Schematic of Open Volumetric Receiver

- Closed Volumetric Receivers

Closed volumetric receivers are also called as pressurized volumetric receivers, in which the HTF (usually air) is mechanically charged through the receiver by a blower and the receiver aperture is sealed by a transparent window. The HTF will get heated up at the dome shaped portion of the receiver by the concentrated solar energy and the heated air will be used either in a Rankine cycle via heat exchanger or in a Brayton cycle for generating electricity. The schematic of a closed volumetric receiver is shown in Figure 6 (Source: European Commission Report: Solar hybrid gas turbine electric power system).

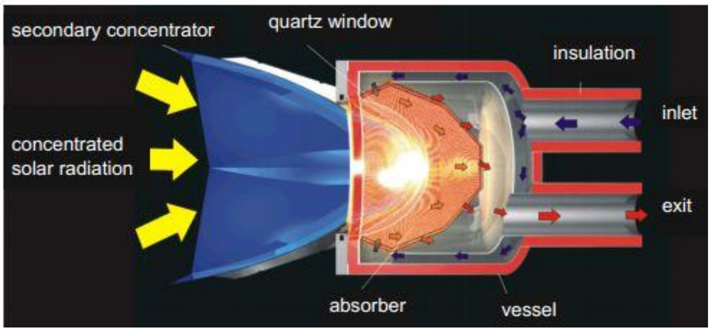

Figure 6: Schematic of the Pressurised Volumetric Receiver

2.3 Heat Transfer Fluid

Different types of HTFs can be used in ST based on the type of receiver and power cycle employed in the system. The HTF used in the operational ST plants are water, molten salt and air. Other possible candidates are liquid sodium, Hitec salt and synthetic oil. The merits and demerits of these HTFs are given in Table 1. A brief note on the use of each of the principal HTFs is given below.

2.3.1 Water

When water is used as HTF, the solar field generates steam directly (Direct Steam Generation) and the Rankine steam cycle is used for power generation. As the HTF is itself water, it eliminates the need of a heat exchanger in order to transfer the heat from the HTF to water (or steam) which is used to drive the turbine in the power block. The minimum temperature at inlet is around 250°C while the maximum possible temperature that has been achieved with water is 566°C.

2.3.2 Molten salt

In the case of molten salt as HTF, a heat exchanger is used to transfer the thermal energy from the HTF to water in order to generate steam. Rankine steam cycle is used for power generation. Use of molten salt as HTF allows easy thermal storage. When the plant is not in operation, HTF from the receiver has to be drained out as the freezing temperatures of the molten salt are relatively high, around 238°C (5). It can be noted that using molten salt as the HTF is preferred in a ST system rather than a PT system as gravity helps aid the draining of the molten salt at the end of the day in order to prevent it from freezing in the pipes. In a

PT system, this HTF will have to be pumped out to drain the pipes and this is not very convenient as some auxiliary power source will be required for this purpose.

2.3.3 Air

Air is used as a HTF when the receiver used is a volumetric receiver, as discussed in the previous section. However, the receiver design is rather complex and also one disadvantage is that air has poor heat transfer properties (thermal conductivity, film coefficient etc) and therefore, the efficiency of heat transfer to the power block is not very high. However, when a CO_2 Brayton cycle is being used, this is minimised to some extent. Compressed air has better heat transfer properties as compared to uncompressed air as it is denser. Air at higher 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.

2.4 Power Cycle

The power block is also a very important component of the plant as it is here that the solar energy collected by the receiver is converted to a more usable form which is electricity. The two main power cycles used in ST plants are discussed in the following sections.

2.4.1 Rankine cycle

In the Rankine cycle, the working fluid is water. Here the water is heated up (either directly if HTF used is water, or in a heat exchanger when HTF used is not water) and converted to steam.

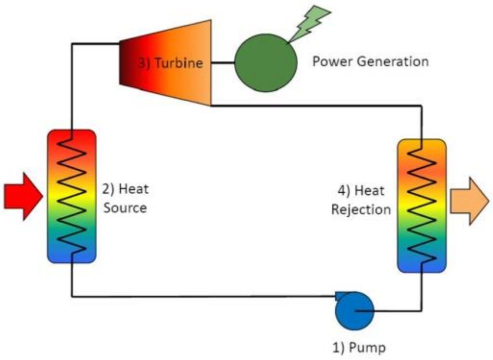

Figure 7: Rankine Cycle

This dry saturated vapour expands through a turbine generating power. After leaving the turbine, at low pressure, the low quality steam now passes through a condenser where it is converted to a saturated liquid state (water). This is now pumped from low pressure to a high pressure. Heat is taken up by this sub cooled water while getting converted to steam (at constant pressure) and the cycle repeats.

Figure **7** (Source: http://www.tas.com/renewable-energy/geothermal/overview.html) gives the schematic diagram of the working of a Rankine cycle. The only difference here is that instead of being heated in a conventional coal-fired boiler, water (the working fluid) is heated by solar energy.

2.4.2 Brayton Cycle

One of the potential advantages envisaged in ST technology is the use of compressed air as HTF to raise its temperature to about 1000°C to run a turbine on Brayton cycle. This is yet to be proven commercially. The Brayton cycle has the same processes as the Rankine cycle, however it does not operate within the vapour dome. It operates at much higher pressures and temperatures. The working fluid used here is generally compressed gas. The CO_2 Brayton cycle is being explored for ST technology and is under R&D mode. Figure 8 (Source: http://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html) depicts the schematic diagram of the Brayton cycle. The advantage of this cycle is that there is lesser requirement for water and higher efficiencies can be achieved.

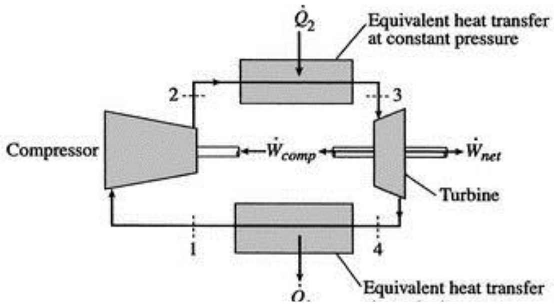

Figure 8 Brayton Cycle

Table 1: Merits & Demerits of HTF used in ST Plants

HTF	Merits	Demerits
Water	• 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.	• Dissimilar heat transfer coefficients in liquid, saturated vapour and superheated gas phases. Consequent problems with temperature gradient and thermal stress to be tackled • Flow control problems with varying solar flux • Thermal Storage for long hours difficult
Molten Salt (KNO_3 + $NaNO_3$)	• Stable and non-toxic and environmentally benign. • High thermal conductivity and thermal capacity. • Operating temperatures can go up to 560°C.	• High melting point (~222°C); Needs auxiliary heating to prevent solidification • Highly corrosive at elevated temperatures
Air	• High temperatures of the order of 1000°C can be utilized.	• Poor heat transfer properties (conductivity and film coefficient etc.) compared to other fluids. • Complex receiver design
Liquid Sodium	• Higher solar field outlet temperatures are possible and thus higher power cycle efficiencies • Low Melting Point (97.7°C) • High boiling point (873°C)	• Handling is difficult • Accidental leakage is highly hazardous
Hitec Salt	• Melting point is 142°C	• Temperatures are limited to less than 535°C
Synthetic Oil	• Freezes at 15°C	• Operating temperature limited to 390°C which limits the power cycle efficiency

3 A Brief Description of Existing Solar Tower Plants

3.1 Operational

3.1.1 PS 10

The Planta Solar 10 (PS 10) plant is the world's first commercial ST plant to be constructed near Seville in Spain. It is the first plant producing grid connected solar power using tower technology. It is a 10 MW_e plant. The technologies used by it are – glass-metal heliostats, pressurised water thermal storage system (with 1 hour storage capacity) and a saturated steam turbine (HTF used is water). The receiver system used in this tower is the cavity receiver system with a tower height of 115m. The plant uses 55 ha (550000 m^2) of land area with 624 heliostats. Each heliostat has an aperture area of 120m^2. Since the heliostat size is so large, keeping the mirrors clean and dust-free is a major challenge. The solar receiver which is at the top of the tower produces saturated steam at 275°C (6).

3.1.2 Jülich Power Tower

This 1.5 MW_e capacity power tower in Germany is an experimental 60m high tower plant. It uses a volumetric receiver with non-compressed air as the HTF. Due to the poor heat transfer coefficient of air, the efficiency of this plant is not so high. The working fluid is water. It also has 1.5 hours of storage capacity. It uses 2153 heliostats each of 8.2 m^2 area. The heliostats and tower are spread across a land area of 80000 m^2. It is a demonstration plant. This plant started operation in 2008 (7). The air (HTF) is heated up to 700°C and is used to heat water (in the power cycle) up to 500°C at pressures of 100 bars (8).

3.1.3 PS 20

Planta Solar 20 (PS 20), a tower plant which started operation in 2009 is beside PS 10 at Seville in Spain. It is a 20 MW_e capacity plant with a tower 165m high. This plant occupies 80 ha (800000 m^2) of land area. It is made up of the glass-metal 120m^2 area heliostats as the PS 10 plant, but 1255 in number. This plant also has a cavity receiver (9). This tower is higher than the PS 10 tower by 50m. The land area /MW is lower for the PS 20 plant, however, the mirror area/ MW is higher.

3.1.4 Sierra Sun Tower

This plant, which started in 2009 is one of the operating power tower plants in the United States. It is located in Lancaster, California. The 5 MW_e capacity project site occupies 8.1 hectares (81000 m^2) in an arid valley in the western corner of the Mojave Desert at 35°N. It has 24360 heliostats of 1.136m^2 each. It uses a tower height of 55m. The HTF used is water. This plant has two towers and hence two receivers. One is the dual cavity type and the other is the external rectangular receiver type (10).

3.1.5 Gemasolar Thermosolar Plant

The Gemasolar Thermosolar plant, which started operation in 2011, is the first commercial high-temperature solar plant using molten salt as the HTF and storage medium, which provides 15 hours of thermal storage with an annual capacity factor of about 75%. This plant is located in Spain. Here the HTF reaches temperatures of 565°C. The land area occupied by this plant is 1950000 m^2. It has a 140m high tower and a capacity of 20 MW_e. It has 2650 heliostats, 120 m^2 each. The plant has been able to supply uninterrupted power for a complete day to the grid, using thermal transfer technology developed by SENER (11). The receiver is 8m in diameter and 10m high.

3.1.6 ACME Bikaner

This is a 2.5 MW_e capacity plant which was set up in 2011 in Bikaner, Rajasthan, India. This plant has a total of 14280 heliostats each with an area of 1.136m^2. The heliostats used in this plant are manufactured by eSolar. They are smaller than the industry norm, allowing for pre-fabrication, mass-manufacturing, and easy installation, thereby reducing production and installation costs (12). The Plant was supposed to be a 10MW_e but it is running at reduced capacity (only one unit is operational) (13).

3.1.7 Dahan Power Plant

This plant is situated in Beijing, China and started operating in 2013. It is a 1 MW_e plant for experimentation and demonstration. It uses 100 heliostats each of 100 m^2 area. Each heliostat has 64 facets. The tower height is 118m. It uses a cavity receiver with water as the HTF. The receiver tilt angle is 25° and receiver aperture size is 25 m^2. The water is heated to about 400°C at the outlet of the receiver (14). It has one hour of thermal storage. The storage system is a combination of high temperature and low temperature oil storage tanks and a set of heat exchangers (15).

3.1.8 Solugas Plant

This plant is a 4.6 MW_e capacity plant located in Spain. The construction for this plant was finished in early 2012. It is built over a land of area 60000m^2 (16). It uses 69 heliostats of 121 m^2 area each. It has a 75 m high tower. Since the area of each heliostat is high it is made up of 28 facets. The cavity receiver is located at a height of 65m with an inclination of 35° with the horizontal. The diameter of the receiver is 5 m, however, the sun's rays are concentrated to an area of 2.7 m diameter. The length of the receiver is 6 m and it has a cylindrical cavity region. (17).This plant uses a Brayton cycle and uses air as HTF (18).

3.1.9 Themis Solar Tower

This is a 2 MW_e capacity tower constructed for research and development purposes. It is located in France. This solar tower plant is the refurbished and upgraded version of the tower initially built in the seventies to test a 10 MW_{th} scale electricity to concentrated solar energy production facility. It uses a new high performance, high precision heliostat tracking system which will allow the receiver temperature to reach 900°C. It has 201 mirrors to concentrate the solar energy on top of a concrete tower of 101 m height (19). The HTF employed is compressed air. (20).

3.1.10 Ivanpah Solar Electric Generating Station (ISEGS)

This project is a 392 MW_e capacity plant in Ivanpah, California. It is a commercial plant which covers 14170000m^2 with 173500 heliostats, each with an area of 15 m^2. The tower height is 140m (21). This plant is made up of three units (three towers and their respective heliostat fields) and utilizes BrightSource energy's 'luz power tower' (LPT) 550 technology (22). This plant started operation in December 2013. This plant uses a Solar Receiver Steam Generator (SRSG) wherein the boiler is contained in the receiver itself. A high efficiency boiler is positioned at the top of the tower and the heat concentrated on the receiver tubes is directly transferred to the water to generate superheated steam in a forced circulation drum boiler. (23).

Figure 9 (Source: http://www.prometheusturbine.info/prometheusturbine_ivanpah.html) shows the temperature distribution across the receiver.

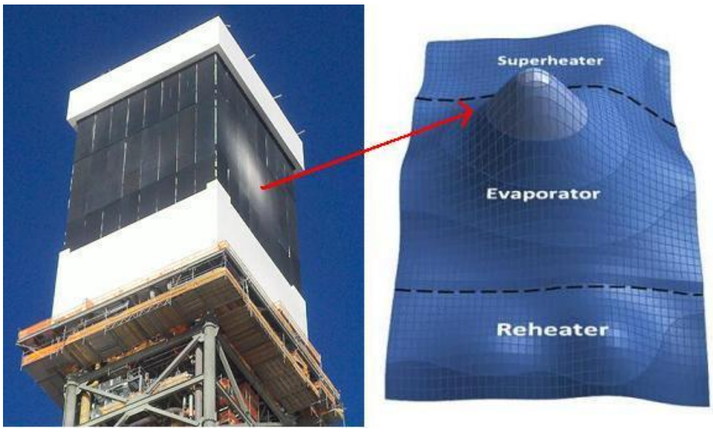

Figure 9: Ivanpah Solar Receiver Steam Generator (SRSG)

3.2 Plants closed

The following plants were operational for a few years in the past. Even though they have been demolished a brief description of them is presented below.

3.2.1 Solar One

This plant was a 10 MW_e demonstration plant which was set up in Barstow, California. It used 1818 heliostats of 40 m^2 aperture area each. It was constructed with an external cylindrical receiver and water as HTF. The height of the tower was 90.8 m (24). Solar One is said to have been producing electricity from 1981 to 1988 (25).

3.2.2 Solar Two

In 1995 Solar One was converted to Solar Two, by increasing the mirror field by adding more heliostats. Now the total number of heliostats increased to 1900. It was the first plant to demonstrate the use of molten salt as HTF and storage medium using ST technology. Solar Two generated electricity from 1996 to 1999. And after 10 years of not producing any electricity it was demolished in 2009 (25). This plant incorporated thermal storage using molten salt (26).

3.3 Under Construction

3.3.1 Crescent Dunes Solar Power Project

The Crescent Dunes Solar Power Project is a 110 MW_e plant which is situated in Tonopah in Nevada, USA. It aims to use an external cylindrical receiver with molten salt as the HTF. It is made up of 17170 heliostats of 62.4 m^2 area each. These heliostats need to be canted due to their large size. The height of the tower being constructed is 165m. The plant targets to have 10 hours of storage. The plant was expected to be operational by the end of 2013 (27).

3.3.2 Rice Solar Energy Project

This project aims to achieve a capacity of 150 MW_e. It is located in the Mojave Desert in California. Similar to the Crescent Dunes project, the Rice Solar project also uses an external cylindrical receiver with molten salt as the HTF. It has 17170 heliostats of 62.4 m^2 area each. The height of this power tower is 165 m and the plant is set to include a molten salt storage system. This plant is expected to start production by January, 2016 (28).

3.3.3 Gaskell Sun Tower

This tower, located in Lancaster, California has a capacity of 245 $MW_{e.}$. It covers 4.45 km^2 of land area. Construction for this plant was started in 2011. (29).

3.3.4 Khi Solar One Tower

This plant is set up in South Africa. It is a 50 MW_e capacity plant with 4120 heliostats, 140 m^2 each. The height of the tower is 200m. This plant is expected to start operation in 2014 (30). Two hours of storage is to be incorporated into this plant using molten salt as storage medium as well as HTF. It can reach a maximum temperature of 530°C. This system uses air cooled condensers. The cooling tower operates without fans as it uses the towers to distribute air across the fin blades in order to disperse the heat. It is the first large scale natural draft condenser. (31)

3.3.5 Palen Solar Electric Generating System

The Palen Solar Electric Generating System, is a 500 MW_e plant, located in Riverside California, for which electricity production is scheduled to start by 2016. It is to cover around 15.4 km^2 of land area. It will be made up of 2 units and will not have a storage facility. The project is being taken up jointly by Brightsource and Abengoa (32).

3.3.6 Supcon Solar Project

It is a 50 MW_e power plant located in China. It has 217440 heliostats, each of 2 m^2 area and a tower height of 80m. It is envisaged to have a provision for molten salt storage (33).

3.4 Collation of Information on Existing Plants

The list of ST plants which are operational and under construction (for which considerable amount of data is available) is given in Table 2 (34). This table gives information on the location, capacity, heliostat and tower height of these plants. Information about receivers, HTF and power cycle for various plants, which are in operation and under construction are given in Table 3. Among the plants in operation, five plants use cavity tubular receivers, one uses external cylindrical receiver. The Sierra sun tower has two towers, one with external cylindrical receiver and one with a dual cavity receiver, each of 2.5 MW_e. Jülich solar tower uses volumetric receiver with air as HTF. Among the plants under construction, information is available only for a few plants. When water is used as the HTF, the maximum outlet temperature is only 566°C

Table 4 gives some overall data about the existing plants including the gross cost of plant (wherever available) and the packing density, which is defined as the ratio of the mirror area to land area.

Table 2: Basic Information on Existing ST Plants

Plant name	Country	Developer	Capacity (MW_e)	No of Heliostats	Heliostat Aperture Area (m^2)	Tower Height (m)
OPERATIONAL						
PS-10	Spain	Abengoa Solar	11	624	120	115
PS-20	Spain	Abengoa Solar	20	1255	120	165
ACME	India	ACME, eSolar	2.5	14280	1.14	46
Dahan	China	IEEE of Chinese Academy of Sciences	1.5	100	100	118
Solugas	Spain	Abengoa Solar	4.6	69	121	75
Gemasolar	Spain	Torresol Energy	19.9	2650	120	140
ISEGS	USA	Bright Source	392	173500	14.08	140
Sierra Sun Tower	USA	eSolar	5	24360	1.14	55
Jülich Solar Tower	Germany	Kraftan lagen	1.5	2153	8	60
UNDER CONSTRUCTION						
Rice Solar	USA	Solar Reserve	150	17170	62.4	165
Crescent Dunes	USA	Solar Reserve	110	17170	62.4	165
Khi Solar One	South Africa	Abengoa Solar-IDC	50	4530	128	200
Supcon Solar	China	Supcon Solar	50	217440	2	80

Table 3: Information on Receiver and Power Block Details of Existing ST plants

Plant	Receiver Type	HTF	Receiver Inlet Temperature (°C)	Receiver Outlet Temperature (°C)	Power Cycle	Pressure (bar)	Power Block Temperature (°C)	Cooling Method
OPERATIONAL								
PS 10	Cavity	Water	50	250-300	Rankine	45	250-300	Wet
PS 20	Cavity	Water	50	250-300	Rankine	45	250-300	Wet
ACME	Cavity	Water	218	400	Rankine	60		Wet
Dahan	Cavity	Water	104	400	Rankine			Wet
Solugas	Cavity	Air		850		10	850	
Gemasolar	External Cylindrical	Molten Salt	290	656	Rankine			Wet
Ivahpah SEGS	External Rectangular	Water	249	566	Rankine			Dry
Sierra Sun Tower	Dual-cavity & external	Water	218	440	Rankine	60	440	Wet
Jülich Solar Tower	Volumetric	Air	120	680	Rankine	26	485	Wet, Dry
UNDER CONSTRUCTION								
Rice Solar	External Cylindrical	Molten Salt	288	566		115		Dry
Crescent Dunes	External Cylindrical	Molten Salt	288	566		115		
Khi Solar	To Be Decided	Water						Dry
Supcon tower	To Be Decided							

Table 4: Detailed Existing Plants Data

Plant	Rated Capacity (MW_e)	Thermal Storage (Hours)	Eq. Capacity (MW_e)	Tower Height (m)	Mirror Area (m^2)	Land Area (ha)	Mirror Area/Eq Capacity (m^2/MW_e)	Land Area/ Eq Capacity (m^2/MW_e)	Gross Cost of Plant (Rs. Crores)	r/h ratio	Packing Density	Land Area/ Mirror Area
OPERATIONAL												
PS 10	11.02	1	12.2	115	7.5E4	55	6125	44918	192	6.5	0.136	7.4
PS 20	20	1	22.22	165	1.5E5	80	6750	36000		5.6	0.188	5.3
ACME	2.5	0	2.5	46	1.6E4	4.85	6489	19425			0.334	3
Dahan	1.5	1	1.67	118	1E4	5.2	6000	31200	33.312		0.192	5.2
Solugas	4.6	0	4.6	75	8.3E3	6	1815	13043			0.132	7.2
Receiver Type : External Cylindrical												
Gemasolar	20	15	53.3	140	3.9E5	195	5992	36746	1942	6.2	0.163	6.1
Ivahpah SEGS	392	0	392	140	2.6E6	1.417	5857	36148		10.4	0.162	6.1
Receiver Type : External Rectangular and Dual Cavity												
Sierra Sun Tower	5	0	5	55	2.8E4	8.1	5534	16200		2.3	0.342	2.9
Receiver Type : Volumetric												
Jülich	1.5	1.5	1.75	60	1.8E4	8	10285.7	45715		2.3	0.225	4.4
UNDER CONSTRUCTION												
Receiver Type : External Cylindrical												
Rice Soar	150	8		165	1.1E6	571					0.188	5.3
Crescent Dunes	110	10	232.22	165	1.1E6	648	9740	58909		9.7	0.165	6.1
Receiver Type : To Be Decided												
Khi Solar	50	2	61.11	200	5.8E4	140	11536	22910			0.412	2.4
Supcon tower	50	0	50	80	4.3E5	330	8698	66000			0.132	7.6

4 Available Literature on the Performance of Operating Plants

ST technology is a nascent technology as compared to the parabolic trough technology. The growth of the ST technology in the past decade has been significant and is increasing enormously. In this section, the available literature on existing ST plants and their characteristics is presented.

Burgelata et al., 2011 have given an overview of the Gemasolar plant, the first commercial tower plant with molten storage. The work describes the characteristics, construction, start up and operation of the plant (35). Zunft et al., 2011 have done an experimental evaluation of the storage subsystem and performance calculation of the Jülich Solar Power Tower. They set up a test facility at the plant to monitor performance as well as the storage subsystem of the plant. The results from the analysis carried out affirm that the plant (including the storage system) is functioning to its full capacity. They also confirmed that cycling can be done at high discharge rates of heat transfer accompanied by low heat losses (36). Koli et al., 2009 have done an analysis of the Jülich Tower plant. This paper describes the mechanism of the plant with the aim of using it to as a means to devise methods, mechanisms and procedures that will help in the construction and operation of plants using similar technology in the future (37).

Xu et al., 2010 have performed the modelling and simulation of the 1 MW Dahan ST plant. They discuss the generation of response curves for various solar irradiance changes and have shown that the receiver outlet pressure and flow change moderately, regardless of radiation changes. However, the receiver response is more rapid to outlet temperature and power (15). Quero et al., 2013 have studied the operation experience of the Solugas ST plant, which is the first solar hybrid gas turbine system developed at the MW scale. They concluded that while the plant is operating satisfactorily in its capacity, further modifications like incorporation of storage, turbine improvements and receiver distribution can be incorporated (38). Tyner et al, 2013 have designed a reference plant using eSolar's modular, scalable molten salt power tower. They proposed a thermal modular design for a plant using these heliostats after performing a detailed risk assessment (39). Meduri et al., 2010 carried out the performance characterization and operation of eSolar's Sierra Suntower plant (40). Siva Reddy et al., 2013 have done a review of the various state of the art solar thermal plants worldwide. They have performed a comparative study of the parabolic trough, parabolic dish and solar tower systems in terms of economic viability. They concluded that the parabolic dish technology provides electricity at a lower cost per unit in comparison with the other two technologies (41). Zhang et al., 2013 have performed a review of CSP technologies and talks about the advantage of the power tower technology. They also give a method to estimate the hourly beam radiation flux from available monthly radiation data (42). M. Romero et al., 2002 have presented a review of the existing central receiver technologies (43).

5 Assessment of Existing Solar Tower Plants

An assessment of the existing ST plants is discussed in this section where the overall efficiency of solar to electric energy conversion is discussed. Also, the mirror and land area per MW_e of capacity is explored, the various layouts are described, receiver size estimation is carried out and the tower height of the plants with respect to their capacity is assessed.

5.1 Overall Efficiency of Conversion of Solar to Electric Energy

The efficiency of conversion of solar to electrical energy is as follows:

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

The values of overall efficiency for the various existing plants are also included in Table 5 and lie in the range of 15.51 to 17.30.

Table 5: Solar to Electric Conversion Efficiency for Existing Plants

Plant Name	Rated Capacity (MW_e)	Tower Height (m)	Mirror Area (m^2)	Land Area (hectares)	Packing Density	Expected Annual Electricity generation (MWh)	Annual Solar resource (MWh/m^2)	$\eta_{s-e=}$ (%)
OPERATIONAL								
Receiver Type : Cavity								
PS 10	11.02	115	7.5E4	55	0.136	23400	2.012	15.51
PS 20	20	165	1.5E5	80	0.188	48000	2.012	15.9
ACME	2.5	46	1.6E4	4.85	0.334			
Dahan	1.5	118	1E4	5.2	0.192			
Solugas	4.6	75	8.3E3	6	0.139			
Receiver Type : External Receivers								
Gemasolar	19.9	140	3.9E5	195	0.163	110000	2.172	15.93
Ivahpah SEGS	392	140	2.6E6	1417	0.162	1079232	2.717	17.30
Receiver Type : External Rectangular and Dual Cavity Receiver								
Sierra Sun Tower	5	55	2.8E4	8.1	0.342			
Receiver Type : Volumetric Receivers								
Jülich	1.5	60	1.8E4	8	0.225			
UNDER CONSTRUCTION								
Receiver Type : External Cylindrical Receivers								
Rice Solar	150	165	1.1E6	571	0.188	450000	2.598	16.17
Crescent Dunes	110	165	1.1E6	648	0.165	485000	2.685	16.86
Receiver Type : To Be Decided								
Khi Solar	50	200	5.8E4	140	0.412			
Supcon tower	50	80	4.3E5	330	0.132			

5.2 Comparison of Mirror Area and Land Area for Existing Plants

Important information such as capacity, solar resource, land area used, total heliostat aperture area, number of hours of storage etc., of the ST plants have been presented in Table 2, Table 3 and Table 4 for plants in operation and under development. From this data, one can observe that the mirror area and land area per MWe of rated capacity vary from plant to plant due to variations in thermal storage hours. Hence it is necessary to normalise the mirror/land area requirements taking into consideration the number of hours of thermal storage.

In order to take into account the thermal storage, it is assumed that plant with no thermal storage can generally operate for nine hours. If x hours of thermal storage have been provided, then the mirror area and correspondingly the land area has to be increased (9+ x)/9 times compared to the plant with no thermal storage. A comparison of the mirror area and land area with rated and equivalent capacity for plants that are operational and under construction is made separately for each type of receiver used.

5.2.1 Mirror Area

Table 6 gives the normalised values of the mirror area with respect to 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 range from 5999 to 6750 and for plants using external receivers range from 3781 to 6633. It can also be seen that both Rice Solar and Crescent Dunes plants have lesser mirror area compared to other plants as these two sites have a higher solar resource.

Table 6: Mirror Area Based on Capacity

Plant Name	Capacity	TES (hours)	Eq. 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	7.5E4	6806	6125
PS-20	20	1	22.22	1.5E5	7500	6750
ACME	2.5	0	2.5	1.6E4	6512	6512
Dahan	1.5	1	1.667	1E4	6667	5999
Solugas	4.6	0	4.6	8.3E3	1815	1815
Receiver Type : External Cylindrical						
Gemasolar	19.9	15	53.07	3.9E5	15980	5992
Ivanpah	392	0	392	2.6E6	6633	6633
Receiver Type : External Rectangular and Dual Cavity						
Sierra	5	0	5	2.8E4	5534	5534
Receiver Type : Volumetric						
Jülich	1.5	1.5	1.75	1.8E4	12000	10286
UNDER CONSTRUCTION						
Receiver Type : External Cylindrical						
Rice Solar	150	8	283.33	1.1E6	7142	3781
Crescent Dunes	110	10	232.22	1.1E6	9740	4614
Receiver Type : To Be Decided						
Khi Solar One	50	2	61	5.8E4	1160	951
Supcon	50			4.3E5		

5.2.2 Land Area

Table 7 gives 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, sizes of heliostats used and further due to the variations in packing density.

Table 7: Land Area Based on Capacity

Plant Name	Capacity (MW_e)	TES (hours)	Equivalent Capacity	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	2.4	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 Rectangular 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 : To Be Decided						
Khi Solar One	50	2	61	14	2.8	2.3
Supcon Tower	50	0	50	33	6.6	6.6

This data could be used as guidance values for plants being planned in India. ACME and Sierra use the e-Solar's technology for modular heliostat layout which requires less land area.

5.3 Field Layout Configuration

There are some standard layout patterns which are generally considered for the heliostat field design. They are described in this section.

5.3.1 Radial Configuration

In this configuration, the heliostats are arranged such that they form circles around the tower. This can be seen in Figure 10 (Source: Google Maps) which is the heliostat field of the Gemasolar plant. In Figure 11 (Source: Google Maps), the field for the PS 10 and PS 20 towers have been shown. As seen in the radial staggered configuration, the heliostats are arranged such that a heliostat immediately behind another one is offset circumferentially by a small distance so that they are not in a line.

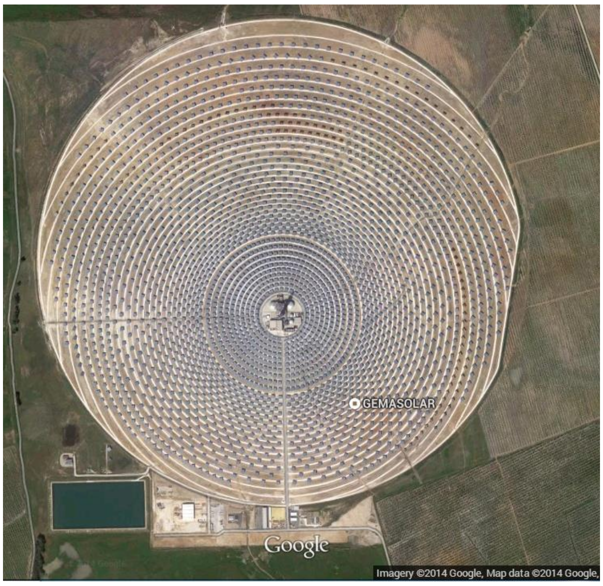

Figure 10: Heliostat Field for Gemasolar, Spain

Figure 11: Heliostat Field for PS 10 and PS 20, Spain

5.3.2 Cornfield Configuration

In the 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 Figure 12 (Source: Google Maps) and Figure 13 (Source: Google Maps). In Figure 13 it is a single side field (the field is only on one side of the tower) as in the Jülich tower, a cavity receiver is used with a single side aperture.

Figure 12: Heliostat Field of Sierra Sun Tower, USA

Figure 13: Heliostat field of Jülich plant, Germany

From the figures, one can infer that the layout of the heliostats does not follow any particular norm.

It is interesting to note that all these plants (except the Dahan and Jülich plants) are located at nearly the same latitude (28°11' N to 38°14' N) but the 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, consequently the heliostats are located all around the tower (surround field), but higher number of heliostats are on the northern side. The r/h ratio on the north side of the field is 6.11 whereas on the south side it is 4.34. In one unit of the Sierra Sun tower plant a dual cavity receiver is used and hence heliostats are located on both sides of the tower. The other unit has an external rectangular receiver and also has its heliostat field on either side. Depending on the capacity of the plant, multiple modules are used and steam collected from each tower is fed into a common turbine. Thus the heliostat field layout is closely linked with the choice of the receiver and other design considerations.

5.4 Estimation of Receiver Size

To estimate the receiver size, we start with the power block. Depending upon the equivalent capacity of the plant, the HTF used and turbine inlet temperature, we have assumed values for the power block efficiency as shown in Table 8 (44). Then from this, the thermal power input to the receiver is estimated as follows:

$$Power\ input\ to\ the\ power\ block{=}P_{input,PB}){=}\ \frac{Eq\ Cap.)100{=}}{\eta_{Power\ Block{=}}}$$

Once we find out the power input to the power block, we assume that the receiver efficiency is 85% and thereby obtain the power input to the receiver as follows:

$$Power\ Input\ to\ the\ receiver{=}P_{input,{=}eceiver}){=}\ \frac{P_{input,PB})100{=}}{85{=}}$$

Depending upon the type of HTF used, the maximum allowable flux density on the receiver is fixed. We assume that this maximum allowable power is incident on the receiver. Now that we know the flux on the receiver in kW/m^2, we can estimate the receiver area as follows:

$$Calculated\ Receiver\ Area{=}\ \frac{P_{input,{=}eceiver})1000{=}}{Flux\ on\ receiver{=}}$$

This calculated receiver area is compared with the actual receiver area. The actual area for the receivers of the various plants - Julich, PS10, Solar Two and Gemasolar (17), Dahan (15), Solugas (45) were found out. The maximum allowable flux density for molten salt is 1000 kW/m^2 (46) for water it is 350 kW/m^2 (46)and for air it is assumed to be 1200 kW/m^2.

The factor of $\frac{Actual\ Receiver\ A\ \ ea{=}}{Calculated\ Receiver\ A\ \ ea}$ has been computed and is seen to vary from 1.73 to 2.72 when molten salt is used as HTF, it is 1.12 to 1.83 when water is used as HTF and 3.37 and 6 when volumetric receiver is used with air as HTF as shown in Table 8.

It can be seen that this factor is high for receivers using air as HTF. It is clear that the actual receiver size should exceed the one which is obtained by calculation to take into account various factors like spillage and also the fact that the flux impinging throughout the course of the day varies. The value of the flux on the receiver might be quite low during some time of the day.

Table 8: Receiver Size Estimation

Plant Name	Equivalent Capacity (MW)	Power Block Inlet Temp. (˚C)	Power Block Efficiency (%) *	Power input to the Power Block (MW_{th})	Power input to the Receiver (MW_{th})	HTF	Max. Allowable Flux Density for HTF = 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	36.48	Molten Salt	1000	36.48	99.30	2.72
Gemasolar	53.3	565	43	123.41	145.19	Molten Salt	1000	145.19	251.33	1.73
PS-10	12.24	250	27	45.35	53.35	Water	350	152.44	279.54	1.83
Dahan	1.67	400	25	6.67	7.84	Water	350	22.41	25	1.12
Julich Solar Tower	1.8	680	25	6.67	7.84	Air	1200	6.54	22	3.37
Solugas	4.6	850	30	15.33	18.04	Air	1200	15.03	90.25	6.00

Values marked with * are assumed values

5.5 Tower Height

Table 9 gives the available information on tower heights and the distances of the farthest heliostat from tower. From Table 9 and Figure 14 no correlation is evident between the tower height and equivalent capacity of the plant. Once the capacity of the plant is fixed, the thermal storage and solar resource are known, the land and mirror area can be determined. Then based on the type of receiver and design, the heliostat field can be designed. However, the basis on which the height of the tower is fixed is not clear. From Table 9, it can be seen that the ratio of the farthest distance of the heliostat to the tower height 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 much smaller. As r/h increases, the blockage effect increases and also as $'r'$ becomes more than 1 km, attenuation losses increase. So it is a bit surprising that for ISEGS plant $'r'$ is of the order of 1400 m and hence the r/h is more than 10. It is felt that, it is better to restrict r/h to less than seven and $'r'$ to 1 km.

Table 9: Tower Height of ST Plants

S. No.	Plant	Capacity (MW_e)	TES (hours)	Eq. Capacity (MW_e)	Height (m)	r/h
OPERATIONAL						
Receiver Type : Cavity						
1	PS 10	11	1	12.2	115	6.5
2	PS 20	20	1	22.2	165	5.6
3	ACME	2.5	0	2.5	46	
4	Dahan	1.5	1	1.667	118	
Receiver Type : External						
5	Gemasolar	19.9	15	53.1	140	6.2
6	ISEGS	130	0	130.0	140	10.4
	Receiver Type : External Rectangular and Dual Cavity					
7	Sierra	5	0	5.0	55	2.3
Receiver Type : Volumetric						
8	Jülich	1.5	1.5	1.8	60	2.3
UNDER CONSTRUCTION						
Receiver Type : Cavity						
9	Rice Solar	150	8	283.3	165	
10	Crescent dunes	110	10	232.2	165	9.7
Receiver Type : To be decided						
11	Khi Solar One	50	2	61.1	200	
12	Supcon	5	0	5.0	80	

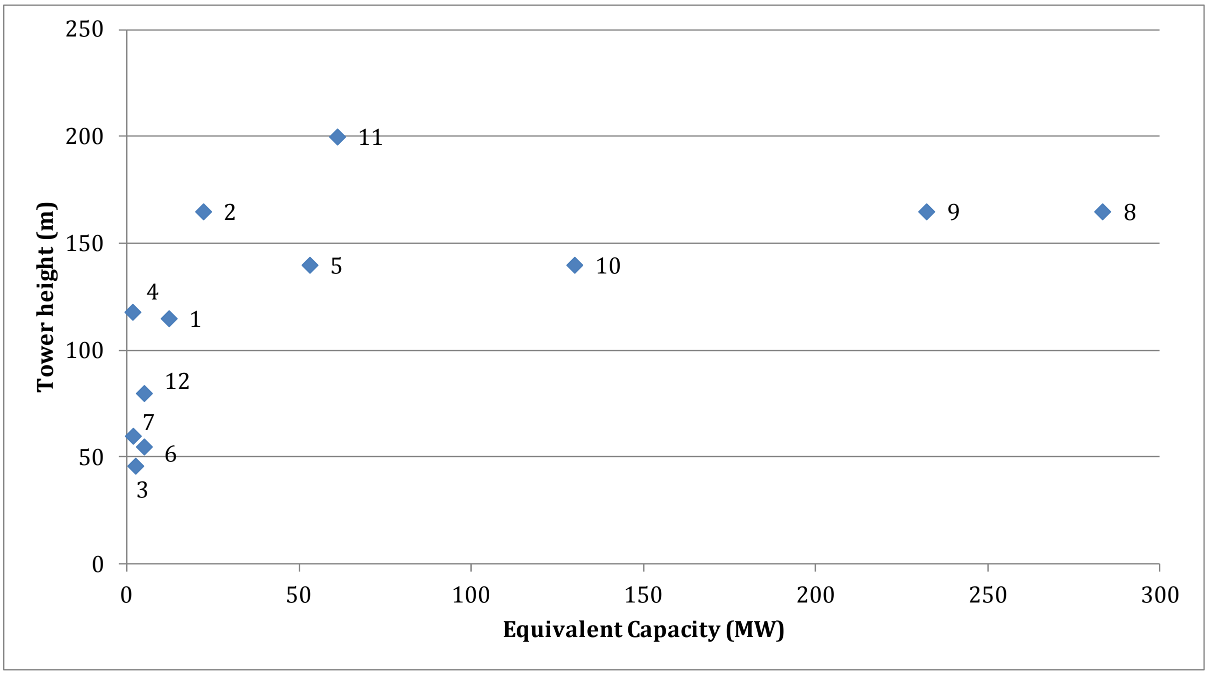

Figure 14: Variation of Tower Height with Equivalent Capacity

5.6 Comparisons for Existing Plants

The following plots have been generated for an estimation of the variation of land area, heliostat aperture area with respect to equivalent capacity. These are shown in Figure 15 and Figure 16.

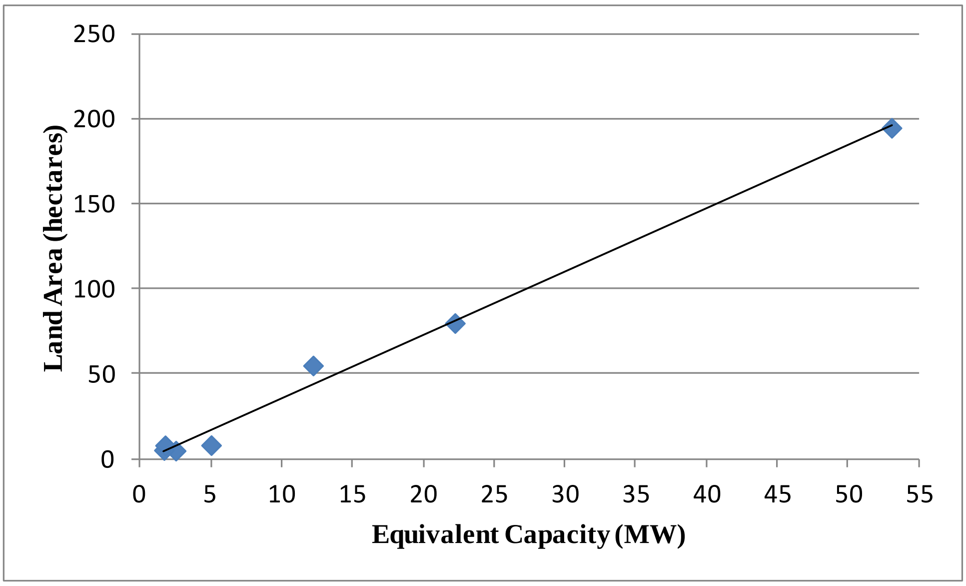

Figure 15: Land Area vs. Equivalent Capacity

Figure 15 gives the variation of land area with equivalent capacity of the plants. From this plot we can see that it is somewhat linearly varying. However there is no clear correlation.

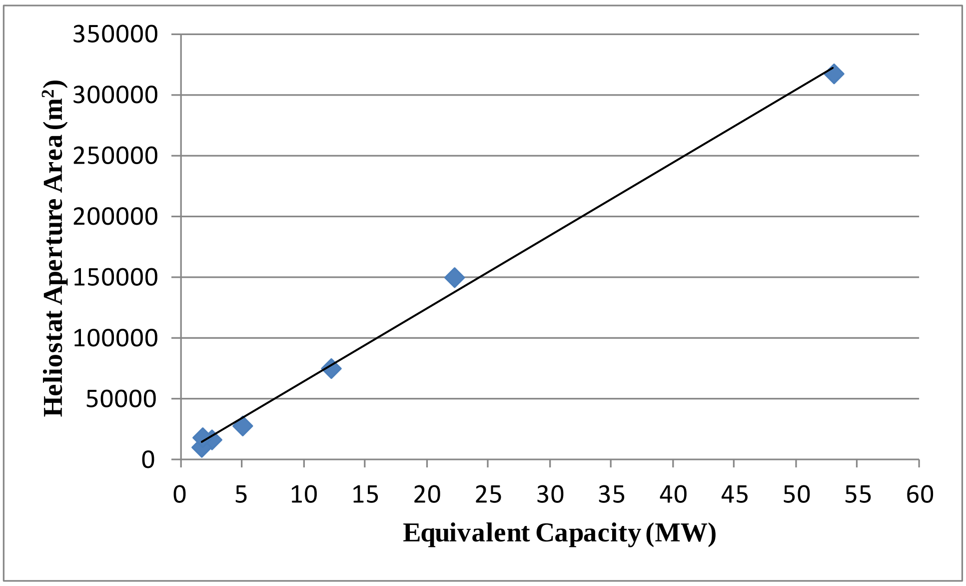

Figure 16: Heliostat Aperture Area vs. Equivalent Capacity

In Figure 16 the heliostat aperture areas are plotted with respect to the equivalent capacity. Here also a linear variation is observed.

6 Cost of ST Technology

The data available on the gross costs for the 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 (47)). The gross cost for the Dahan Plant (cavity receiver) is approximately Rs. 20 crores per MW_e (32 million CNY (48)). The overall cost of the Gemasolar plant (external cylindrical) is Rs. 36 crores per MW_e (419 million USD (49)). This is data depicted in Table 10. Data for most of the other existing plants was not available.

Table 10: Available Gross Costs of Plants

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

The costs of some of the components of the ST, namely the heliostat field, receiver and tower for specific capacities according to some reports are given in Table 11.

Table 11: ST Component Costs

	Solar Field			**Capacity (MW)**	**Receiver Type**
Source	**Heliostat Field (Rs./m2)**	**Receiver (Rs./kWth)**	**Tower**		
CSIRO 2011 (50)	6674	893	1363 Rs./kW_{th}	100	
UNDP 2012 (51)	12090	14950	3.37E+08 Rs.	20	External Cylindrical
UNDP 2012 (51)	12090	5525	2.73E+08 Rs.	20	Cavity
SANDIA REPORT, 2011 (52)	9000	6390	2610 Rs./kW_{th}	100	External Cylindrical
ECOSTAR 2004 (53)	8250	6875	1.1E+08 Rs.	17	Cavity
ECOSTAR 2004 (53)	7810	6380	3.06E+08 Rs.	50	Cavity

7 Challenges for ST Technology Deployment in India

India has limited experience in the development of power tower systems. Apart from a couple of small scale demonstration plants, there have been no plants in the pipeline for India. ACME company in India have partnered with e-solar, USA in developing a 2.5 MW_e (to be scaled up to 10 MW_e) tower plant in Bikaner, Rajasthan. The heliostat field for the 2.5 MW_e plant set up utilises small size flat mirrors of 1.16 m^2. 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. The plant, of 2.5 MW_e, was commissioned in 2010. However it is not running to its full capacity. Some of the possible problems were attributed to lack of sufficient Direct Normal Irradiance (DNI), difficulties in tracking and accumulation of dust on the mirror.

SunBorne energy is setting up a 1 MW_{th} ST system, with support from 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 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 (54).

The challenges for using ST technology in India are as follows:

- Dust on the heliostats reduces its life and efficiency. Most of the areas in India with abundant solar irradiation (for example, Gujarat and Rajasthan) are areas which are prone to very high dust factors. In these cases maintenance of each heliostat is of prime importance which is not an easy task in a field with thousands of mirrors.
- There are only three suppliers of molten salt HTF globally, namely, SQM, Haifa Chemicals and Durferrit Salts and Auxillary Products. Lack of domestic suppliers of HTF is one of the main challenges in implementing ST plants with storage (as molten salt storage is the most efficient presently). This is due to the fact that the major cost contributor of any storage system is the storage medium.

- Absence of an established supply chain for the main ST components is also 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 extremely costly receivers.
- Unlike the parabolic trough which has a well-established supply chain and standards, ST, due to its variants in technology has seen limited suppliers as well as standards. Furthermore there is no benchmarking for reliability testing of ST components. Due to this, market acceptability of in-house manufactured components reduces. As a result of the lack of demand, even components for which a domestic market can be set up, the question of sustainability looms at large.
- There exists no policy support or incentive from the government for setting up of ST plants as well as promoting hybridization. This is also a huge challenge which currently hinders the implementation of ST plants in India.

8 Opportunities for ST Technology India

India is situated between 8°N to 37°N latitude and 70°E to 96°E longitude. For these geographical coordinates, the sun is in the southern side for a larger part of the year and on the northern side for a smaller duration annually for any particular location.

Based on this geographical positioning, the opportunities for ST deployment in India are as follows:

- High temperatures in the range of 300 to 565°C are possible with the use of suitable HTFs. The presence of higher operating temperatures results in a higher power cycle efficiency as well as number of hours of storage.
- India has a good solar zone with high solar resource (DNI values) almost throughout the year which has the potential to be tapped. The best sites in India, receive around 2100 kWh/m^2/annum which is at par with most of the existing tower plants. This sets the benchmark for commercial viability of this technology under Indian conditions.
- The land requirement for ST plants can be fulfilled by utilising the huge wastelands present in India. Approximately 472200 km^2 of wasteland is available in India (55). Even if 1% of this land is utilised for solar projects the potential goes beyond India's current installed capacity. Hence land constraint is not a deterrent to growth of ST technology in India.
- Since ST technology does not require land of constant slope, terrains (of up to 5° difference) need not be filled in or levelled. This reduces the construction time and installation (set up) cost.
- 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. Further, the structural designing and manufacture of heliostat support structure, the requisite drive mechanisms and tower can be accomplished in India at lower costs.
- Establishment of an indigenous market for receiver technology, external cylindrical and cavity receivers can be done since for both these technologies, once the specifications are known, the manufacturing and fabrication process is relatively straightforward.
- 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.

The total capacity of grid connected solar projects in India currently stands at 2632 MW as on March 31st, 2014 (56). The contribution from CSP in Phase-1 has been very less as compared to the contribution of Photovoltaic (PV) based 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 the Jawaharlal Nehru National Solar Mission (JNNSM), given the mandate of 30% capacity addition from CSP (57). Assuming that 30% of the target could be tapped from solar thermal technologies, the CSP share 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. Using a mix of cavity and external cylindrical receiver technologies, the approximate land required per MW is about three hectares resulting in a land requirement of 54 km^2 for the 1800 MW target.

9 Conclusion

As seen from the existing plants, most of the tower plants are employing either the external cylindrical or the cavity type receiver. By using molten salt one can achieve high 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 as well as the storage medium.

India has indigenous manufacturers of components such as mirror, support structure and power block components. However, as pointed out earlier, the experience in designing and manufacturing of receivers is limited. Therefore, given the considerations mentioned above, the system configuration that could be ideal for Indian conditions are:

- Molten salt as HTF and storage medium,
- External cylindrical receivers with a larger north side field or cavity receiver with north side field.
- Thermal storage for utility scale plants, as it can provide reliable and dispatchable power and further help in meeting the peak-time demands.
- Biomass hybridisation which would require more R&D.

The total installed capacity of the ST plants worldwide is shown in Table 12 (58). It has been compared with the Parabolic Trough technology to see the growth potential of ST in the next few years.

Table 12: Status of ST and PT CSP plants

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

We can note that ST under construction capacity is almost comparable to that of Parabolic Trough technology and therefore it needs to be explored and will certainly prove to be a very useful form of energy conversion (solar to electric), in the years to come.

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