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Technical and economic potential of concentrating solar thermal power generation in India

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A R T I C L E I N F O

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Key barriers and policy implications

A B S T R A C T

This study aims to assess the technical and economic potential of concentrating solar power (CSP) generation in India. The potential of CSP systems is estimated on the basis of a detailed solar radiation and land resource assessment in 591 districts across the country. The land suitability, favorable solar resource conditions and wind power density over the vicinity have been considered key parameters for potential estimation. On the basis of a district-wise solar and land resource assessment, the technical potential of CSP systems is estimated over 1500 GW at an annual direct normal irradiance (DNI) over 1800 kWh/m^2 and wind power density (WPD) ≥150 W/m^2 after taking into accounts the viability of different CSP technologies and land suitability criteria. The economic potential of CSP is estimated at 571 GW at an annual DNI over 2000 kWh/m^2 and WPD≥150 W/m^2 in India. The technical evaluation of CSP technologies over the potential locations have been carried through System Advisor Model (SAM) Software using the Typical Meteorological Year data of Meteonorm 7.0 weather database. In near future, it is anticipated that locations with DNI values ≥1600–1800 kWh/m^2 could also become economically feasible with the development of new technologies, advancement of materials, efficient and cost-effective thermal energy storage, economy of scale, manufacturing capability along with the enhanced policy measures, etc. In the long-term, it is possible to exploit over 2700 GW solar power through CSP in India with an annual DNI ≥1600 kWh/m^2 and WPD≥150 W/m^2. The findings of this study can be used for identification of niche areas for CSP projects in India.

1. Introduction

Energy is the vital ingredient in the world economy. The global energy demand is steadily increasing due to the increasing world population and the rising living standards. The current world population of 7.2 billion is projected to increase by almost one billion people within the next twelve years, reaching 8.1 billion in 2025 and 9.6 billion in 2050 [1]. Moreover, rapid urbanization will bring with it changes in life styles and consumption patterns. Over 70% of the world's population is expected to be urban by 2050 [2]. Without any change in our current practice, the global primary energy demand increase in 2040 would be 45% higher than 2013 levels in the current policy and 32% under a more restrained scenario [3]. At the same time, over 1.2 billion people – 16% of the global population have no access to electricity and 2.7 billion people – 38% of the world's population rely on traditional biomass for cooking and heating [3]. With global energy demands on the increase, coupled with the depletion of natural resources and the negative impact of fossil-based energy sources on the environment, the issues of clean, sustainable energy and the importance thereof in economic development and global wellbeing

Abbreviations: AD, Accelerated Depreciation; AWS, Automatic Weather Stations; CEA, Central Electricity Authority; CERC, Central Electricity Regulatory Commission; CRS, Central Receiver Systems; CSP, Concentrated Solar Power; C-WET, Centre for Wind Energy Technology; CUF, Capacity Utilization Factor; DNI, Direct Normal Irradiance; DOLR, Department of Land Resources; ESIA, Environmental and Social Impact Assessment; FIT, Feed-in Tariff; GBI, Generation Based Incentives; GHI, Global Horizontal Irradiance; GoI, Government of India; HTF, Heat Transfer Fluid; IFC, International Finance Corporation; IMD, Indian Meteorological Department; IEA, International Energy Agency; ITC, Investment Tax Credit; JNNSM, Jawaharlal Nehru National Solar Mission; LCOE, Levelized Cost of Electricity; LFC, Linear Fresnel collectors; MNRE, Ministry of New and Renewable Energy; MoRD, Ministry of Rural Development; NAPCC, National Action Plan on Climate Change; NASA, National Aeronautics and Space Administration; NIWE, National Institute of Wind Energy; NREL, National Renewable Energy Laboratory; NTPC, National Thermal Power Corporation; NVVN, NTPC Vidyut Vyapar Nigam Limited (NVVN); PCM, Phase Change Material; PDS, Parabolic Dishes System; PPA, Power Purchase Agreement; PTC, Parabolic trough collector; RE, Renewable Energy; REC, Renewable Energy Certificates; REID, Renewable Energy Infrastructure Development Fund; RPO, Renewable Purchase Obligation; SEC, Solar Energy Centre; SECI, Solar Energy Corporation of India; SEGS, Solar Energy Generating Systems; SERC, State Electricity Regulatory Commission; SRRA, Solar Radiation Resource Assessment; TES, Thermal Energy Storage; TMY, Typical Meteorological Year; UWA, Usable Wasteland Area; TWA, Total Wasteland Area; UNFCCC, United Nations Framework Convention on Climate Change; VGF, Viability Gap Funding; WPD, Wind Power Density

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Nomenclature

Albedo Albedo is the fraction of solar energy (shortwave irradiance) reflected from the Earth back into space. It is a measure of the reflectivity of the earth's surface.
Capacity Utilization Factor (CUF) CUF is the ratio of the actual output from a solar plant over the year to the maximum possible output from it for a year under ideal conditions.
Direct Normal Irradiance (DNI) DNI is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky.
Global Horizontal Irradiance (GHI) GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground.
Levelized Cost of Electricity (LCOE) LCOE is the price at which electricity must be generated from a specific source to break even over the lifetime of the project

have become a pressing reality worldwide [4–6]. The world needs another industrial revolution in which energy sources are affordable, accessible and sustainable [7]. Energy efficiency and conservation, as well as decarbonizing our energy systems, are essential to this revolution.

At present, India faces insurmountable challenges to its economy, environment and energy security [8,9]. India today is home to one-sixth of the world's population and its third-largest economy, but accounts for only 6% of global energy use and one in five of the population– 240 million people– still lacks access to electricity [3]. Nearly, 30% of the households classified as below the poverty line as per recent estimates [10]. Over 80% of the total oil requirement in India is imported [11] and more than 60% coal thermal power generation is based on fast depleting coal reserves [12]. Increased import dependence also exposes the country to greater geopolitical risks and international price volatility. The Government of India (GoI) has voluntarily agreed to reduce the emissions intensity of its gross domestic product (GDP) by 33–35% from 2005 levels by 2030 [13] as per the Intended Nationally Determined Contributions (INDCs) submitted by GoI to the UNFCCC in preparation of the Paris Agreement, although overcoming energy poverty and ensuring economic and social development remains a top priority. India needs economic growth for sustainable development, which in turn requires access to clean, convenient and reliable energy for all. Renewable energy (RE) sources offer a viable option to address the key energy policy issues of the country in providing energy services in a sustainable manner and, in particular, in mitigating climate change [14].

1.1. Overview of Indian power sector

The electricity sector in India had an installed capacity of 310 GW as of end December 2016 [12]. India became the world's third largest producer of electricity in the year 2013 with 4.8% global share in electricity generation surpassing Japan and Russia [15,16]. Captive power plants have an additional 47 GW capacity as on 31st March 2015 [17]. Out of 310 GW installed capacity, 189 GW is generating through coal, 25.3 GW by gas, 0.9 GW by oil and 5.8 GW from nuclear. The share of hydropower is 13.9% (43.1 GW) followed by 14.8% (45.9 GW) through RE resources. During the 11th Five Year Plan (FYP) from 2007–12, nearly 55 GW of new generation capacity was created whereas the 12th FYP (2012-17) aims to add another 88 GW [18]. For 2015–16 fiscal year, a base load energy deficit and peaking shortage anticipated at 2.1% and 2.6% respectively [19]. This has also accentuated by non-decentralized nature of power generation with vast areas in the rural segment which are not connected by the grid for reliable and quality power. As on 31st December 2016, total RE based electricity generation capacity in the country is estimated to be 51,447 MW including 1429 MW off-grid capacities [20]. Approximately, 57% of the RE capacity is accounted by wind (Fig. 1) followed by solar (18%), small hydro (9%) and biomass power/bagasse cogeneration (16%). The rate of growth has been particularly significant for solar over the last six years (2010–2016), which grew from less than 20 MW in early 2010 to more than 9000 MW by December 2016. The share of concentrating solar power (CSP) is relatively small (0.5%) in the RE mix of the country as compared to solar PV (17.5%), wind (57.4%) and other RE technologies (24.6%) in spite of having several advantages (dispatchability, thermal energy storage, hybridization, etc.) and huge potential across the country.

1.2. Global status of CSP technologies

At the global level, renewables represented approximately 58.5% of net additions to global power capacity in 2014, with significant growth in all regions [21,22]. In 2014, solar PV marked another record year for growth, with an estimated 40 GW installed for a total global capacity of about 177 GW [22]. However, CSP market remains less established than most other RE markets despite far greater potential for CSP systems to meet global electricity demand [22,23]. With advanced industry development and high levels of energy efficiency, solar thermal electricity could meet up to 6% of the world's power needs by 2030 and 12% by 2050 [24]. As of February 2016, the CSP market has a total capacity of 7.4 GW worldwide, among which 5 GW is operational and 2.4 GW is under construction [25]. Spain and the United States lead the world in terms of the installed capacity of CSP projects followed by India, South Africa and Morocco. Nevertheless, in terms of CSP projects under construction Oman leads with about 1 GW followed by China (430 MW), Morocco (350 MW), Israel (121 MW), Chile (110 MW) and South Africa (100 MW). Miraah (translated as 'mirror' in Arabic), a proposed 1021 MW CSP facility to be located in South Oman, is expected to be one of the world's largest CSP plants. Construction of the plant is started in late 2015, while operations are scheduled to begin in 2017.

1.3. CSP in Indian context

The Jawaharlal Nehru National Solar Mission (JNNSM) under the National Action Plan on Climate Change (NAPCC) of India was launched in 2010 with the objective of achieving grid parity by the year 2022. It aimed at the deployment of 20 GW of grid connected and 2000 MW of off-grid solar power during the three phases of its operative period [26]. However, given the progress that has been achieved thus far in the form of grid-interactive power (Fig. 1) and off-grid/captive power (406 MW) [12], GoI has raised the target of the JNNSM to 100 GW [13] to be achieved through grid connected projects, off-grid projects and solar parks by 2022. The idea in the first phase of the JNNSM (2010-13) was to give equal emphasis to both solar photovoltaic (PV) as well as CSP technologies. Therefore, 500 MW each was allocated to solar PV as well as CSP technologies in Phase-I. For CSP, 7 projects (470 MW) were awarded out of which only 225 MW capacities is implemented by end 2015 [27]. Further three projects of 10 MW capacities each were awarded through migration scheme of the Indian Ministry of New and Renewable

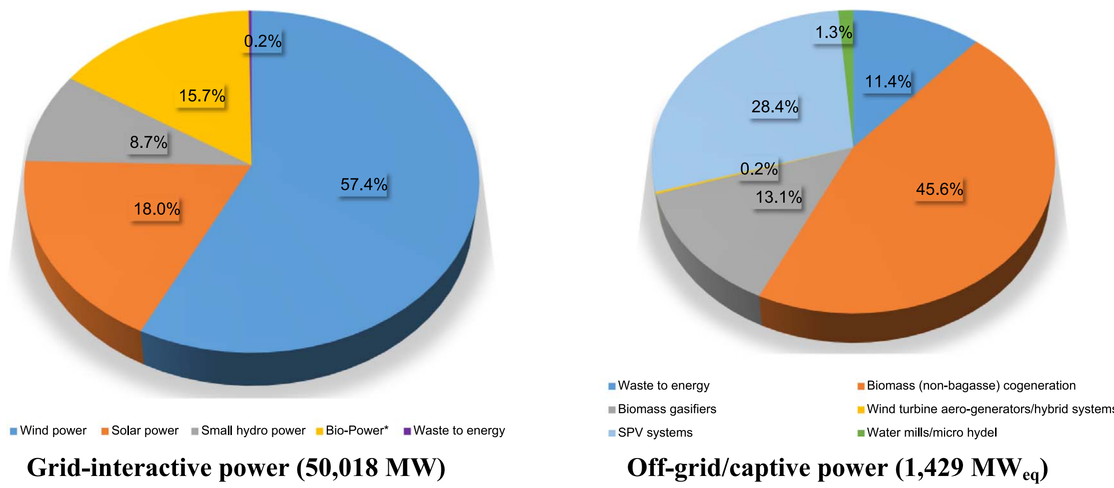


Fig. 1. Installed capacity of electricity generation from RE sources [18].

Energy (MNRE) out of which only 2.5 MW capacity is implemented.

The option to integrate cost effective storage systems directly into the plant environment represents a significant advantage of CSP plants against other RE technologies like solar PV or wind. Further, CSP power plants have the advantage of dispatchability. Within the increasing share of solar power generation (transient) in the overall energy mix of the country the concern of the technical reasons of power quality and compliance of the applicable grid codes are essential for which CSP technologies are more convenient. The anticipated amendment in the policy in the country towards forecasting and scheduling of renewables is more reliably predictable with CSP as compared with other RE options. Even with the anticipated acceleration of CSP in India through JNNSM, several barriers exist that challenge the long-term sustainability of India's CSP industry. Availability of long-term solar radiation data over the potential locations across the country is one of the most important technical barriers towards financial closure of the solar power projects (SPPs) [28–30]. Additionally, the meteorological information, land availability and timely acquisition, water availability, grid loading and availability, etc. were bottlenecks experienced by CSP projects across the country. The intermittency associated with solar resource makes SPPs more specific as compared to their conventional counterparts (viz. coal, oil, gas, etc.); as the magnitude of solar resource availability varies with location, season of the year and time of the day [31–33]. It is in this context an attempt to assess the potential of CSP generation in India has been made in this study to facilitate a realistic assessment of their potential role in future policy planning of energy sector in the country.

The paper is set out as follows. Section 2 provides some salient features of the Central/State government policies for promoting solar power in India. A brief description of CSP systems is presented in Section 3, while Section 4 presents a comprehensive framework based on a detailed land and solar resource assessment for CSP technologies in India. In Section 5, energy yield and levelized cost of solar electricity at the district level in India is estimated by using the System Advisor Model (SAM) developed by National Renewable Energy Laboratory (NREL), USA for all commercialized CSP technologies. Major barriers and policy implications for the development of CSP industry are briefly discussed in Section 6. Section 7 concludes.

2. Policy framework for promoting solar energy in India

India's strategy is to encourage the expansion of renewable sources of energy by the use of financial/fiscal incentives provided by the federal/State governments [34–38]. A long-term energy policy perspective is provided by the Integrated Energy Policy Report 2006 [8] which provides policy guidance on energy-sector growth. As stated in the NAPCC [39], deploying RE is a strategic priority for India. In Union Budget 2015/16, India plans to quadruple its RE capacity to 175 GW by 2022 as part of the GOI's plan to supply electricity to every household. India will seek to add 100 GW of solar capacity, 60 GW of wind power, 10 GW of biomass and 5 GW of hydro projects by 2022 [13,40]. The previously articulated targets under the 12th FYP (2012–2017) aimed to install an additional 20 GW of solar by 2022 [41]. To meet the scaled up target of 100 GW, MNRE has proposed to achieve 40 GW through rooftop solar projects and 60 GW through large and medium scale SPPs.

Large-scale development and dissemination of solar energy for power generation will require financial support and incentives [23,42–48], facilitation of technology transfer [49–54], and a large-scale research and development program [22,23,55–57]. To create demand and attract investment in solar, GoI is providing various incentives [58]. State utilities are mandated to buy green energy via a long-term Power Purchase Agreement (PPA) from solar farms. Mechanisms like the feed-in tariff (FIT) can provide long-term and assured security to investors [59–63]. As of year-end 2015, feed-in policies (i. e. feed-in tariffs and feed-in premiums) remained the most widely adopted form of renewable power support, in place in 75 countries at the national level and in 35 States/provinces/territories [64]. Table S.1 presents State-wise policies for grid-interactive SPPs in India [65]. A brief description of a variety of incentives available for the promotion of electricity generation through solar thermal route [63,64] in India is provided in the following sub-sections:

2.1. Feed-in-tariffs (FiT)

FiT is a policy mechanism designed to accelerate investment in RE technologies [66]. In India, CERC sets the guidelines and norms for setting tariffs; however, States can remain flexible and announce their own version of tariffs. The minimum tariff determined by CERC is INR 12.08/kWh for solar thermal and INR 5.68/kWh for solar PV projects (grid connected) for FY 2016-17 [67]. When any FiT contract is awarded to a project, it will remain fixed for a period of 25 years. FiT based on Gujarat Solar Power Policy 2009 is a unique experiment of the Gujarat State to develop individual solar projects as well as public-private partnership based large-scale ‘Solar Parks’.

2.2. Power purchase agreements (PPAs)

A PPA is the principal agreement that defines the revenue and credit quality of a project and is thus a key instrument of project finance. Under the JNNSM, solar power project developers (SPPD's) have provision to sign a long term (10 years and 25-years) PPAs with special tariffs [68]. The structure of PPA is designed in such a way that provides a considerable incentive for the SPPD's but at the same time it seemed like an intense load for the power distribution companies, which are bound to purchase a power at the FiT rate but sell it at lesser price i.e. government determined average grid price retail rates. Under the Phase-I of JNNSM, several CSP project developers have signed 25 years PPA with NVVN (on behalf of GoI).

2.3. Generation based incentives (GBI)

GBI is higher component that the PPA tariff and preferential tariff offered by State utility. MNRE introduced GBI schemes separately for wind and solar energy in 2011. The amount of GBI for SPPD's is determined after deducting the PPA tariff signed with distribution utility [67]. The minimum eligible capacity of the solar power plant for availing GBI incentive is 1 MW plant which should be grid connected [69]. The Indian Renewable Energy Development Agency (IREDA) Ltd. is the main authority for issuing GBI from MNRE.

2.4. Renewable purchase obligation (RPO)

RPO necessitates that a specified fraction of the annual amount of electricity supplied by the utility is produced from RE. Often a specific solar fraction is desired within an overall RPO. As per Electricity Act 2003, the implementation of RPO in India is guided by the regulatory provisions, terms and conditions issued by respective SERCs. In accordance with the provisions of section 86(1)(e) of the Electricity Act (2003), each SERCs has to fix a minimum percentage for purchase of energy from renewable sources taking into account availability of such resources in the region and its impact on retail tariffs [70,71]. Several States had earlier specified RPO targets – the RPO limits ranged from as low as 0.8% for Madhya Pradesh to as high as 10% for Tamil Nadu – but enforcement was not stringent [72]. Also, only instate generation was allowed for compliance purposes. In 2016, GoI released State-wide targets in order to achieve its newly-revised RPOs of 17% by 2022, which includes an 8% minimum provision for solar energy.

2.5. Renewable energy certificates (RECs)

Under RECs mechanism, RE producers may offer green energy at special tariffs and/or offer electricity covered with 'environmental attributes' related to green energy separately [60]. These attributes are tradable like REC. MNRE launched the RECs trading mechanism in March 2011. States with low RE potential can now support RE and meet their RPO by purchasing RECs. For States with high RE potential, this would reduce the burden on State utilities to purchase RE beyond the RPO fixed by the SERCs. This would help to minimize cost of power procurement, and lead to efficient resource utilization across the country. The REC market mechanism was widely touted as the solution to drive investment into RE generation.

2.6. Viability gap funding (VGF)

VGF means a grant one-time or deferred, provided to support infrastructure projects that are economically justified but fall short of financial viability. The lack of financial viability usually arises from long gestation periods and the inability to increase user charges to commercial levels. In the wake of falling solar tariffs and increasing capacity addition, the Union Cabinet recently approved setting up 5000 MW grid-connected SPPs on a build, own and operate basis. A similar move was taken in 2012 during the second phase of JNNSM with benchmark price of INR 5.5/kWh [73] for solar PV projects by Solar Energy Corporation of India (SECI).

2.7. Interest subsidy

Interest subsidies are available in the form of zero or low interest rates from banks, utilities, governments or other organizations. These are very uncommon and are usually available only for a limited period of time. It is important to understand that until solar energy reaches grid parity, it is going to be widely supported by these financial incentive mechanisms. The effective implementation of these incentives enhances the financial viability of solar projects. Such a provision has been made in the past for the promotion of wind power [44] and solar systems for lighting [74], water pumping [37], water heating [75,76], cooking [77,78] etc. in India.

2.8. Other benefits

The federal government provides tax benefits for SPPs. It is divided into two parts. First is indirect tax benefit such as sales tax exemptions or reductions, excise and custom duty exceptions. Another is direct tax benefit in which project developers are exempted from income tax on earnings by selling the power produced by SPPs in first 10 years of operation. This can provide significant savings to a SPP developer who is a taxable assesse and has sufficient profits against which the depreciation can be charged. Table S.1 in the supplementary section presents several financial/fiscal incentives provided by State governments for SPPs. Renewable Energy Infrastructure Development Fund (REID) is infrastructure support fund which is generally required as a last mile of the project. The quantum of this fund is approximately 5–10% of the total project cost [79]. Rajasthan is the first State who has initiated this fund and provides financial support for transmission lines and related infrastructure of green energy projects [69]. REID support may further help to accelerate commissioning of the project as well.

Nevertheless, if the utilities are to comply with higher solar RPO requirements while the consumers are willing to accept only marginal increase in the electricity tariff, the required extent of each of the incentives (such as VGF, interest subsidy, RECs, etc.) is rather high. In fact, for several combinations of solar RPO requirement and the value of increase in tariff acceptable to the consumer, any extent of incentive is not sufficient [63].

3. Overview of concentrating solar power technologies

CSP systems comprise concentrated solar radiation as a high temperature thermal energy source to produce electricity. These systems are appropriate for the areas where direct solar radiation and number of clear sunny days in the year are high [23]. CSP systems produce heat or electricity using hundreds of mirrors to concentrate the solar radiation to a temperature typically between 400 and 1000 °C [24]. This thermal power triggers Rankine, Brayton or Sterling cycles and finally mechanical energy is converted into electricity through an electric generator which is further injected into the transmission grid. The major components of CSP are concentrators/reflectors, receivers, power conversion system, thermal storage system (optional) and hybrid system (optional). The performance of concentrator is measured by optical efficiency which depends on transmission, interception, absorption and shadowing in the path of DNI. The receiver or absorber tube generates thermal energy from collected direct solar radiation by the concentrators. The heat transfer fluid (HTF) flows through the solar receivers; which might be water, molten salts, synthetic oil, air, helium, nitrogen etc. The CSP technology can be classified into parabolic trough, central receiver, linear Fresnel, and parabolic dish, according to the way they focus the sun's ray and whether the receiver is fixed or mobile. In parabolic trough and linear Fresnel systems, the mirror tracks the sun along one axis (line focus) and in tower and dish systems, the mirror tracks the sun along two axes (point focus). The receiver is fixed in linear Fresnel and tower systems and it is mobile in parabolic trough and dish systems. For each technology, various options exist for the HTF, thermal energy storage (TES) technology and power cycle.

3.1. Parabolic trough collector (PTC)

PTC systems consist of parallel rows or loops of parabolic trough-shaped mirror reflectors curved in one dimension to focus the incident direct solar irradiance (Fig. 2). The mirror arrays can be more than 100 m long with the curved surface 5–6 m across. Stainless steel pipes (absorber tubes) with a selective coating serve as the heat collectors. All parabolic trough plants currently in commercial operation rely on HTF (i.e. synthetic oil, mineral oil, water or molten salt etc.) as the fluid that transfers heat from collector pipes to heat exchangers, where water is preheated, evaporated and then superheated. The temperature of concentrated heat reaches to 400 °C in case of synthetic thermal oil, 550 °C in case of molten salt or 500 °C in case of pressurized water [80,81]. The superheated steam runs a turbine, which drives a generator to produce electricity. PTC systems are currently the most proven CSP technology and dominate the global market, being installed in 78% of the CSP plants in operation and under construction [25,82].

PTC systems have multiple distinctive features and advantages over other types of solar systems. For e.g., PTC systems are scalable, as their trough mirror elements can be installed along the common focal line [83]. The largest CSP systems using PTC technology include, the 354 MW Solar Energy Generating Systems (SEGS) plants in California, the 280 MW Solana Generating Station that features a molten salt heat storage, the 280 MW Mojave Solar Project (MSP) in the Mojave Desert in California, the 250 MW Genesis Solar Energy Project, that came online in 2014, as well as the Spanish 200 MW Solaben Solar Power Station, the 200 MW Solnova Solar Power Station, and the Andasol (I,II,III) solar power station, using a Eurotrough collector. As of March 2016, 104 MW CSP systems using PTC were in operation in India that include (50 MW Godawari Solar Project in Rajasthan and 50 MW Megha Solar Plant in Andhra Pradesh) and 275 MW were under construction.

3.2. Linear Fresnel reflectors (LFRs)

LFR is a one axis tracking technology, which consists of fixed collector and elevated inverted linear fixed receivers [84,85]. The radiation is reflected and concentrated onto fixed linear receivers mounted over the mirrors, combined or not with secondary concentrators (Fig. 3). One of the advantages of this technology is its simplicity and the ability to use low cost components [86]. Direct saturated steam systems with fixed absorber tubes have been operated at an early stage of use with LFR technology. This technology eliminates the need for HTF and heat exchangers. Superheated steam up to 500 °C has been demonstrated at pilot plant scale and the first large commercial superheated LFC plant has recently begun operation. Although PTCs are still today the most mature CSP technology [87] however, LFRs have been identified as a candidate to reduce the levelized cost of electricity [88], although with lower efficiencies [89] that may be achieved via capital cost reductions, as mirrors are easier to manufacture (Table 1), the structure is lighter, wind effects are less important, etc. [90,91]. LFCs with secondary reflector receiver achieve higher concentration factors than PTCs whereas central tubes of LFCs with multi-tube receiver achieve similar concentration than PTCs [92].

LFC technology has been used to operate or construct solar projects worldwide; few and most of them are either prototypes or demonstration projects generated by few MWe to prove that the technology is technically and commercially viable, and its ability to integrate it with fossil fuel or storage system. The largest CSP systems using LFC technology include, the 125 MW Reliance Areva CSP plant in India.

3.3. Central receiver systems (CRS)

A circular array of heliostats (large mirrors with dual axis sun-tracking motion) concentrates DNI on to a central receiver mounted at the top of a tower (Fig. 4). A heat-transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy that is used to generate superheated steam for the turbine. To date, the heat transfer media demonstrated include water/steam, molten salts, liquid sodium and air. If pressurized gas or air is used at very high temperatures of about 1000 °C or more as the heat transfer medium, the gas or air can be used to directly replace natural gas in a gas turbine. This application makes use of the excellent efficiency (≥60%) of modern gas and steam combined cycles.

The key advantage of CRS is the opportunity to use TES to raise capacity factors and allow a flexible generation strategy to maximize the value of the electricity generated, as well as to achieve higher efficiency levels. After PTC, the CRS technology is the second most matured technology till date. The largest CSP systems using CRS technology include, the 392 MW Ivanpah Solar Electric Generating System in the Mojave Desert of California and the 110 MW Crescent Dunes Solar Energy Project in the Nye County of Nevada. In India, a CSP project of 2.5 MW capacities has been implemented by ACME Solar in Bikaner district of Rajasthan.

3.4. Parabolic dishes system (PDS)

Dish Stirling is one of the oldest solar technologies [93]. A parabolic dish/engine system produces relatively small amounts of electricity compared to other CSP technologies - typically in the range of 3–25 kW. PDS consists of a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focus. (Fig. 5). The working fluid in the receiver is heated to 250–700 °C and then used by a Stirling engine to generate power [94]. PDS systems provide high solar-to-electric efficiency and scalability due to their modular nature. According to its developer, Ripasso Energy, a Swedish firm, in 2015 its Dish Sterling system being tested in the Kalahari Desert in South Africa showed 34% efficiency [95]. PDS installation in Maricopa, Phoenix was the largest Stirling Dish power installation in the world until it was sold to United Sun Systems. Subsequently, larger parts of the installation have been moved to China as part of the huge energy demand.

There are number of past and current demonstration projects, mostly in Europe, Japan, Australia and in the United States [89,96]. Infinia Corporation in the United States has developed a 3.5-kW-class, solar power generation system using a free-piston Stirling engine [97]. A solar farm consisting of 429 dishes (1.5 MW) using PDS is under construction at the Tooele U.S. Army Depot in Utah [25]. A 10 MW Dalmia Solar Power in Bap village in Jodhpur district of Rajasthan, India using PDS is at the development stage. Among all CSP technologies, PDS has special design that allows deploying them individually for remote applications, or grouped together for small-grid or end-of-

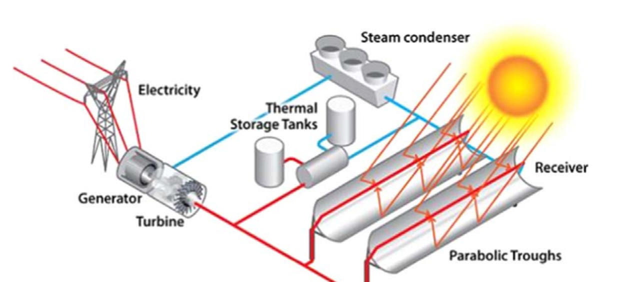


Fig. 2. Schematic diagram of parabolic trough systems.
Source: Adapted from ⟨http://stem-works.com/external/cool_job/23⟩.

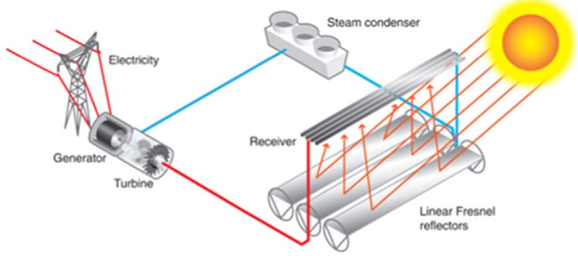


Fig. 3. A Linear Fresnel Reflector power plant.
Source: Adapted from ⟨http://stem-works.com/external/cool_job/23⟩.

line utility applications, and to place them on uneven terrain or slopes surface [80]. Besides that, it has the highest overall efficiency because the generating unit is located attached to the receiver of each dish that leads to reduction in the thermal loss of the technology [81].

3.5. Thermal energy storage for CSP systems

CSP is unique among RE technologies because even though it is variable, like solar PV and wind, it can easily be coupled with TES as well as conventional fuels, making it highly dispatchable [98–100]. The use of both latent and sensible heat are also possible with high temperature solar thermal input. Since a CSP plant primarily produces heat, the heat produced can be stored by using various technologies, most prevalent being molten salt technology [101]. These molten salts (i. e. nitrates of potassium, calcium, sodium, and lithium etc.) have the property to absorb and store the heat energy that is released to the water, to transfer energy when required for operation. The stored heat can be released to produce electricity by running a steam turbine at a later stage. The advantages of TES are manifold viz. increase in capacity factor due to increased number of operating hours, grid-flexibility and flexibility in configuration. TES system often consists of three contributions: the storage medium, HTF, and containment system [102]. High efficiency and stability, low cost and low environmental impact are the key factors for design and application of TES [103]. Additionally, the methods of TES system can be classified as:

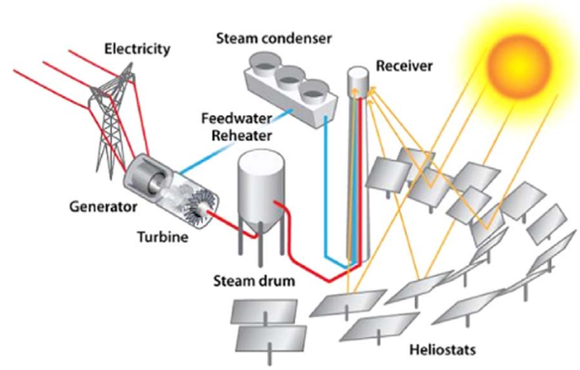


Fig. 4. Schematic diagram of solar tower or central receiver system.
Source: Adapted from ⟨http://stem-works.com/external/cool_job/23⟩

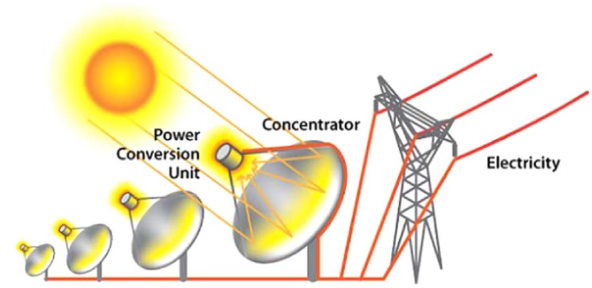


Fig. 5. Schematic diagram of parabolic dishes system.
Source: Adapted from ⟨http://stem-works.com/external/cool_job/23⟩.

sensible heat storage, latent heat storage, and thermo-chemical storage.

Kuravi et al. [98] reviewed the TES system design methodologies and the factors to be considered at different hierarchical levels for CSP plants. Ongoing research efforts in the area of TES focus on developing new technologies that can reduce the cost from the present LCOE of TES of 5¢/kWh to 1¢/kWh by 2020 [104], with the current trend moving towards higher temperatures. Madaeni et al. [105] observed

Table 1
Comparison of CSP technologies [35,54,81].

Technical parameter (s)	**Unit**	**CSP Project based on**			
		PTC	**CRS**	**LFR**	**PDS**
Capacity rang	MW	1–250	1–400	1–125	0.01–10
Focusing	–	Line	Point	Line	Point
Tracking	–	Single-axis	Two-axis	Single-axis	Two-axis
Concentration ratio	–	50–90	> 1000	50–70	> 1300
Operating temperature	°C	393 (therminol),	250–500 (water),	250–400 (Water)	250–700 (Hydrogen or helium)
		550 (molten salt)	550 (molten salt), 680 (air)		
Peak solar-to-electric efficiency	%	23–27	20–27	18–22	29–32
Annual solar to electric efficiency	%	10–16	10–20	8–12	16–29
Relative capital cost	–	Low	High	Low	Very high
Technology development risk	–	Low	Medium	Medium	Medium
Power-generating cycle	–	Steam Rankine, organic Rankine	Steam Rankine, brayton	Steam Rankine, organic Rankine	Steam Rankine, brayton, Stirling
Water consumption	m^3/MWh	3 (Wet cooling) 0.3 (dry cooling)	2–3 (Wet cooling) 0.25 (dry cooling)	3 (Wet cooling) 0.2 (dry cooling)	0.05–0.1 (for mirror washing only in dish-Stirling system)
Storage system	–	Indirect two-tank molten salt or direct two-tank molten salt	Direct two-tank molten salt	Short-term pressurized steam storage in DSG systems	No storage for dish-stirling system
Key Players	–	Solar Millennium, Schott, Rio Glass, Abengoa etc.	Abengoa	Areva, Novosol	Infenia

that adding TES to a CSP plant can increase its economic viability by increasing its operating revenues to the point that the capital cost of CSP can be justified. Molten salt (60% of $NaNo_3$ and 40% of KNO_3) is most commonly used TES material in two tank storage systems for CSP projects. At present, the TES systems of 7.5 h (i.e. PTC based Andasol I, II & III CSP project of 50 MW in Spain) to 15 h (CRS based Gemasolar CSP project of 19.9 MW in Spain) are operational [106]. In India, no operational CSP project comprises TES system however a CSP project of 25 MW capacity is under implementation with 9 h TES system in the State of Gujarat by Cargo Solar (i.e. Gujarat Solar One CSP Project). TES systems can make noticeable impact on the economic viability of CSP projects if transient tariff (i.e. higher tariff for RE power during peak demand which could met through CSP projects using TES systems reliably) mechanism is adopted.

In order to improve the overall efficiency and techno-economic viability of CSP projects the approach of integrating CSP projects with gas has been explored by several project developers through integrated solar combined cycle (ISCC) [107–110]. The ISCC system is essentially a combination of a solar field of CSP project with gas turbine-combined cycle. The waste heat from the gas turbine is used to generate some steam to be expanded in a steam turbine; however, the solar field supplies extra heat to the thermal cycle. The additional heat from the solar field results in electricity generation increase during DNI hours. Globally, ISCC systems have been implemented mostly with PTC technology. This approach has been used from PTC based CSP projects from 20 MW capacity (i.e. Kuraymat Plant in Egypt) to 75 MW (i.e. Martin Next Generation Solar Energy Centre in Florida) Capacity. The CSP Expert group of MNRE recommended that the auxiliary fuel (i.e. gas, biomass and grid electricity) support of 20% for projects with storage and 10% for projects without storage should be allowed to keep the system warm during non-sunshine period. In addition the new CSP projects should invariably have at least 3 h TES system.

4. Assessment of CSP potential in India

4.1. Methodology

The special characteristics, conditions and design of CSP projects require a more cautious and elaborated approach of conducting deployment potential studies as well as an assessment of economic, ecological and social issues than applied for other renewables [111–115]. A strong solar resource is one of the key criterions for the effective deployment of large-scale CSP systems. The land must also be relatively flat, unoccupied, and suitable for development. In view of the fact that the economics of utility-scale CSP systems favour large size, land areas smaller than 1 km^2 may not be relevant [87,116]; however rectangular size plots are best preferred for CSP projects. Moreover, the regional water scarcity parameter limits the choice of the cooling (wet and dry) technology options [117]. Fig. 6 presents details of the methodology developed for district-wise CSP potential assessment and identification of niche areas for CSP based electricity generation in India. In this study, district-level potential of CSP is estimated after taking into account the three suitability criteria – a) suitability of wasteland, b) suitability of annual DNI, and c) suitability of wasteland for wind power generation.

Total land availability for CSP projects, TLA_{CSP}, is estimated by using the following expression

$$TLA_{CSP} = \sum_{i=j=1}^{m,n} TGA_{i,j}\xi_{i,j}\zeta_{i,j}\xi_{i,j}^{DNI}(1-\xi_{i,j}^{WPD}) \quad (1)$$

Where $TGA_{i,j}$ represents the total geographical area of ith district in jth State, $\xi_{i,j}$ the total wasteland availability as a fraction of $TGA_{i,j}$ of ith district in jth State, $\zeta_{i,j}$ the total usable wasteland availability (UWA) of the of ith district in jth State, $\xi_{i,j}^{DNI}$ the fraction of UWA where annual direct solar irradiance is equal to and above a threshold DNI at which the CSP potential (UWA_{CSP}) is estimated (i.e. DNI≥1600 kWh/m^2, ≥1800 kWh/m^2 and ≥2000 kWh/m^2) and $\xi_{i,j}^{WPD}$ the fraction of UWA_{CSP} where wind power density (WPD) is equal to and above a threshold WPD (i. e. ≥150 W/m^2 and ≥200 W/m^2) at which the CSP potential is estimated. Key assumptions for applying WPD criterion are summarized in Section 4.3.

The following sub-sections briefly summarize the key assumptions and data sources used in resource assessment for CSP systems in India.

4.2. Solar resource assessment

The techno-economic feasibility of solar power projects is more complex as compared to it's conventional counterparts due to intermittent nature of the solar resource [87,118–120]. The solar radiation received on Earth's horizontal surface (i. e. global horizontal irradiance or GHI) essentially comprises two components namely direct (beam) and diffuse radiation [29,30,121]. On the basis of the optical geometry of the solar concentrators it is possible to focus direct solar radiation either on a line using single-axis tracking or on a point using two-axis tracking. When the direct component of GHI is treated in such a way that it incident on the collector surface normally (i.e. zero angle of

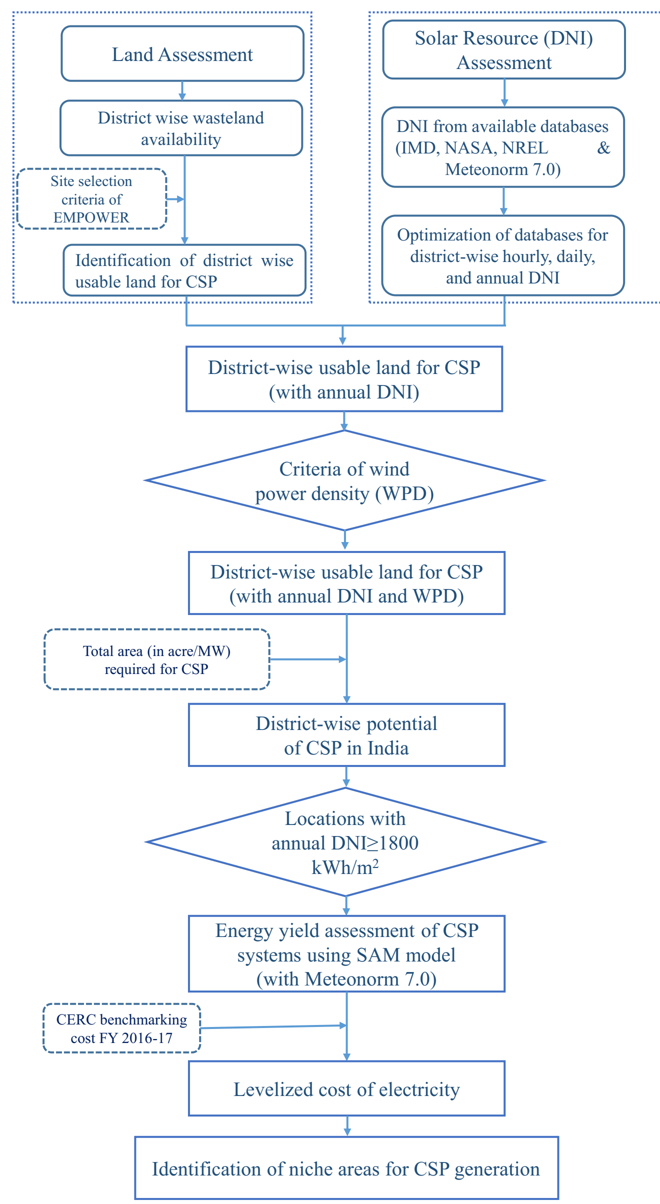
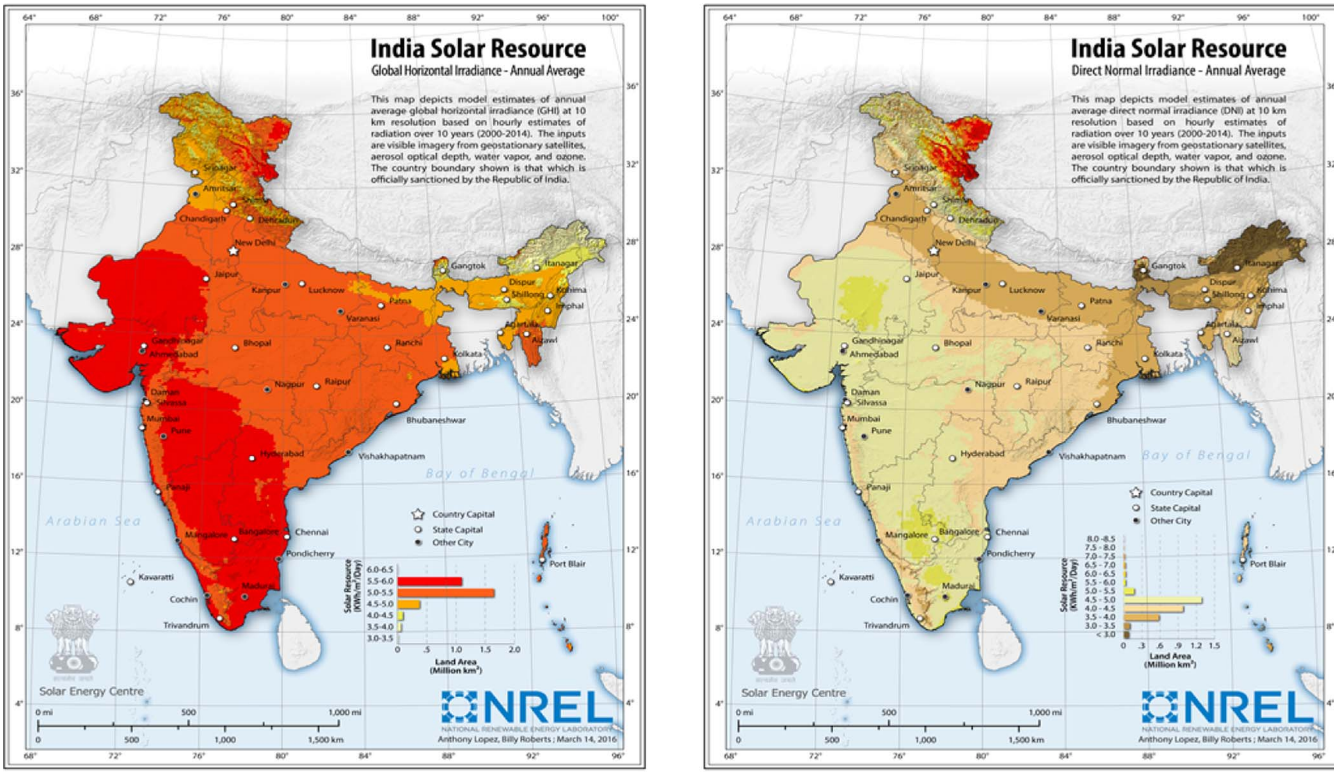


Fig. 6. Methodology adopted for district-wise CSP potential assessment and identification of niche areas for CSP systems in India.



(a) Global horizontal solar irradiance (b) Direct normal solar irradiance

Fig. 7. GHI and DNI maps of India. a) Global horizontal solar irradiance b) Direct normal solar irradiance.
Source: [123].

incidence with the normal of surface) it is called Direct Normal Irradiance (DNI). DNI is an essential component of GHI, especially under cloudless conditions, and represents the solar resource that can be used by CSP technologies [122]. Fig. 7 presents the GHI and DNI (annual average) maps of India [123]. The 10 km hourly solar resource map and data were developed using weather satellite (METEOSAT) measurements incorporated into a site-time specific solar modeling approach developed at the State University of New York at Albany. These maps (Fig. 7) and data were originally produced in 2012 for the period from 2002 to 2007 and updated in 2014 extending the period to 2011. The latest update was released in February 2016 and includes data from 2002 to 2014, and incorporates enhanced aerosols information to improve estimates of DNI.

The daily average global solar radiation is around 5–7 kWh/m^2 across the country [87] with the sunshine hours ranging between 2300 and 3200 per year [124,125]. The annual GHI varies from 1600 to 2200 kWh/m^2 whereas the diffuse fraction is around 25–30% in most of the Indian locations [33]. Unavailability of the long-term ground DNI data over potential locations is a major barrier towards dissemination of large-scale CSP projects in India especially building the confidence of project developers and potential lenders for bankability [32]. There are several approaches towards DNI estimation especially using satellite data or satellite data with interpolation techniques. Prediction of solar irradiance is more challenging for India as there are six major climatic zones [126]. Most of the regions of the country where waste land and higher solar insolation is available are desert regions located in hot & dry and composite climates. It has been observed that the mutual deviation on the LCOE of CSP projects in India might be 0.65–35.12% only due to DNI data over 23 reference locations of IMD [33].

There are three alternatives for assessing DNI over any location: a) by measurements (using pyreheliometer of radiometers), b) measurement of reflected radiation (taken with geostationary satellites which allow the GHI to be deducted using Albedo of the earth's surface), and c) statistical approach (in which DNI is determined through ground and satellite data sets). Purohit and Purohit [33] analyzed several DNI databases available in Indian context. The long-term measured data is the best preferred DNI source in order to design CSP projects. At present, there is no long-term measured DNI data over any location for India. In line with the launch of JNNSM, MNRE has started its project on Solar Radiation Resource Assessment (SRRA) with National Institute of Wind Energy (NIWE), Chennai targeted towards measurement of solar radiation and climatic parameters within the potential regions of the country where large-scale deployment of SPPs is potentially feasible. NIWE is currently offering the short term (1–2 years) solar irradiance and meteorological data for around 110 locations of India commercially. In order to carry out the DNI assessment for India the data has been taken from three sources namely NASA, SEC-NREL and Meteonorm 7.0 databases. In this study, district-wise DNI assessment has been carried out for all 29 States and 6 UT's of the country. The district headquarter is assumed as a representative of the entire district in terms of solar radiation pattern as well as the climatic conditions. The annual average and total values of solar irradiance (GHI and DNI) through selected databases namely NASA, SEC-NREL and Meteonorm 7.0 for all States and respective districts of India are presented in Table S.2 of the supplement along with their geographical coordinates. Table 2 presents the DNI assessment over India using these weather databases.

The DNI data has been taken from SEC-NREL and NASA interfaces however using Meteonorm software the data has been generated in TMY[1] format. The accuracy of Meteonorm 7.0 database seems higher

[1] A typical meteorological year (TMY) is a collation of selected weather data for a specific location, generated from a data bank much longer than a year in duration. It is specially selected so that it presents the representative meteorological conditions for the intended application for the location consistent with the long-term behavior for the location, while still maintaining a distribution that comes close to the one included in the time series.

Table 2
DNI Assessment over India.

State	Districts/ Stations	Annual DNI (kWh/m^2) through NASA Data			Annual DNI (kWh/m^2) through NREL Data			Annual DNI (kWh/m^2) through Meteonorm Data		
		Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Andhra Pradesh	23	1707	1845	1990	1753	1883	2018	1184	1529	1867
Arunachal Pradesh	16	1308	1440	1773	933	1225	1462	870	1077	1220
Assam	23	1333	1726	2161	1369	1465	1609	1154	1576	1916
Bihar	35	1887	2106	2325	1477	1612	1804	1213	1394	2020
Chhattisgarh	16	1820	1901	1982	1868	1950	2006	1621	1694	1824
Delhi	1	2114	2114	2114	1565	1565	1565	1913	1913	1913
Goa	2	2305	2305	2305	1998	1998	1998	1806	1806	1806
Gujrat	25	2021	2176	2688	1932	2086	2197	1548	1967	2321
Haryana	21	2044	2138	2490	1582	1667	1824	1653	1922	2052
Himachal Pradesh	12	1840	2271	2497	1584	1837	2057	995	1709	2195
Jammu & Kashmir	14	1944	2147	2471	1384	1802	2350	1075	1661	2015
Jharkhand	24	1659	1836	2086	1561	1828	1960	1395	1613	1779
Karnataka	27	1752	1903	2185	1778	1966	2139	1643	1845	2040
Kerala	14	1663	1888	2101	1666	1867	2001	1389	1642	1825
Madhya Pradesh	45	1922	1998	2058	1783	1999	2059	1524	1847	1943
Maharashtra	33	1890	2055	2484	1879	1959	2048	1473	1696	1947
Manipur	9	1705	1723	1735	1510	1644	1723	1317	1567	1736
Meghalya	7	1600	1725	1833	1381	1480	1624	1152	1576	1714
Mizoram	8	1681	1737	1794	1693	1799	1894	1842	1944	2063
Nagaland	7	1546	1673	1717	1279	1401	1575	1154	1274	1422
Orissa	28	1656	1784	1894	1682	1827	1977	1295	1494	1808
Punjab	20	2067	2355	2499	1681	1713	1830	1337	1527	1961
Rajasthan	32	1940	2024	2127	1667	2021	2249	1454	1935	2330
Sikkim	4	1872	1876	1880	1121	1391	1872	1184	1318	1399
Tamil Nadu	30	1532	1700	1952	1776	1917	2077	1454	1680	1864
Tripura	4	1683	1700	1708	1553	1578	1588	1701	1733	1780
Union Territory	10	1710	2092	2657	1682	1888	2199	1233	1661	2081
Uttar Pradesh	70	1886	2119	2443	1507	1641	2008	1201	1642	2362
Uttarakhand	13	2188	2408	2451	1701	1975	2168	1773	2305	2620
West Bengal	18	1676	1818	2037	1067	1532	1760	1223	1412	1849

than the satellite as it has been derived from ground and satellite data of higher resolution as compared with NASA and SEC-NREL [33]. Therefore, in order to carry out energy yield estimation of CSP projects using SAM computer software in the selected locations Meteonorm 7.0 database has been used for DNI and other associated meteorological parameters. The minimum, maximum and average annual DNI over all States (based on the district-level analysis) is presented in Table 2 through NASA, NREL and Meteonorm 7.0 databases. The benchmark DNI for bankable CSP projects has been reported above than 1800 kWh/m^2 [85] hence in order to select or reject any location based on DNI the approach of DNI estimation of a specific location should be optimum.

4.3. Land resource assessment

Site selection is the key activity associated with the planning and designing of any large-scale solar power project [127–130]. Appropriate site selection for CSP project essentially comprises three major dimensions namely land, meteorology and infrastructure [87,131]. In this study, the site assessment has been carried out based on the guidelines of “Site Selection Guidelines for CSP” developed under the Empower program [132]. In order to implement the CSP project, environmental and social impact assessment (ESIA) is critically important through addressing the performance standards of International Finance Corporation [129]. The Department of Land Resources (DOLR) of the GoI has developed the Wasteland Atlas of India [133] in which a detailed wasteland analysis for all districts and States of India has been carried out. As per DOLR, there are 23 categories of wasteland. Table 3 presents the suitability of waste land for large-scale CSP projects using the above-mentioned criterion for site selection. The above criteria have been applied on the wasteland database of all districts/States of India to assess the utilizable land availability for CSP projects. We have excluded waste land areas that do not meet the site selection criteria mentioned above.

After applying the site selection criteria [132], the usable land for CSP has been estimated which could be considered as baseline for

Table 3
Suitability of wasteland for large-scale CSP projects.
Source: [133]

Notations	Categories of wasteland	Suitability for CSP
C-1	Gullied and/ or ravenous land (*Medium*)	✓
C-2	Gullied and/ or ravenous land (*Deep*)	×
C-3	Land with Dense Scrub	✓
C-4	Land with Open Scrub	✓
C-5	Waterlogged and Marshy land (*Permanent*)	✓
C-6	Waterlogged and Marshy land (*Seasonal*)	×
C-7	Land affected by salinity/alkalinity (*Medium*)	×
C-8	Land affected by salinity/alkalinity (*Strong*)	×
C-9	Shifting Cultivation - Current Jhum	×
C-10	Shifting Cultivation - Abandoned Jhum	×
C-11	Under-utilized/degraded forest (*Scrub domin*)	×
C-12	Under-utilized/degraded forest (*Agriculture*)	×
C-13	Degraded pastures/ grazing land	×
C-14	Degraded land under plantation crop	×
C-15	Sands-Reverie	✓
C-16	Sands-Coastal	✓
C-17	Sands-Desertic	✓
C-18	Sands-Semi Stab.-Stab > 40 m	×
C-19	Sands-Semi Stab.-Stab 15 – 40 m	✓
C-20	Mining Wastelands	×
C-21	Industrial wastelands	×
C-22	Barren Rocky/Stony waste	×
C-23	Snow covered /Glacial area	×

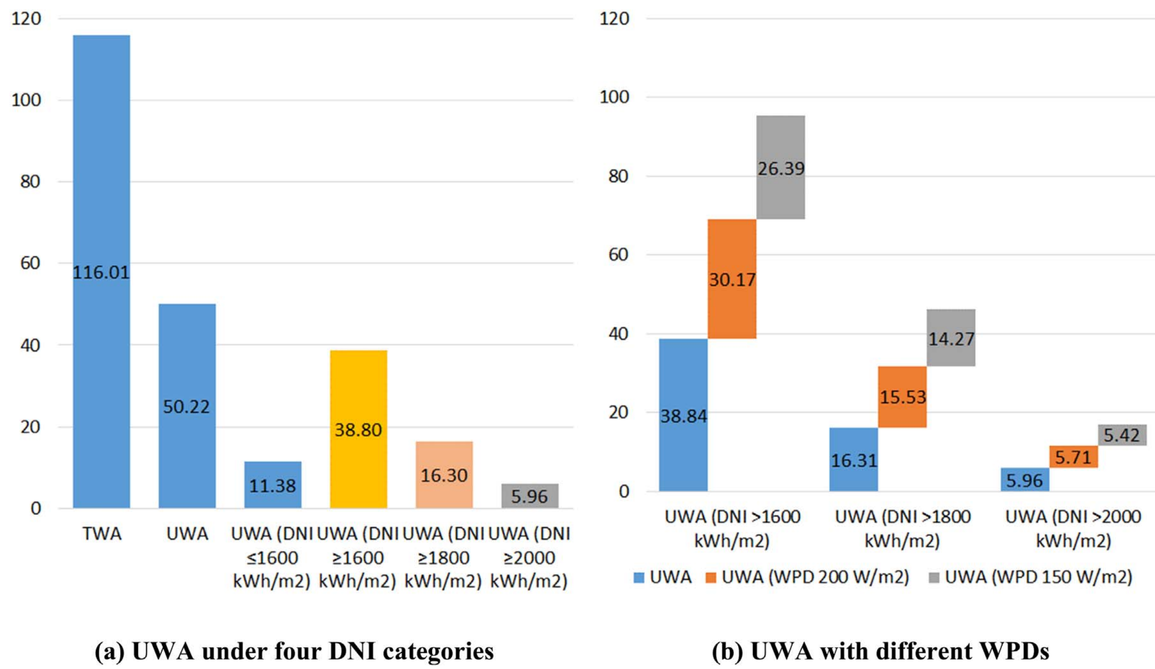


Fig. 8. Total useful wasteland area for CSP system. (a) UWA under four DNI categories b) UWA with different WPDs.

estimating technical and economic potential of CSP in India. As discussed in the previous section, CSP systems require a certain minimum value of DNI to function as compared to solar PV. Globally, the locations with annual DNI higher than 1800 kWh/m^2 are best recommended for commercial CSP projects [87,134]; however solar PV projects could be implemented in the locations where annual GHI is lower than referred DNI. As per DOLR, the total geographical area (TGA) of India is around 782.95 Million acres out of which around 116 Million acres (i.e. 14.82%) is the declared wasteland i.e. total wasteland area (TWA). Theoretically, the usable wasteland may be considered as the potential land for CSP; but as its techno-economic viability is mostly governed by DNI and other micro-climatic conditions the realistic technical/economic potential will be different. After applying the site selection criteria of EMPower program [132] the usable wasteland has been estimated at 50.2 Million acres (i.e. 6.41% of TGA and 43.3% of TWA). Further, on the basis of annual DNI availability (using the reference time series data of Meteonorm 7.0 database) the land has been categorized as follows:

- **No potential locations:** Location with annual DNI of ≤1600 kWh/m^2; could directly be recommended for exploring other resource-technology combinations (but not for CSPs).
- **Long-term potential locations:** Locations with annual DNI ≥1600–1800 kWh/m^2 that is not techno-economically feasible with the current status of CSP technology, market etc. but may be feasible in near future with technology development (i. e. receivers, reflectors, turbines etc.), materials (HTF, TES, coatings, salt etc.) and financial mechanisms (Section 2).
- **Moderate potential locations:** Locations with annual DNI ≥1800–2000 kWh/m^2 which might be techno-economically feasible with current technology and attractive financial/fiscal arrangements.
- **High potential locations:** Locations with annual DNI ≥2000 kWh/m^2 (i.e. comparable with the locations of Spain and USA where most of the commercial CSP projects are functional).

Taking in to account the above mentioned approach the effective area available for CSP is presented in Fig. 8(a). It has been estimated that around 43.3% (i.e. 50.22 Million acres) of the TWA could be considered for CSP without taking into account the DNI criterion over the respective locations. Out of total usable wasteland area (UWA) of 50.2 million acres, 22.7% area (i.e. 11.4 Million acres) is not relevant for CSP (annual DNI ≤1600 kWh/m^2). Similarly, the UWA under the annual DNI range of ≥1600 kWh/m^2 (i.e. long-term potential) is around 77.3% of UWA (i.e. 38.8 Million acres). The area under the range of annual DNI of ≥1800 kWh/m^2 (i.e. mid-term or technical potential) has been estimated as 32.5% of TUGA (i.e. 16.3 Million acres). The area under the criteria of annual DNI of ≥2000 kWh/m^2 (i.e. for high potential locations) has been estimated as 11.87% of TUGA which is equivalent to 5.96 Million acres.

There are several States (viz. Gujarat, Rajasthan, Andhra Pradesh etc.) in the country where DNI conditions are favorable along with suitable wind resource for power generation. The second criteria of land assessment have been taken as the WPD at district level of the country. NIWE published the wind speed and WPD data over 800 locations of the country measured/extrapolated through the wind masts at 50 m height. In April 2010, NIWE released Indian Wind Atlas at a at a hub height of 50 m with 5.0 km resolution estimating the overall potential to be 49 GW [135]. The indicative values at 80 m and WPD greater than 200 W/m^2 increased the estimated potential to 102 GW [135,136]. Taking into consideration the present industrial trend (most of the manufacturers are offering WTGs of minimum capacity of 2.0 MW) in wind sector of India [135]. NIWE revised the potential to 302 GW at 100 m hub height with 500 m resolution using advanced modeling techniques and data from 1300 actual measurements across the country [136].

Sharma et al. [55] considered the wind speed data of 4.0 m/s as minimum criteria for eliminating the wind sites from identifying suitable areas for CSP projects. Instead of wind speed we have considered WPD as the base criteria for potential estimation since the performance of a WTG is not governed by wind speed only at hub height but also critically depends on the air density (function of ambient temperature and pressure) of the respective location. The WPD takes into account the wind speed as well as air density of the location. At present, wind developers in India prefer the locations with a WPD ≥200 W/m^2 however, with new technical developments (viz. increasing rotor diameter with similar hub heights, hybrid towers of more height, blade aerodynamics and generator efficiency etc.) it is anticipated that the locations comprising 150 W/m^2 WPD may also come under potential wind zone of the country.[2] Therefore, in order to assess CSP potential, WPD criteria is applied for WPD≥150 W/m^2 and ≥200 W/m^2. The suitable land availability for CSP remains at 20.4 Million acres with WPD of ≤200 W/m^2 and 17.5 Million acres with WPD of ≤150 W/m^2 respectively at a DNI ≥1600 kWh/m^2.

Taking in to account the current trends of wind power deployment in India it is observed that direct elimination of the usable land for CSP through suitable WPD is not a practical approach as GoI is promoting all RE segments effectively. Therefore, for the land assessment for CSP under WPD criteria we have assumed that;

- If WPD ≥200 W/m^2 (or ≥150 W/m^2) then 100% land within such wind regime (i. e. WPD class) will be attributed for wind projects with annual DNI of 1600–1800 kWh/m^2,
- If WPD ≥200 W/m^2 (or ≥150 W/m^2) then 50% land within such wind regime will be attributed for wind projects with annual DNI of 1800–2000 kWh/m^2, and
- If WPD ≥200 W/m^2 (or ≥150 W/m^2) then 25% land within such wind regime will be attributed for wind projects with annual DNI ≥2000 kWh/m^2.

Fig. 8(b) presents the area under the WPD criteria over the potential CSP sites in India whereas Tables S.2–S.3 present the district-wise land availability for CSP projects with WPD≥150 W/m^2 and ≥200 W/m^2. Out of 591 districts, 347 districts have wasteland available at a DNI ≥1600 kWh/m^2, 188 districts have wasteland available at a DNI ≥1800 kWh/m^2 and only 66 districts have wasteland available at a DNI≥2000 kWh/m^2 with WPD≥150 W/m^2. Total land area suitable for CSP with WPD≥200 W/m^2 is estimated at 30.2 Million acres in which 14.65 Million acres is with the annual DNI of 1600–1800 kWh/m^2, 9.82 Million acres with annual DNI of 1800–2000 kWh/m^2 and 5.71 Million acres with the annual DNI of ≥2000 kWh/m^2. It is well established that the potential of CSP will reduce with consideration of WPD≥150 W/m^2 over the filtered locations. A total land of around 26.4 Million acres has been estimated as the potential usable land for CSP in which around 12.13 Million acres is with the annual DNI of 1600–1800 kWh/m^2, 8.84 Million acres with annual DNI of 1800–2000 kWh/m^2 and 5.42 Million acres with the annual DNI of ≥2000 kWh/m^2.

The Solar field (collectors, receiver tubes, structures etc.) of a CSP project comprises maximum land area. Based on the review of operational global CSP projects it is observed that a PTC based CSP project without TES system comprises around 300,000 m^2 aperture area i.e. around 6000 m^2 per MW aperture area. Further there is requirement of land in between the loops, passage for piping, provision for operation and maintenance etc. Ong et al. [137] reported land requirement of all CSP technologies based on a study of 25 operational CSP projects as presented in Table 4 based on the direct and total used areas. The direct area is essentially the footprint area of solar block (solar field collectors assembly, connecting insulated HTF pipes, heat exchangers and pumps etc.) and power block (condensers, TES block and tanks if used, steam turbine, generator, switchyard, etc.) of a CSP project along with the additional facilities required (roads, water reservoir, ware house, store, administrative building, security and firefighting arrangement etc.) for operation and maintenance.

The district-wise analysis of CSP potential is presented in the supplement (Table S.2-S.3). The estimated potential of PTC systems under the category of WPD of 200 W/m^2 has been estimated as 3176 GW in which 1542 GW is of annual DNI from 1600 to 1800 kWh/m^2, 1033 GW of annual DNI of 1800–2000 kWh/m^2 and 601 GW with annual DNI of more than 2000 kWh/m^2. Simultaneously, CSP potential for PTC systems under the condition of WPD of 150 W/m^2 has been estimated as 2778 GW in which 1276 GW is of annual DNI from 1600 to 1800 kWh/m^2, 931 GW of annual DNI of 1800–2000 kWh/m^2 and 571 GW with annual DNI of more than 2000 kWh/m^2. Fig. 9 presents the overall aspects of CSP potential in India. As discussed above, long-term, mid-term, and short-term potential is estimated for all CSP technologies. For LFR, CSP potential is higher due to small land requirement as compared to other CSP systems (Table 4).

Table 4
Summary of land-use requirements for CSP Projects [137].

Technology	Tracking	Direct Area		Total Area	
		(Acres/ MW)[a]	[b] (Acres/ GWh/yr)	(Acres/ MW)[a]	[b] (Acres/ GWh/yr)
PTC	Single axis	6.2	2.5	9.5	3.9
CRS	Two axis	8.9	2.8	10	3.2
PDS	Two axis	2.8	1.5	10	5.3
LFR	Single axis	2.0	1.7	4.7	4.0

[a] Capacity-weighted average land use;
[b] Generation-weighted average land use

Fig. 10 presents the CSP potential for PTC systems by State at DNI≥1800 kWh/m^2 and WPD a) ≥150 W/m^2 and b) ≥200 W/m^2. It is observed that Rajasthan, Madhya Pradesh and Maharashtra have the largest potential followed by Gujarat at a WPD≥150 W/m^2. Similarly, Rajasthan and Madhya Pradesh have the largest CSP potential followed by Maharashtra and Gujarat at a WPD≥200 W/m^2.

Further the refinement could be done on the basis of water availability and power evacuation facilities. As at this stage, due to lack of information on district-wise availability of water these two considerations have not been taken into account in this study. Additionally, the water requirement of a CSP project depends on the approach of water use by the respective developer (e.g. wet cooling or dry cooling etc.). The best estimation of the water requirement is essentially estimated on MWh (generation) rather than the MW (Capacity) as it depends on the hours of operation (i.e. function of steam turbine). At present, no specific conditions have been imposed for CSP projects towards utilization of water in India. Once the guidelines for ground water use are imposed the water criteria could also be implemented towards potential estimation. Similarly power evacuation of CSP project is essentially governed by the regulations i.e. under which policy (Section 2) the project has been implemented. The policies mentions about the technical requirements (i.e. voltage level, grid code etc.) for power evacuation however, no specific conditions have been imposed on the CSP developers in India.

4.4. Water availability

In contrast to other RE technologies like solar PV or wind, CSP requires a considerable amount of water, mainly for cooling purposes, when using re-circulating wet cooling, a characteristic this technology shares with other thermal power technologies [117]. CSP also requires a considerable amount of water to spin steam turbines [138]. Meldrum et al. [139] reviewed and classified the existing literature of electricity's water withdrawal and water consumption for several renewable and conventional energy technologies and concluded that the water used for cooling purposes dominated the life cycle water use of electricity generation. The regional water scarcity parameter limits the choice of the cooling (wet and dry cooling) technology options [140]. Use of underground water does not seem a suitable solution due to high

[2] When energy yield of a WTG is carried out in any energy yield estimation tool (viz. Wind Farmer or WAsP etc.) than the site specific air density corrected power curve is used considering the fact that energy comprises by wind is dependent to air density. In general, the power curve of a WTG is presented through a graph between prevailing wind speed and power output but in standard conditions; hence WPD more realistic and appropriate criteria to identify the potential locations.

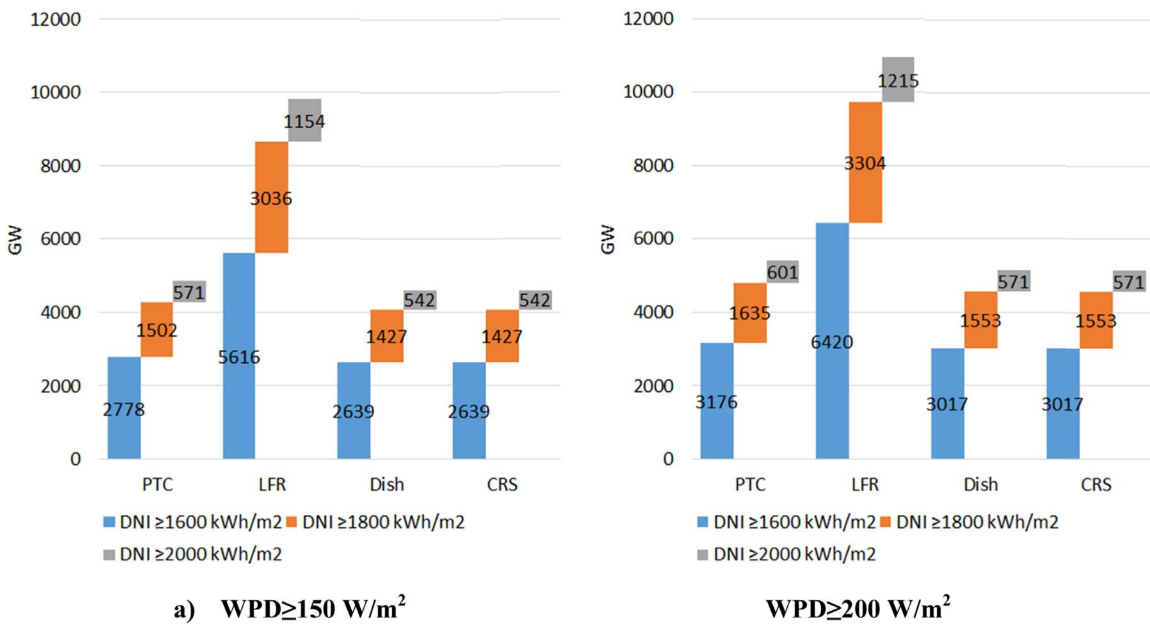


Fig. 9. CSP potential in India with different DNI and WPD criterion. a) WPD≥150 W/m^2 , WPD≥200 W/m^2.

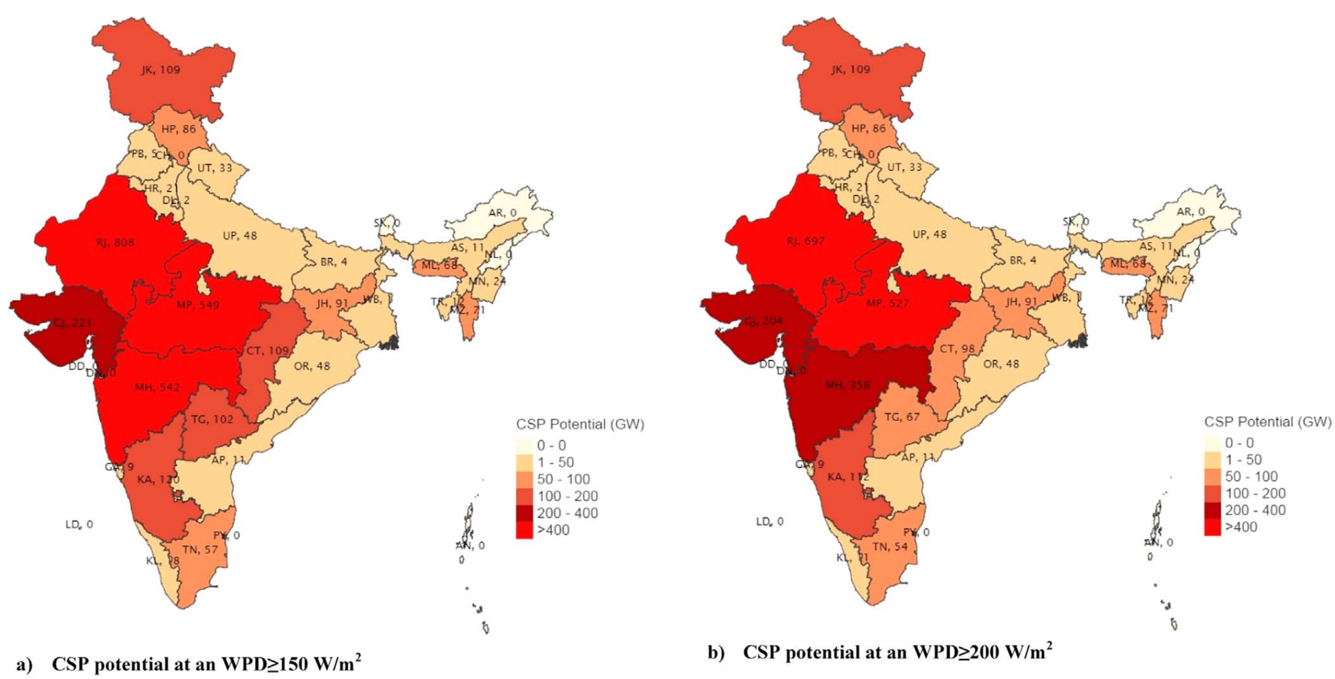


Fig. 10. CSP potential in India by State (DNI≥1800 kWh/m^2/year).Andaman & Nicobar Islands:AN; Andhra Pradesh:AP; Arunachal Pradesh:AR; Assam:AS; Bihar:BR; Chandigarh:CH; Chhattisgarh:CT; Dadra & Nagar Haveli:DN; Daman & Diu:DD; Delhi:DL; Goa:GA; Gujarat:GJ; Haryana:HR; Himachal Pradesh:HP; Jammu & Kashmir:JK; Jharkhand:JH; Karnataka:KA; Kerala:KL; Lakshadweep:LD; Madhya Pradesh:MP; Maharashtra:MH; Manipur:MN; Meghalaya:ML; Mizoram:MZ; Nagaland:NL; Odisha:OR; Puducherry:PY; Punjab:PB; Rajasthan:RJ; Sikkim:SK; Tamil Nadu: TN; Telangana:TG; Tripura:TR; Uttar Pradesh:UP; Uttarakhand:UT; West Bengal:WB. a)CSP potential at an WPD≥150 W/m^2 b) CSP potential at an WPD≥200 W/m^2.

degree of minerals available in the water as well as the approval from the respective State governments to use underground water for commercial projects. The degree of salinity could be assessed from the scenario of commercial manufacturing of salt in the region directly evaporating underground water over the salt-field. For example, a lot of such salt manufacturing units could be seen in Pokharan, Phalodi, Bap, and Kutch regions of Rajasthan and Gujarat States where the Solar Park of the Rajasthan government is under development.

While dry cooling could save more than 90% of water consumption [141,142] however, the overall performance of such a plant is reduced under higher ambient temperatures. This results in higher investment costs for dry cooled power plants than those of wet cooled plants with the same power production capacity. Liqreina and Qoaider [143] observed that dry cooling of CSP plants is an economic and technical feasible option for desert regions. In Rajasthan, the government allotted water from Indira Gandhi Nahar Project (IGNP) to fulfill plant operational requirements to all CSP project developers under Phase-I of JNNSM. Moreover, several large capacity conventional (thermal) projects are also using water from IGNP canal in the State. This situation may also continue for next phases of JNNSM. Therefore, the government needs to ensure the sufficient amount of water availability in IGNP canal. The 25 MW under construction CSP project of Cargo group has received water allocation from State Government as per the policy guidelines. Hybrid wet/dry cooling reduces water consumption by 50% with only 1% drop in annual electric output, or 85% with only a 3% drop in output. In this case, cost would increase by 5% compared to a water cooled plant. Therefore, for the large-scale implementation of CSP in India requires that additional water needs can be effectively met, or technologies with lower water use must be implemented.

4.5. Power evacuation facilities

Another key issue towards the large-scale penetration of CSP in India is infrastructural requirements for connectivity and accessibility to the remote locations and power evacuation facilities. India needs to tackle the renewable power injection into the grid by creating dedicated transmission infrastructure and subsequently through smart grid. At present, power evacuation through CSP projects is recommended on minimum 33 kV and above voltage levels under JNNSM whereas as per Gujarat Solar Power Policy it is mentioned at 66 kV level [87]. At present, India has around 313,437 circuit km (ckm) of transmission lines and 596,100 MVA of substation transformation capacity out of which 106,804 ckm of inter-state transmission lines are owned by the Power Grid Corporation of India Ltd. (PGCIL) [144]. In the financial years 2014-15 around 22,100 ckm of transmission lines and 65,554 MVA of transformation capacity have been achieved [144]. As RE based power generation is the key focus of GoI; the PGCIL on the advice of Forum of Regulators (FOR) of the CERC and MNRE has evolved transmission infrastructure requirement and other related services for integration of large scale envisaged renewable capacity in 12th Five Year Plan into the grid. Respective State Nodal Agencies/ State Transmission Utilities have provided information regarding renewable capacity program in the 8 renewable potential rich states namely, Tamil Nadu, Karnataka, Andhra Pradesh, Gujarat, Maharashtra, Rajasthan, Himachal Pradesh and Jammu & Kashmir to PGCIL.

Currently, upgradation of existing facilities along with new infrastructure development work for power evacuation is ongoing in several States. So far, 34 solar parks are identified for the deployment of around 20 GW solar power under the Solar Park scheme of MNRE for which PGCIL needs to develop the power evacuation infrastructure with at least 400 kV network. This could be experienced in the Solar Parks operational and under development in the States of Rajasthan, Gujarat, Madhya Pradesh, Karnataka etc. Till date power evacuation and connectivity approvals has not been observed a key technical barrier in India for solar power (PV/CSP) projects. However in few States (Tamil Nadu, Karnataka etc.) the curtailment issues have been reported as those States also comprises significant capacity of wind power projects and fulfills the applicable renewable purchase obligations (RPOs). In line with the increasing capacity and targets of SPPs, GoI is effectively working on strengthening of power evacuation infrastructure through specific green energy corridors.

5. Energy yield and levelized cost of CSP in India

The following sub-sections presents the average energy yield along with levelized cost of electricity (LCOE) using CSP technologies in India. It may be noted that the estimation of LCOE has been carried out over those locations where annual DNI has been received more than 1800 kWh/m^2 through METEONORM 7.0 database. District wise capacity factors and LCOE for DNI≥1600 kWh/m^2 are presented in the supplementary section at WPD≥150 W/m^2 (Table S.2) and WPD≥200 W/m^2 (Table S.3).

5.1. Energy yield of CSP systems

Assessment of CSP at the district level in India is carried out by using the System Advisor Model (SAM). SAM is essentially a performance and financial model designed to facilitate decision making for professionals involved in RE industry which makes performance prediction and cost of energy estimates for grid connected power projects based on installation and operating cost along with system design parameters. It includes energy performance models for all CSP technologies viz. PTC, CRS, LFR and Dish-Sterling system along with other RE systems. SAM essentially required input DNI and weather data in TMY (*.tm2 or *.csv) format which has been generated through Meteonorm 7.0 computer software for all the selected locations (Table S.2-S.3) of India. In the energy yield estimation exercise at this stage we have not considered TES. Table 5 presents the technical assumptions for line focusing CSP technologies. The PTC technology has been implemented mostly at the capacity of 50 MW; hence for energy yield estimation the simulation is carried out for specific capacity of 50 MW. LFR is emerging CSP technology and demonstrated up to 5 MW to 100 MW (in India) capacities; however large capacity CSP projects on LFR technologies are under construction across the globe. For the energy yield estimation for LFR technology the default module of SAM for 10 MW capacities is explored.

Table 5
Technical assumptions for energy yield calculation of PTC and LFR systems.

Technical Parameters	Unit	Parabolic trough collector	Linear Fresnel Reflector
Capacity	MW	50	10
Useful life	Years	25	25
Degradation/year	%	0.25	0.25
System availability	%	96	96
Solar multiple	–	2.0	2.0
Number of loops	–	115	11
Aperture are	m^2	432,676	90,394
Cycle conversion	%	37.7	38
Thermal energy storage	–	0.0	0.0
Heat transfer fluid	–	Therminol VP−1	NA
Inlet temperature	°C	293	230
Outlet temperature		391	440
Collector Specifications			
Collector manufacturer		Solargenix SGX-1	Novatec Solar
Reflective aperture area	m^2	470.3	513.6
Length of collector assembly	m	100	44.8
Receiver model	–	Schott PTR70 2008	NA
Absorber tube inner diameter	m	0.066	NA
Absorber tube outer diameter	m	0.07	NA
Design gross output	MW_e	55.56	10.7
Gross to net conversion	%	90	94

The technical detailed considered for energy yield estimation of two-axis tracking based CSP technologies namely CRS and Dish-Sterling systems are given in Table 6. The solar multiple (SM) and the design point radiation (DPR) have been optimized for all CSP technologies over selected locations and the energy yield estimation were carried out accordingly.

Table 7 presents the average energy generation and capacity utilization factor through all four types of CSP technologies considered in this study. It may be noted that districts with annual DNI≤1800 kWh/m^2 are not presented in this table. The average DNI and annual CUF has been estimated only considering the potential districts in the respective States. The numbers of potential districts over the potential States are also presented in Table 7 (in brackets of the second column). It is observed that across the country out of 591 districts 184 districts are suitable to CSP generation. CERC has considered annual CUF of 23% to estimate the benchmarking cost. From Table 7 the States comprising annual CUF of more than 20% could be identified for respective CSP technologies. It is well visible that the States with higher potential of CSP viz. Rajasthan, Gujarat, Madhya Pradesh etc. could achieve the annual CUF more than 23% for PTC systems. As the Table 7 presents average pattern of energy generation

Table 6
Technical assumptions for energy yield calculation of CRS and Dish-Sterling systems.

Technical parameter	Unit	Central receiver system	Dish-Sterling System
Capacity	MW	10	100
Useful life	Years	25	25
Degradation/year	%	0.25	0.25
System availability	%	96	96
Solar multiple	–	1.5	NA
Absorber's absorptance	m^2	NA	0.9
Cycle conversion (%)	%	41.2	NA
Heliostat width	m	12.0	NA
Heliostat length	m	12.0	NA
Total heliostat reflective area	Number	638,477	NA
Reflectance	%	NA	0.94
Receiver aperture diameter	m	NA	0.184
Stirling engine capacity	kW	NA	25
Solar field area	m^2	NA	900,000

of each State; there are several districts within the State which receives annual CUF more than 28% as shown in Table S.2-S.3 of the supplementary section. The capacity factors for all the CSP technologies at select locations with DNI≥1800 kWh/m^2 and WPD≥150 W/m^2 (Table S.2) and WPD≥200 W/m^2 (Table S.3) are also estimated and presented in the supplementary section (Table S.2-S.3).

5.2. Levelized cost of CSP in India

In India, the experience of CSP projects is limited with the 3–4 operational projects under JNNSM Phase-I in which most of the technologies and components are imported. The cost of CSP projects in taken from the benchmark cost of CERC for the financial year 2016-17 for India [145]. Table 8 presents the details of key assumptions and input parameters used for assessing levelized cost of CSP electricity in India. It may be noted that CERC provides capital cost of CSP projects irrespective of any specific technology (i.e. PTC, CRS, etc).

Table 8
Key considerations for economic analysis [145].

Economic parameter	Unit	Value
Capital cost	Million INR/MW	120.00
Useful life	Years	25.00
Debt	%	70.00
Equity	%	30.00
Interest rate on loan	%	13.00
Repayment period	Years	12.00
Return on equity (for first 10 years)	%	20.00
Return on equity(11th year onwards)	%	24.00
Discount rate	%	10.81
Depreciation (for first 12 years)	%	5.83
Depreciation (13thyear onwards)	%	1.54
Interest on working capital	%	13.50
O & M expenses (2016–17)	Million INR/MW	1.87
O & M expenses escalation per year	%	5.72

Table 9 presents the levelized cost of electricity generation by CSP projects. Taking in to account the energy yield estimation carried out through SAM and key economic parameters presented in Table 8 a financial model has been developed in order to carry out the LCOE. Average LCOE of all CSP technologies by Indian States are presented in Table 9. As expected, LCOE is lower for the States (such as Rajasthan, Haryana, Gujarat, etc.) with high DNI. In terms of technology, LCOE for PTC is lower followed by Dish-Sterling, LFR and CRS technologies. LCOE for all the CSP technologies at select locations with DNI≥1800 kWh/m^2 and WPD≥150 W/m^2 (Table S.2) and WPD≥200 W/m^2 (Table S.3) are also estimated and presented in the supplement.

Fig. 11 presents the top 50 locations in the country with lowest LCOE for PTC systems. The top 10 locations with lower LCOE are Sikar, Jaipur, Banswara, Dungarpur and Sirohi in Rajasthan State and Garhwal, Nainital, Dehradun, Hardwar and Udham Singh Nagar in

Table 7
Energy yield for CSP projects at select location in India.

State	No of total/ potential districts	Annual DNI (≥1800 kWh/m^2)	PTC Systems		CRS Systems		LFR Systems		PDS Systems	
			CUF[a] (%)	AEG[b] (GWh/ MW)	CUF (%)	AEG (GWh/ MW)	CUF (%)	AEG (GWh/ MW)	CUF (%)	AEG (GWh/MW)
Andhra Pradesh	13(1)	1867	25.4	2.2	23.1	2.0	16.5	1.4	23.2	2.0
Assam	23(7)	1854	21.8	1.9	21.6	1.9	16.5	1.4	20.0	1.8
Bihar	35(1)	2020	15.4	1.3	13.3	1.2	9.3	0.8	12.7	1.1
Chhattisgarh	16(1)	1824	23.4	2.0	22.1	1.9	15.8	1.4	21.3	1.9
Delhi	1(1)	1913	27.1	2.4	24.1	2.1	16.1	1.4	23.1	2.0
Goa	2(2)	1806	23.3	2.0	22.2	1.9	15.7	1.4	21.9	1.9
Gujarat	25(18)	2062	26.5	2.3	25.1	2.2	17.8	1.6	24.9	2.2
Haryana	21(18)	1948	26.9	2.4	24.8	2.2	16.9	1.5	23.0	2.0
Himachal Pradesh	12(5)	1979	22.3	2.0	22.5	2.0	17.3	1.5	20.2	1.8
Jamu & Kashmir	14(4)	1928	20.8	1.8	21.5	1.9	17.0	1.5	18.6	1.6
Karnataka	27(18)	1912	22.6	2.0	22.0	1.9	16.7	1.5	21.8	1.9
Kerala	14(1)	1825	23.5	2.1	22.0	1.9	15.9	1.4	22.1	1.9
Madhya Pradesh	45(23)	1985	25.3	2.2	23.7	2.1	16.8	1.5	23.3	2.0
Maharashtra	33(4)	1856	24.2	2.1	22.8	2.0	16.3	1.4	22.4	2.0
Mizoram	8(7)	1944	23.1	2.0	22.7	2.0	17.1	1.5	21.5	1.9
Orissa	30(1)	1808	22.6	2.0	21.7	1.9	15.7	1.4	20.9	1.8
Punjab	20(1)	1961	25.3	2.2	24.3	2.1	17.2	1.5	21.9	1.9
Rajasthan	32(22)	2060	27.0	2.4	25.1	2.2	18.0	1.6	24.6	2.2
Tamil Nadu	30(6)	1845	22.7	2.0	21.5	1.9	15.8	1.4	21.7	1.9
Telangana	10(1)	1816	23.9	2.1	21.9	1.9	15.5	1.4	21.9	1.9
Union Territory	10(2)	2000	26.4	2.3	24.8	2.2	17.2	1.5	23.6	2.1
Uttar Pradesh	70(26)	1929	26.2	2.3	24.3	2.1	16.7	1.5	22.7	2.0
Uttarakhand	13(12)	2349	26.8	2.3	27.3	2.4	21.3	1.9	25.0	2.2
West Bengal	18(2)	1829	21.0	1.8	21	1.8	16.4	1.4	19.4	1.7

[a] CUF: Average capacity utilization factor;
[b] NEG: Net electricity generation

Table 9
Levelized cost of electricity generation by CSP projects.

State	Parabolic trough collector (PTC) System	Central receiver system (CRS)	Linear Fresnel Reflector (LFR) System	Dish-Sterling System
Andhra Pradesh	10.9	12.0	16.8	12.0
Assam	12.7	12.9	16.8	13.9
Bihar	18.0	20.9	29.8	21.9
Chhattisgarh	11.9	12.6	17.6	13.0
Delhi	10.2	11.5	17.2	12.0
Goa	11.9	12.5	17.7	12.7
Gujarat	10.5	11.1	15.6	11.2
Haryana	10.3	11.2	16.5	12.1
Himachal Pradesh	12.6	12.4	16.1	13.9
J & K	13.4	13.0	16.4	15.0
Karnataka	12.3	12.6	16.7	12.7
Kerala	11.8	12.6	17.5	12.6
Madhya Pradesh	11.0	11.8	16.6	12.0
Maharashtra	11.5	12.2	17.1	12.4
Mizoram	12.0	12.3	16.2	12.9
Orissa	12.3	12.8	17.7	13.3
Punjab	11.0	11.4	16.1	12.7
Rajasthan	10.3	11.1	15.5	11.4
Tamil Nadu	12.2	12.9	17.6	12.8
Telangana	11.6	12.7	17.9	12.7
Union Territory	10.5	11.2	16.1	11.8
Uttar Pradesh	10.6	11.5	16.7	12.3
Uttarakhand	10.5	10.3	13.1	11.3
West Bengal	13.2	13.2	17.0	14.3

Uttarakhand State (Fig. 11). On the basis of technical and economic parameters used in this study it is observed that out of 591 districts, the LCOE is less than the CERC's levelized total tariff of INR 12.08/kWh for FY 2016/17 (Section 2) at the 142 districts/locations.

6. Major barriers and policy implications

There are a range of barriers to the widespread deployment of CSP systems in electricity markets around the world. Energy markets consider three main factors in deciding on power sources: cost of energy, ancillary services and power dispatchability on demand [146]. Obviously, in a recently long-shaken and uncertain global economic environment, energy investors consider competitive cost of energy the most important issue. For example, in 2011 a sudden shift is observed in the United States from planned CSP power plants converted to Solar PV. Similarly, in JNNSM (Phase-II), CSP share is reduced to 30%. As long as energy price of Solar PV plants is less than the energy price of equivalent CSP, and continue to decline, PV will remain a preferable solution over CSP for energy investors. CSP systems will need to demonstrate high performance in all three attributes, competitive thermal-energy-storage costs, energy dispatchability and reliability as an ancillary solution, in order to remain attractive and competitive against solar PV.

For India, some of these barriers have been addressed through policy initiatives briefly discussed in Section 2 above. So far, only three CSP projects (out of seven) with a cumulative capacity of 225 MW were commissioned under the Phase-I of the JNNSM. The reasons for delays are insufficiently accurate DNI data, expensive financing leading to very difficult financial closure, unclear future of government subsidies, difficulty securing land and water, need for a local manufacturing, and the tight profit margins and even stiffer time limitations [147]. The following sub-section examines the barriers, analyses how they are being addressed and discusses further options that may be considered.

6.1. Financial barriers

The primary barrier to utility-scale solar power is project financing. High up-front cost of CSP projects increases levelized cost of electricity as compared to fossil fuels where the full pollution costs are not reflected in energy pricing. This is a significant barrier as financiers are unfamiliar with CSP investments, risk averse and often focus on the short term. To achieve financial closure, the revenue equation must provide investors with an acceptable IRR with all risks appropriately mitigated and allocated. Other barriers also contribute to the risk profile that increases the challenge to secure financing.

6.2. Policy and regulatory barriers

As mentioned above, some level of government support is required to allow CSP projects to earn sufficient revenue to be able to reward equity investors and pay back debt (Section 2). Other government policy settings are also very important, such as industry development policies, Intellectual Property (IP) law, general law and country stability. The risk of policy uncertainty can also be a barrier for CSP developers. If CSP is to succeed in India, various changes need to be made at policy level. If reverse auctioning is used for future scale-up of CSP in India, its design has to be improved to increase the chances that winning bidders actually implement their projects all the way through. Some of the key factors to focus are a) improving data on the available solar resource at the time of bidding, b) allowance of minimum auxiliary/back up fuel and provision of minimum TES in the projects, c) more realistic timelines for submitting bids and constructing plants, d) stricter enforcement of penalties for missing deadlines, and e) strengthening requirements for participating in the bidding.

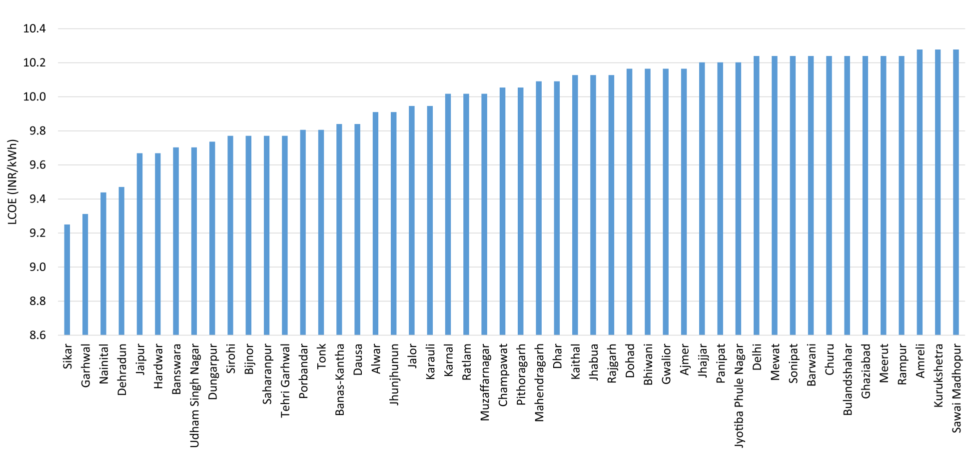


Fig. 11. Top 50 locations with lowest LCOE for PTC systems.

The 2014, CSP Today markets scorecard ranked India as the fifth most promising market for CSP compared to the first position the country held in the 2013 ranking. This captures the uncertainty seen in the market during 2013 with ongoing delays and doubts about the viability of the projects awarded in JNNSM Phase-1. However, the increased availability of measured DNI data together with the increasing local manufacturing capabilities and changes at the policy level are expected to pave the way towards the successful deployment of CSP in the country.

6.3. Infrastructural barriers

Without suitable sites and approvals, no project can proceed. CSP projects are essentially implemented in isolated areas or declared wastelands where resettlement and rehabilitation issues are minimum. Until now, the development of CSP has mostly been restricted to the States of Rajasthan and Gujarat with only one project being located in Andhra Pradesh. The States of Rajasthan and Gujarat are home to the biggest deserts of India, the Thar Desert and the Rann of Kutch. Adequate land availability in these States is not an issue. Moreover, access to high-voltage transmission lines is key for the development of utility-scale SPPs to move electricity from the solar plant to end users. Like other thermal power plants, such as natural gas, coal and nuclear CSP require access to water for cooling. All require small amounts of water to wash collection and mirror surfaces. CSP plants can utilize wet, dry, and hybrid cooling techniques to maximize efficiency in electricity generation and water conservation. Gas, water, sewerage, roads and fencing must also be considered to varying degrees and according to the technology type being implemented.

6.4. Technical barriers

The ideal CSP technology has a low initial capital cost and achieves high performance, high reliability and minimal O & M costs. Technology shortcomings for any given technology/ technology proponent include those inherent to the technology and those that emerge with the specific project.

6.4.1. Solar resource data

The lack of accurate DNI data is seen as one of the main reasons, which has limited the growth of the Indian CSP market. The earliest data on solar radiation came from Mani [124] that provided long-term solar radiation values for 18 locations and a solar radiation map of India. Further, solar radiation maps of India were released by NREL in 2009-10 using satellite data that overestimated the DNI [148] by 15–25% higher than the actual resources measured. Accordingly, the levelized cost of electricity (LCOE) increased by 15–30%, putting the financial viability of the projects at a serious risk. Most of the DNI data available in Indian context is static data (i.e. available in monthly available daily values) that is either estimated through ground GHI or satellite data of low resolution (NASA, NREL, SWERA etc.) which is not considered as bankable. The long term time series data is available through Meteonorm, 3TIER and SolarGIS databases which are either interpolated or satellite databases but with high resolution. At present, time series databases are preferred by the developers and lenders to execute the project. NIWE has started offering short term DNI data over around 110 locations but it need to be develop in TMY formats comprising associated level of uncertainties. As a result of the increased availability of more accurate DNI data, developers will be able to better design and price their future plants to adapt to real DNI conditions reducing risk and uncertainty.

6.4.2. Manufacturing scale-up

India has a large potential to manufacture its own components for CSP, given the right policy incentives, public support for demonstration of CSP plants, and increased investment in R & D. It could lower the costs of some components by up to 40% [149] and create thousands of new jobs. For CSP, to achieve significant penetration in a given market, millions of square meters of solar concentrator systems of various types along with all the supporting plant will need to be manufactured and maintained. Facilities and the skilled human resources to do this are required. The CSP industry has seen many Indian manufacturers attempt to develop a local supply chain - starting to specialize in receiver tubes, frames, curved mirrors and other key components. This not only provides a strong cost reduction potential for developers but also offers a possible strong manufacturing base for key components to be exported, strengthening India's balance of payments. This carries the provision that the components produced pass international standards testing, which some manufacturers (such as Thermosol Glass) are already following. Recently, it has been reported that Rajasthan Sun Technics 125 MW Linear Fresnel CSP plant achieved up to 61–71% of local content manufacturing estimates [150]. This also demonstrates the technology's promise for meeting GoI's goal to create a CSP industry hub in India.

New manufacturers mainly from China are offering competitive prices of the key components of CSP projects. The manufacturers like Royal Tech CSP (Model RTUVR 2015/70), TRX Solar (Model TRX 70–125 HCE) etc. of China are offering fourth generation receiver tubes with almost similar technical specifications of Schott Solar (Model PTR 70 Premium). MNRE has recently empanelled 22 manufacturers for manufacturing and supply of concentrating solar collectors; out of which there are seven manufacturers for PTC systems [151]. At present, Indian manufacturers are supplying concentrating collector to industrial process heating industry. The manufacturing unit of Thermosol Glass (annual production around 40 MW capacity parabolic trough collectors) has started the production of PTC collectors of CSP plants. Several Indian (i. e. APS India, Karmtara etc.) and Chinese (i. e. Yinchinn, CSCEC, Royel Tech etc.) players are entering in the structure market of CSP and offering the technical specifications similar to Ingemetals of Spain. In the HTF and TES market there are new players like Lavachem, Haldor Topse, Enesoon, BASF etc.

7. Conclusions

This study analyses the CSP potential in India on the basis of a detailed solar radiation and land resource assessment in 591 districts across the country. CSP potential is estimated after taking into account the selection criteria i.e. i) suitability of wasteland, ii) appropriateness of annual DNI, and iii) average WPD of ≥150 and ≥200 W/m^2. Applying the suitability criterion of wasteland for large-scale CSP projects, the effective land area available for CSP is estimated over 38 Million acres under the annual DNI ≥1600 kWh/m^2 (i.e. long-term potential) whereas the area under the annual DNI ≥1800 kWh/m^2 (i.e. mid-term potential) is estimated around 16 Million acres. Land area under the criteria of annual DNI≥2000 kWh/m^2 (i.e. for high potential locations) is estimated at 6 Million acres. Out of the 591 districts, 184 districts of the country meet the criteria of solar resource availability, land accessibility and wind power density. CSP potential under the criteria of WPD≥200 W/m^2 is estimated at 3176 GW in which 1542 GW is within the annual DNI range of 1600–1800 kWh/m^2, 1034 GW is within the annual DNI range of 1800–2000 kWh/m^2 and 601 GW is within the annual DNI of more than 2000 kWh/m^2. Simultaneously, CSP potential under the category of WPD≥150 W/m^2 is estimated as 2778 GW in which 1277 GW is within the annual DNI range of 1600–1800 kWh/m^2, 931 GW is within the annual DNI range of 1800–2000 kWh/m^2 and 571 GW is within the annual DNI range of more than 2000 kWh/m^2.

The technical potential of CSP systems is estimated over 1500 GW at an annual DNI ≥1800 kWh/m^2 and WPD ≥150 W/m^2 after taking into accounts the viability of different CSP technologies and land suitability criteria. The economic potential of CSP is estimated at 571 GW at an annual DNI ≥2000 kWh/m^2 and WPD≥150 W/m^2 in

India. It is expected that in near future locations with lower DNI values could also become financially feasible with the development of new technologies, advancement of materials, economy of scale, manufacturing capability along with the enhanced policy measures, etc. In the long-term, it is possible to exploit over 2700 GW solar power through CSP in India with an annual DNI ≥1600 kWh/m^2 and WPD≥150 W/m^2. The findings of this study can be used for identification of niche areas for CSP projects in India. As expected, the levelized cost of electricity is lower for the locations/districts with high DNI in the northwestern India (particularly Gujarat and Rajasthan States). Our analysis indicates that at 142 district/locations (Out of 591 districts) the LCOE of parabolic trough technologies is less than the CERC's levelized tariff of INR 12.03/kWh for FY 2016/17. Consequently, apart from northwestern India, several locations in the State of Andhra Pradesh, Madhya Pradesh, Maharashtra, Haryana, etc. are also techno-economically feasible for the large-scale CSP generation in India.

To maximize cost advantages from longer dispatchability and higher capacity factors, the CSP developers must target energy storage capacities based on market needs. Meanwhile, DNI is the key criteria for potential estimation in the country therefore in order to promote CSP in the country it is critically important to develop bankable DNI database in context of potential locations. In addition, the use of back up fuels (diesel or gas) needs to be allowed to project developers for the smooth operation of the plant in low DNI hours (early morning and late evening).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.04.059.

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