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Hotspots of solar potential in India

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ABSTRACT

Solar hotspots are the regions characterized by an exceptional solar power potential suitable for decentralized commercial exploitation of energy. Identification of solar hotspots in a vast geographical expanse with dense habitations helps to meet escalating power demand in a decentralized, efficient and sustainable manner. This communication focuses on the assessment of resource potential with variability in India derived from high resolution satellite derived insolation data. Data analysis reveals that nearly 58% of the geographical area potentially represent the solar hotspots in the country with more than 5 kWh/m^2/day of annual average Global insolation. A techno-economic analysis of the solar power technologies and a prospective minimal utilization of the land available within these solar hotspots demonstrate their immense power generation as well as emission reduction potential. The study evaluates the progress made in solar power generation in the country especially with the inception of an ambitious National Solar Mission (NSM) also termed as 'Solar India'. The organizational aspects of solar power generation with focus on existing policy elements are also addressed so as to probe the actual potential of the identified solar hotspots in meeting the NSM targets and beyond.

Contents

1. Introduction

Life on earth is heliocentric as most of its energy is derived from the sun. Imminent climatic changes and the demand for clean energy sources have induced significant global interest in solar energy. It has been observed that, solar as viable alternative for power generation among the available clean energy sources has the highest global warming mitigation potential [1].

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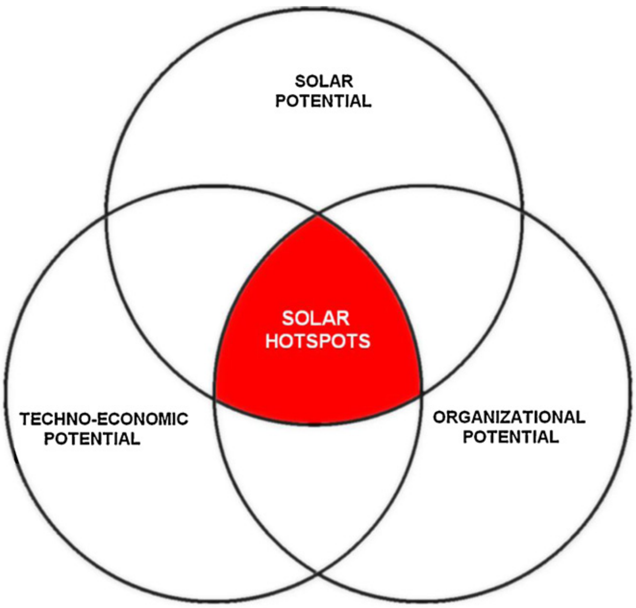

Fig. 1. Diagrammatic representation of the solar hotspots.

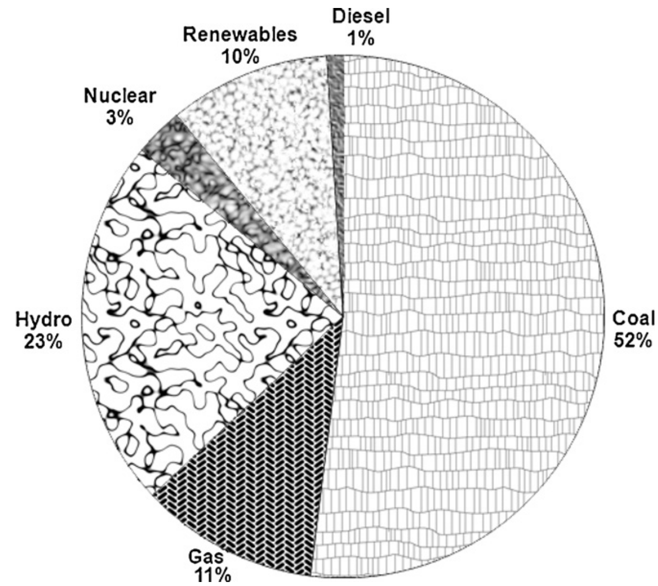

Fig. 2. Share of different sources in installed power generation capacity in India.

Solar energy incident on the earth's surface, also called as insolation primarily depends on parameters like geographic location, earth–sun movements, tilt of the earth's rotational axis and atmospheric attenuation due to suspended particles. The intensity of insolation quantifies the solar resource potential or availability of a region [2]. Solar energy based applications like Solar Photovoltaic (SPV) and Concentrated Solar Power (CSP) systems are limited to utilizing solar radiation wavelengths between 0.29 and 5.5 μm since a major part of the spectrum gets attenuated in other wavelengths due to either absorption or scattering in the atmosphere en route the earth's surface. The sporadic nature of insolation due to its dependence on daily, seasonal, annual and topographic variations insists efficient design of SPV and CSP based solar power generation, conversion, storage and distribution [3]. At the confluence of solar resource potential and technologies like SPV and CSP, certain techno-economic and organizational barriers come into play and influence the implementation and management of these technologies. Solar hotspots are the regions characterized by an exceptional solar power potential suitable for decentralized commercial exploitation of energy with the favorable techno-economic prospects and organizational infrastructure support to augment solar based power generation in a country as visualized in Fig. 1.

1.1. Need to identify solar hotspots in India

Today a low-carbon energy transition at varying rates has been noticed in both the poor as well as rich countries. India has the second highest population in the world with an escalating energy demand. Electricity meets a major portion of this energy demand and is notably related to the socioeconomic progress of the country which is growing at a rate of 8%. The Compound Annual Growth Rate (CAGR) of power generation in India since 2005 is 5.2% while there was a peak shortage of 12.7% (over 15 GW) and average Transmission and Distribution (T&D) loss of 27.2% recorded during 2009–2010 [4]. Unfortunately, over 400 million people do not have access to electricity and nearly 84,740 un-electrified villages (14.3%) in the country, calling for intensive decentralized and efficient power generation [5]. The Integrated Energy Policy (IEPR 2006) in India has envisaged more than 800,000 MW (Megawatts) by 2032 which is 5 times the existing power generation capacity [6]. The scarce fossil fuel based centralized capacity addition is expected to be further expensive, inefficient, polluting and unsustainable. Though mega hydro projects share 23% of the generation capacity, further addition would mean increased environmental disturbance. Nuclear energy is vital but hazardous for environment and national security. Renewable sources contribute only 10% to the nation's power basket where coal is the dominant source (Fig. 2). Currently India is ranked fifth in the world with 15,691.4 MW grid-connected and 367.9 MW off-grid renewable energy based power capacity, hinting at a slow clean power transition compared to other developing economies like China [7]. By and large, it is imperative to boost our renewable energy based power generation capacity, especially through solar.

Although India is one of the best recipients of solar energy due to its favorable location in the solar belt (40°S to 40°N), a meager aggregate of 66 MW_p (Megawatt peak) solar applications (80% of which are solar lanterns, home/street lighting systems and solar water pumps) are installed in the country. This includes a total of 12.28 MW_p grid connected and 2.92 MW_p off grid Solar Power Plants (SSPs) [8]. The National Solar Mission (NSM) launched in January 2010 has given a great boost to the solar scenario in the country. Table 1 shows the targets set by the 'Solar India' mission. It is imperative to identify the solar hotspots in the country to achieve the ambitious target of 2000 MW off-grid and 22,000 MW grid-connected solar generation by 2022 and even higher capacities beyond that time-frame. The identification of hotspots of solar potential hasten the penetration of SPV and CSP based off-grid and grid-connected SPPs, encourage decentralized power generation with the reduced transmission and distribution (T&D) losses while meeting a major part of the country's energy demand. These regions help attract investment, generate employment, abate Green-house Gas (GHG) emissions and realize a sustainable mechanism of power generation. An initial step towards achieving the goal of a 'Solar India' is to assess the solar resource potential and its variability in the country.

1.2. Solar resource potential assessment

Solar resource potential of a region has been assessed in a multitude of ways through long term pyranometric insolation data from surface solar radiation. India with a land area of 3.28 million km^2 has 45 solar radiation stations. As the region of interest expands in geographical area, sparse and expensive pyranometric network

Table 1
Targets set by the National Solar Mission.

	Application segment	Target for phase I (2010–2013)	Target for phase II (2013–2017)	Target for phase III (2017–2022)
1	Solar Collectors (million m^2)	7	15	20
2	Off Grid Solar applications (MW)	200	1000	2000
3	Utility grid power (including roof top) (MW)	1000–2000	4000–10,000	20,000

Source: Jawaharlal Nehru National Solar Mission, Government of India [9].

fails to capture its solar resource variability. Also, these data are often prone to errors due to calibration drift, manual data collection, soiling of sensors, non-standardization and inconsistency of measuring instruments [10]. Data sparseness is often compensated by interpolation, extrapolation and modeling methods based on widely available geophysical and meteorological data. Models based on meteorological satellites which provide reliable insolation data at higher spatial and temporal resolutions are widely recognized. These models are proven to show lower Root Mean Square Error (RMSE) compared to interpolation and extrapolation models for distances beyond 34 km [11]. Hence they are suitable for solar resource potential assessment of larger spatial scales. Nevertheless, surface based pyranometric data remain a good source for validation purposes even today.

Quantification of insolation based on satellite data through different modeling techniques have been reviewed earlier [12] including country level solar resource potential assessments. For example, the solar potential of Kampuchea was estimated based on a statistical model with the visible and infrared images obtained from Japanese Stationary Meteorological Satellite GMS-3 along with ground based regression parameters [13]. The solar potential of Pakistan is assessed by employing a physical model on Geostationary Operational Environmental Satellite (GOES) INSAT images [14] and Chile based on a physical model applied to the GOES-8 and GOES-12 images [15]. Daily Global insolation in Brazil for different clear sky conditions was assessed based on a statistical model on images from a GOES satellite instrument [16]. For the same region, the Global, Direct and Diffuse solar radiation have been assessed based on the 10 km X 10 km satellite derived *Solar and Wind Energy Resource Assessment* (SWERA) project database [17]. Most of these studies when validated with surface data showed Root Mean Square Error (RMSE) in the range of 5–15%. RMSE for different satellite models have been found to be within 20% for daily values and 10% for hourly values [18].

Estimation of insolation and dissemination of large scale solar power applications have been studied based on different methodologies. The potential of grid connected SPV systems in Bangladesh was estimated at 14 sites in the country and observed a generation capacity of 50,174 MW with reduction in annual GHG emissions of 1423 tons using *National Aeronautics and Space Administration* (NASA) *Surface Meteorology and Solar Energy* (SSE) dataset and HOMER optimization software [19]. The power generation potential of High Concentration Photovoltaics (HCPV) in Brazil was assessed using the SWERA insolation database [20]. The Direct Normal Irradiance (Direct insolation) in Turkey based on the NASA SSE dataset was done so as to estimate the viability of CSP for power generation [21]. The Western and Southeastern parts of the country were found to have high solar resource potential as well as large area of waste lands for CSP based power generation. The study also discusses the technical and organizational aspects of CSP based power generation. Similar studies in China [22] and many other parts of the world [23] have also been observed. The solar resource potential assessment efforts in the federal state of Karnataka in India [24,25] and the consequent megawatt capacity SPPs that were installed [26], incite further interest in identifying the solar hotspots in India, assessing relevant solar power technologies and prospects of dissemination.

Table 2
Agro-climatic zones in India.

S. No	Agro-climatic zones	Representative states
1	Western Himalayan region	Himachal Pradesh, Jammu & Kashmir, Uttarakhand
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal
3	Lower Gangetic plain region	West Bengal
4	Middle Gangetic plain region	Uttar Pradesh, Bihar
5	Upper Gangetic plain region	Uttar Pradesh
6	Trans Gangetic plain region	Chandigarh, Delhi, Haryana, Punjab, Rajasthan
7	Eastern plateau & hills region	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Orissa, West Bengal
8	Central plateau & hills region	Madhya Pradesh, Rajasthan, Uttar Pradesh
9	Western plateau & hills region	Madhya Pradesh, Maharashtra
10	Southern plateau & hills region	Andhra Pradesh, Karnataka, Tamil Nadu
11	East coast plains & hills region	Andhra Pradesh, Orissa, Pondicherry, Tamil Nadu
12	West coast plains & ghat region	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu
13	Gujarat plains & hills region	Gujarat, Dadra & Nagar Haveli, Daman & Diu
14	Western dry region	Rajasthan
15	Island region	Andaman & Nicobar Islands, Lakshadweep

Source: Planning Commission, Government of India [27].

2. Objective

Main objective of this study is to identify the solar hotspots based on the exploitable potential using high resolution global insolation data from NASA SSE in India across federal boundaries (Fig. 3) and agro-climatic zones (Table 2). The power generation with the emission reduction potential of the solar hotspots has also been discussed to understand the prospects of achieving the long term targets of the NSM (National Solar Mission) considering the techno-economic and organizational aspects in the dissemination of solar power technologies like SPV and CSP.

3. Methodology

NASA SSE Global insolation datasets are derived from a physical model based on the radiative transfer in the atmosphere along with parameterization of its absorption and scattering properties. The primary inputs to this model include visible and infrared radiation, inferred cloud and surface properties, temperature, precipitable water, column ozone amounts and atmospheric variables such as temperature and pressure measured using diverse satellite instruments. The longwave and shortwave solar radiations reflected to the satellite sensors along with the collected primary inputs are studied to obtain the global insolation for different locations and durations. The 1°X1° spatial resolution SSE global insolation data derived for a period of 22 years (July 1st, 1983–June 30th, 2005) were validated (RMSE of 10.28%) with Baseline Surface Radiation Network (BSRN) data available as daily, monthly and annual

Fig. 3. India with the federal state boundaries.

averages obtained from measured values every 3 h and is accessible at the NASA SSE web portal http://eosweb.larc.nasa.gov/sse/ [28].

In this study, the NASA SSE monthly average Global insolation data is collected for more than 900 grids which optimally cover the entire topography of India within the latitudes 8–38°N and longitudes 68–98°E. A geo-statistical bilinear interpolation is employed to produce monthly average Global insolation maps for the country detailed with isohels (defined as lines/contours of equal solar radiation) using Geographical Information Systems (GIS). Regions receiving favorable annual global insolation for the electricity generation with technologies like SPV and CSP and the prospects for successful solar devices dissemination are demarcated as solar hotspots.

Devices such as CSP depend on Direct component of Global insolation, hence its intensity in the identified solar hotspots in India is verified based on surface measurements obtained from solar radiation stations.

The Direct insolation is given by

$$I = \frac{G - D}{\sin \Phi} \tag{1}$$

where G is the Global insolation, D is the diffuse component and Φ is the sun's elevation angle [2].

4. Results

Fig. 4a–c gives the monthly average Global insolation variations with isohels. During the January (winter) month, major parts of the Southern Peninsula receive above 4.5 kWh/m^2/day reaching a maximum of 5.5 kWh/m^2/day in the Western Coast plains and Ghat regions, while the Western Himalayas in Northern India receives minimum of 2.5 kWh/m^2/day. During February, a major expanse of the Indian landscape receives above 5 kWh/m^2/day while the Western (Himachal Pradesh, Uttarakhand, Jammu Kashmir) and Eastern (Assam, Arunachal Pradesh, Nagaland) Himalayas continue receiving insolation in the range of 3–4 kWh/m^2/day. During April–May as the summer heat sets in, more than 90% of the country is seen to receive insolation above 5 kWh/m^2/day with a maximum recorded 7.5 kWh/m^2/day in the Western dry and Trans-Gangetic plains. During this period, the Eastern Himalayan region receives a minimum 4.7 kWh/m^2/day global insolation. With the onset of the summer monsoon throughout the country in June, there is a remarkable lowering of Global insolation towards the Southern (except for Tamil Nadu) and North Eastern ranges. The least recorded value in this period is 3.9 kWh/m^2/day. This trend continues till September as the summer monsoon recedes. The Northern part of the country remain minimally affected by this monsoon and is observed to receive higher values in the range of 5–7 kWh/m^2/day. The Northeastern monsoon originating from Central Asia in October brings the Global insolation below 4 kWh/m^2/day in the Lower-Gangetic plains, East Coast plains as well as the Northern most tip of the country. The Himalayan foothills, plains, Central Plateau and Western dry zones receive above 4.7 kWh/m^2/day as the Himalayas act as a barrier to this winter monsoon and allows only dry winds to the Indian mainland. With the arrival of winter by October end, the Northern to West-

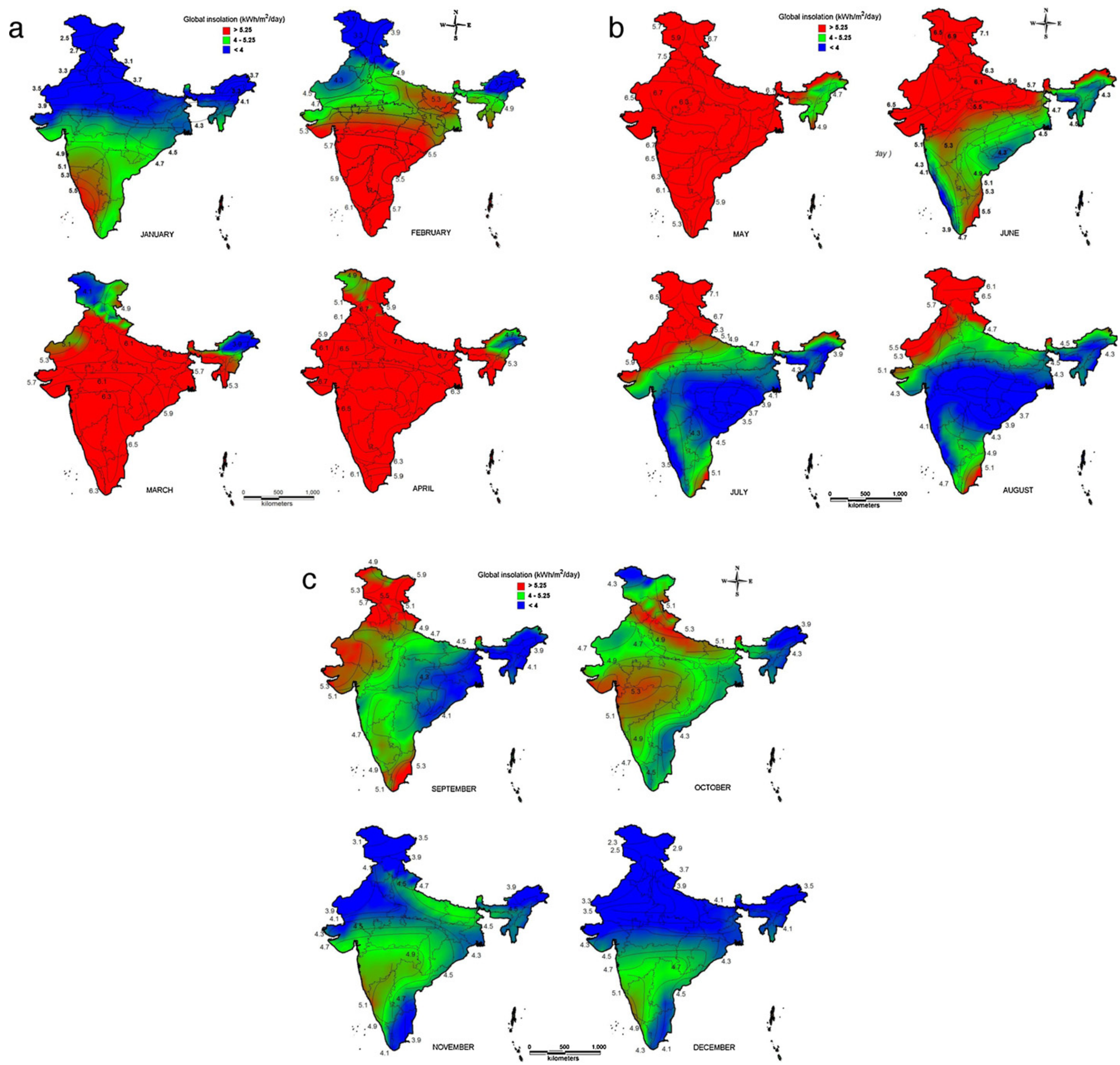

Fig. 4. (a) Monthly average Global insolation maps of India detailed with isohels (January–April), (b) monthly average Global insolation maps of India detailed with isohels (May to August) and (c) monthly average Global insolation maps of India detailed with isohels (September–December).

ern regions in India receive below 4.5 kWh/m^2/day for about three months. These observed seasonal variations of Global insolation throughout the country conforms with the earlier investigations [2] based on 18 surface solar radiation stations.

Fig. 5 illustrates that the Gangetic plains (Trans, Middle and Upper) Plateau (Central, Western and Southern) region, Western dry region, Gujarat Plains and hill region as well as the West Coast plains and Ghat region receive annual Global insolation above 5 kWh/m^2/day. These zones include major federal states of Karnataka, Gujarat, Andhra Pradesh, Maharashtra, Madhya Pradesh, Rajasthan, Tamil Nadu, Haryana, Punjab, Kerala, Bihar, Uttar Pradesh and Chattisgarh. The Eastern part of Ladakh region (Jammu & Kashmir) and minor parts of Himachal Pradesh, Uttarakand and Sikkim which are located in the Himalayan belt also receive similar average Global insolation annually. These regions with viable potential constitute solar hotspots covering nearly 1.89 million km^2 (~58%) of India (Fig. 5) with the favorable prospects for solar based renewable energy technologies. The Eastern Himalayan states of Arunachal Pradesh, Nagaland and Assam receive annual average global insolation below 4 kWh/m^2/day.

4.1. Techno-economic feasibility of solar energy

The true potential of the identified solar hotspots is realized only with the proper dissemination of technologies for large scale power generation. This section focuses on the techno-economic aspects of solar power technologies like SPV and CSP apart from the social and organizational aspects.

SPV based power generation: Electricity generated by SPV cells is proportional to the area exposed and the intensity of

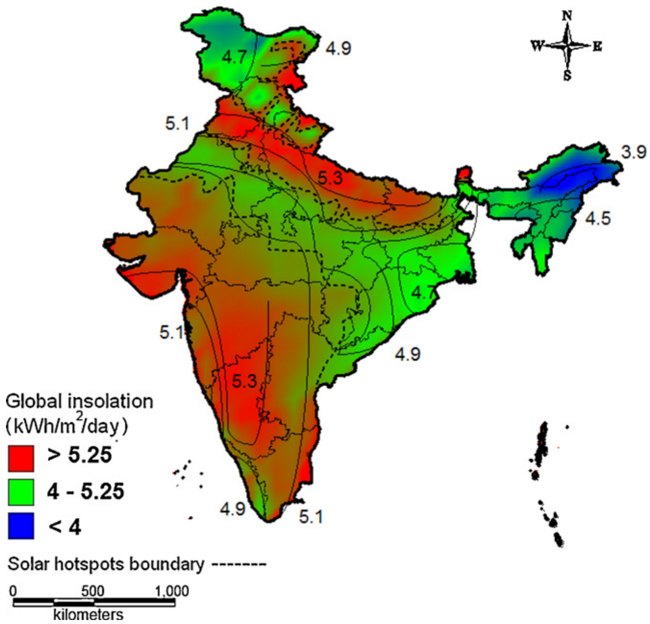

Fig. 5. Annual average Global insolation map of India showing the isohels and solar hotspots.

global insolation received. Its conversion efficiency is defined by $\eta = P_o/P_i$ where P_o is the maximum power output and P_i is the power input at Standard Test Conditions (STC) of 1000 W/m^2 global insolation, 25 °C module temperature and 1.5 air–mass (AM). SPV technology has immensely improved in efficiency in the past few decades. The first generation mono and poly crystalline Silicon (mc-Si and pc-Si) wafers with 15–22% and 12–15% cell efficiencies, respectively continue to dominate the world SPV production. Nearly 98% of SPV cell production in India is Si based and caters to the domestic as well as export needs [7]. The thin film Amorphous Silicon (a-Si) and mc-Si (η = 6–10%), Cadmium Telluride (CdTe) (η = 7–10%), Copper–Indium–Diselenide (CIS) and Copper–Indium–Gallium–Diselenide (CIGS) (η = 10–13%) are being commercialized on experimental basis the world over. The dye-sensitized, organic, multi-junction, concentrator and rectenna based technologies promising very high efficiencies are in their nascent stages of development [29]. The International Energy Agency has set a target of 23% commercial SPV module efficiency by 2020 with 12 months payback time for 1500 kWh/kW$_p$ and 30 years operational time. The commercial efficiency of 16% assumed earlier has already been achieved by 2008 [30].

Component selection and system design plays a pivotal role in the SPV based power generation. SPV system sizing based on Global insolation, seasonal variability, elevation angle, temperature and other aspects like battery capacity for meeting the load is now simplified through optimization tools like HOMER [23]. The SPV cell performance specified at STC is never realized on field conditions [31]. The actual output of a SPV system will slowly rise to maximum at noon and decrease back to zero at night. For a mc-Si SPV cell, the change in efficiency with temperature is found to be ± 0.5% °C^{-1} [32]. For long term power generation, this inverse variation of efficiency with temperature is more or less compensated by diurnal and seasons changes. However an evident dip in cell efficiency will be observed for arid regions like Rajasthan where temperature sores up to 45 °C and more. Water cooling so as to lower the SPV cell temperature is observed to increase electricity generation by 9–12% [33]. A typical Si based solar panel may vary from 0.5 to 2 m^2 in size with an approximate weight of 15–20 kg/m^2. A SPV based system without battery backup on-site may actually only be able to provide 67.5% of the maximum power output on a clear sky. This is attributed to factors like time of the day, internal heating, dust, module mismatch, wiring and DC-AC conversion losses affecting the overall system performance. If a battery is added to the system the output may further reduce by 6–10%. According to the orientation of the panel a correction factor may creep in with values ranging from 0.80 to 1.00 [34]. Components like inverters, batteries, mountings and other electrical appliances usually escalate the price of the SPV system. The overall system prices in 2009 were seen to be nearly Rs 500/Watt for off-grid and Rs 250/Watt for grid-connected SPPs which has certainly gone down with the market demand [35]. It is observed that integrating SPV module, charge controller, inverter, wiring, support structure and foundation as a preassembled unit reduces cost, failures and installation effort [23]. These modules could be commercialized for effective village electrification in India.

CSP based power generation: Unlike low-temperature solar thermal devices like water heaters, room heaters, agro-dryers, cookers etc., CSP technology preferentially utilizes the Direct component of Global insolation which could be forwarded on to a receiver using lenses or mirrors (stationary or sun tracking). The receiver being of smaller area decreases heat loss and hence increases the output efficiency [31]. The heat transfer fluid (pressurized steam, gases, synthetic oil, molten salt etc.) inside the receiver flows to a heat engine where the heat energy is partially converted to electricity. There are four common CSP technologies namely parabolic trough, power tower, parabolic dish and compound linear Fresnel reflectors which are detailed in Table 3. The temperature of the receiver may have a range of 250–1500 °C depending on the concentration ratio (Collector to Receiver area) which can vary from 30 to 10,000 according to the design. Parabolic trough design dominates more than 90% of the CSP market in the world. Dish type system has the highest optical efficiency but is preferred for standalone applications due to the cost factor. Compound Linear Fresnel design has lower installation and maintenance cost and covers lesser land area [36]. Commercial parabolic trough CSP plants show system efficiencies to the range of 10–14% [37]. The integrated solar combustion cycle system (ISCCS) combining parabolic trough and gas turbine is a promising modification to the existing technology. Water is generally used for steam cycle, mirror washing and cooling tower. It could be compensated by dry cooling systems but at an increased generation cost of 10% [21]. A benefit of CSP over SPV technology is the heat storage option which is relatively easier and cost effective than electricity storage. The sensible, latent and thermo-chemical heat storage techniques are being developed and demonstrated. This thermal storage helps in providing balancing power during dark hours and also acts as a substitute for fossil fuels. It is also promising for co-generation. CSP plants are considered to have a minimum life of 20 years. The parabolic trough CSP generation cost ranges from Rs 5 to 7/kWh as of today which is higher than coal based thermal power generation. Experiences in different countries indicate that cost reduction will be realized only with increase in volume, plant scale-up and technological advancement [38]. The Chinese renewable energy policy aims at bringing the CSP generation cost to Rs 2–3/kWh by 2025 through intensive R&D measures [22]. Nearly 50% of the investments in CSP based power plants go for locally available steel, mirrors, concrete, and labour providing socio-economic stability and local support [39]. Undeniably, CSP adapts well to the Indian socioeconomic conditions but needs vigorous R&D up-scaling.

4.2. Prospects of solar power in India

India receives annual sunshine of 2600–3200 h [2]. Table 4 shows the power input (Global insolation), maximum rated and actual on-site output (67.5% of the rated as observed earlier) values at two different efficiencies (16% and 20%) for a system

Table 3
Different types of CSP technologies and their features.

Design	Capacity (MW)	Operating temperature (°C)	Insolation enhancement (%)	Land (ha/MW)	Water (m^3/MWh)
Parabolic trough	10–200	300–400	30–40	4	2.9–3.5
Power tower	10–150	500–1500	60–70	8.4	2.9–3.5
Parabolic dish	0.01–0.04	750	60–70	1.6	Nil
Compound linear Fresnel	1–200	250–300	30–40	0.18	2.8

Sources: [36,38].

Table 4
Maximum and actual on-site power output of a typical Si based SPV cell at 16% and 20% efficiencies assuming 7 h daily sunshine.

Power input P_i		Maximum power output P_o		Actual on-site power output	
kWh/m²/day	W/m²	η = 16%	η = 20%	η = 16%	η = 20%
2.5	357	57	71	39	48
3	429	69	86	46	58
3.5	500	80	100	54	68
4	571	91	114	62	77
4.5	643	103	129	69	87
5	714	114	143	77	96
5.25	750	120	150	81	101
5.5	786	126	157	85	106
5.75	821	131	164	89	111
6	857	137	171	93	116
6.5	929	149	186	100	125
7	1000	160	200	108	135

without battery backup considering the minimum ∼7 h of daily sunshine (or 2600 h of annual). Regions receiving Global insolation of 5 kWh/m²/day and above can generate at least 77 W/m² (actual on-site output) at 16% efficiency. Hence, even 0.1% of the land area of the identified solar hotspots (1897.55 km²) could deliver nearly 146 GW of SPV based electricity (379 billion units (kWh) considering 2600 sunshine hours annually). This power generation capacity would enhance considerably with the improvement in efficiency of SPV technology.

Direct insolation with a minimum threshold value of 1800 kWh/m²/year or ∼5 kWh/m²/day is best recommended for CSP in order to achieve Levelised Electricity Costs (LEC). A minimal inclined (slope 0–3%) non-agricultural and biologically sparse land area of 4 ha/MW (considering the typical parabolic trough) is consequential for CSP based power generation. The proximity to transmission line corridor and availability of water would be favorable factors [21]. CSP technologies perform better in semi arid and arid regions. Surface solar radiation studies in the Trans-Gangetic, Western dry, Plateau and Gujarat plains and hill regions of India show that Direct insolation is higher in intensity to the Global insolation during the summer, post-monsoonal and winter months due to clear sky conditions and variations in elevation angle. During the monsoon months of June, July and August, the Direct component is nearly half of the total Global insolation received [2]. Hence the potential solar hotspots identified in the study receiving excellent Global insolation obtain sufficient Direct insolation as well and support CSP based power generation. However, the solar hotspots in the cold Himalayan belt including Eastern Ladakh and minor parts of Himachal Pradesh, Uttarakhand and Sikkim may not favor CSP technology. Estimates reveal that about 4.89 million ha of barren and unculturable land is available in Gujarat and Rajasthan (Table 5). Even a small fraction of this waste land (0.1% or 4890 ha) could support nearly 1222 MW capacity parabolic trough CSP plants. Comparative studies have shown the financial viability of CSP technologies in Indian conditions especially in the semi arid and arid regions [36] and hence these regions are identified as solar hotspots.

India has a vast potential for solar power generation since about 58% of the total land area (1.89 million km²) receives annual average Global insolation above 5 kWh/m²/day. Being a densely populated country with residential, agricultural and industrial priorities, availability of land for SPPs is of serious concern in some parts and needs further investigation using spatio-temporal data. Recent land use statistics (Table 5) highlights the availability of barren or unculturable land in many states like Rajasthan, Gujarat, Andhra Pradesh, Maharashtra, Karnataka, Tamil Nadu, Uttar Pradesh, Madhya Pradesh and Bihar [47]. It is observed that the per capita electricity consumption is recorded to be the highest in Western India (1029.52 kWh/year) followed by Southern and Northern regions [7]. Most of the identified solar hotspots are also in these regions, and hence solar power generation could reduce transmission losses due to its decentralized distributed nature.

Table 5
Area of barren or unculturable land in representative states of identified solar hotspots in India.

State/union territory	Total area (1000 ha)	Barren or unculturable land (1000 ha)	%
Andhra Pradesh	27,505	2056	7
Bihar	9360	432	5
Chhattisgarh	13,790	308	2
Goa	361	0	0
Gujarat	18,866	2595	14
Haryana	4371	103	2
Himachal Pradesh	4548	656	14
Jammu Kashmir	3781	288	8
Karnataka	19,050	788	4
Kerala	3886	25	1
Madhya Pradesh	30,756	1351	4
Maharashtra	30,758	1718	6
Punjab	5033	24	0
Rajasthan	34,270	2295	7
Sikkim	723	107	15
Tamil Nadu	13,027	492	4
Uttarakhand	5673	224	4
Uttar Pradesh	24,170	507	2
West Bengal	8684	21	0
Chandigarh	7	0	0
Delhi	147	16	11

Source: Directorate of Economics and Statistics, Government of India [47].

According to NTPC Vidyut Vyapar Nigam (NVVN) Limited, the national nodal agency for allotting solar power projects, 620 MW_p of solar power projects (470 MW_p CSP & 150 MW_p SPV) are selected for the first phase of NSM which ends by May 2013. CSP based plants are proposed for Rajasthan (400 MW_p), Andhra Pradesh (50 MW_p) and Gujarat (20 MW_p), while SPV projects are based in Rajasthan (105 MW_p), Andhra Pradesh (15 MW_p), Karnataka (10 MW_p), Maharashtra (5 MW_p), Uttar Pradesh (5 MW_p), Orissa (5 MW_p) and Tamil Nadu (5 MW_p) [40]. Various states like Gujarat, Uttaranchal, Uttar Pradesh and Jharkhand have promised to increase their percentage share of solar based electricity to 1% by financial year 2011–2012. Karnataka has already approved 129 MW_p solar based grid connected power generation of which 6 MW_p have been commissioned by November 30th, 2010 [41]. Rajasthan having the highest share of solar power projects in the country launched a Solar Energy Policy in 2010, which aims for 10,000–12,000 MW_p of solar power generation by 2022 coinciding with the third phase of the NSM [42]. Andhra Pradesh has sanctioned nearly 11 MW_p of standalone off grid SPPs in the state expected to be commissioned by mid 2011 [43]. Uttar Pradesh has approved 32.5 MW SPV based power projects in the state [44] while the state of Jammu Kashmir also launched a solar energy policy. India's progress in solar power generation after the launch of NSM is definitely encouraging. Considering the immense potential of solar resources in the country, the generation capacity could surpass the highest targets set by the NSM under proper mechanisms.

Apart from the power generation potential of SPPs, their environmental attribute could be quantified with the introduction of Renewable Energy Certificates (RECs). The solar power purchase obligation envisaged by the NSM, requires states to buy 0.25% solar based power in its first phase which will be scaled up to 3% by 2022 [9]. This opens up new vistas for the Clean Development Mechanism (CDM) by interstate sale and purchase of solar specific RECs. The average emission from the regional power grid according to the 2008–2009 baseline database of the Central Electricity Authority (CEA) is 860 gCO_2/kWh [45]. Studies show that Si SPV based power generation emits 35–40 gCO_2/kWh equivalent during its life cycle, which is phenomenally lower than the fossil fuel based plants [46]. The assumed Si SPV based output of 379 billion units generated from 0.1% land area of the identified solar hotspots, can offset more than 300 $mtCO_2$ per year. CSP can also offset high amounts of emission by replacing the fossil fuel based conventional power plants. In the international level, this adds to India's efforts in mitigating global warming.

4.3. Organizational aspects of solar power generation in India

Dissemination of SPV and CSP technologies for power generation needs detailed understanding of the organizational structure and market conditions. Capital grant is a major policy instrument of the Indian government with respect to the off-grid renewable energy projects. Rural village electrification envisages decentralized and distributed systems with thrust on renewable energy sources providing capital subsidies. There is a Central Financial Assistance (CFA) of Rs. 70–90/Watt (depending on battery backup) or 30% of the project cost whichever is lower for small scale SPV applications. The government has promised a subsidy of up to Rs. 100/Watt (to a maximum of 40% of the cost of system) for non-profit making bodies for installations of 25–100 kW capacity [7]. The Indian government's policy measure for grid-connected systems encourages competition and efficiency through Generation Based Incentives (GBI). The incentive for SPV is Rs 12/kWh and CSP is Rs 10/kWh for a total of 50 MW_p projects on first come first serve basis. An individual power developer can avail generation based incentive for a minimum of 1 MW_p at a single location and maximum of 5 MW_p for a maximum of 10 years [48]. State level policies also offer incentives for solar power production up to 25 years or life of the plant whichever is earlier.

Fiscal and financial incentives like tax holiday, tax free dividend, abolition of excise duty to investors encourage further investment. Institutional support has been observed to be a major factor for sustaining new technologies while strengthening of R&D and opening up of a local free market need priority rather than subsidy based incentives [23]. Major developing economies like China have realized the importance of R&D so as to bring grid parity for solar based power generation [22]. Since demand for skilled resource persons for promotion, installation and maintenance of solar power systems are on the rise, India needs to strengthen its training institutions with world class infrastructure.

5. Social aspects

While solar resource potential, techno-economic feasibility and organizational aspects play indispensible role, social acceptance gives the final verdict on the long term success of solar power generation. Awareness on the environmental and health benefits of solar energy is essential to mobilise solar technologies in the fuel-wood based grass-root economy of India [49]. The Government of India has taken initiatives for knowledge dissemination in the district level. Developing solar micro-grid systems in village level for meeting the electricity requirements of a cluster of families through financial support for energy service providers, proper fee-for-service models, and micro-finance for consumers could lead the way for decentralized rural electrification and management [50]. This successful strategy is testified in Sundarbans in the federal state of West Bengal where a 345 kW_p SPV based SPP has been established for 1750 consumers [51]. A case study in Sagar Dweep island [52] extols the improvement in education, income generation, social life and health of the people benefited by decentralized solar electrification. While these experiences inspire us to move towards a solar economy, it is essential to expel selfish elements who influence the governance and the citizenry to continue in the unsustainable development track. A holistic approach involving the public, government, academia, media and international organizations need to be adopted to ensure social acceptance of solar power generation.

6. Conclusion

The study identified the solar hotspots in India using high resolution satellite data. It is observed that nearly 58% of the country receives annual average Global insolation of 5 kWh/m^2/day which could help meet her escalating power requirements in a decentralized, efficient and sustainable manner. The solar power technologies like SPV and CSP have been discussed with focus on their techno-economic constraints of implementation. A major thrust for R&D in solar technologies is essential to lower the generation cost and enable a competition with the conventional fossil fuel based options. Solar hotspots in India have the potential to offset a huge volume of GHG emissions as demonstrated and help realize a low carbon economy at a faster rate. It will create numerous employment opportunities especially in the village level. Learning from other developing countries as well as its own past experiences, India can be a world leader in solar power generation. With an ambitious solar mission, and positively evolving policy instruments, the nation will rightly adorn the epithet of 'Solar India' in the near future.

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