Assured solar energy hot-spots over Indian landmass detected through remote sensing observations from Geostationary Meteorological Satellite

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Quantification of assured solar energy potential is essential to select locations for solar photovoltaic, thermal power plants and to quantify solar power potential. The use of remote sensing observations from geostationary satellite sensors is ideal to capture space-time variability of surface insolation. The annual clear solar energy exposure over India was determined using three years' insolation data at 8 km spatial resolution from Kalpana-1 satellite. High density solar energy pockets were diagnosed in western, central and southern India including Gujarat, Rajasthan, Madhya Pradesh, Karnataka, Tamil Nadu and Chhattisgarh states with annual solar energy exposure ranging from 2500 to 3500 kW h m^{-2} yr^{-1}.

Keywords: Geostationary satellite, renewable energy, remote sensing.

THE over-consumption of the available conventional energy resources in the past few decades has brought to light the threat of energy crisis due to depleting non-renewable energy sources and increasing population. Moreover, it has also deteriorated the quality of the environment. The use of alternative forms of energy such as solar, wind, ocean, thermal, biomass, geothermal, hydro and tidal energies reduce our dependency on fossil fuels and serve better to complement national energy security[1]. Among these, solar energy can be a good alternative and renewable energy source to fulfil the current energy needs. Advancement in solar radiation technologies is paving the new way in energy sustainability[2] at global (continent) to local (village) scales. Solar energy data is a fundamental input for power generation potential through photovoltaic systems, solar collectors for heating, solar air conditioning, climate control in buildings and passive solar devices[3]. India being a sub-tropical country has vast potential of solar energy compared to its total energy consumption in a year[4,5], especially in urban and rural sectors. Till date, solar energy is under-utilized in India. It currently accounts for only 0.8% of total power generation capacity in India[1].

The Jawaharlal Nehru National Solar Mission (JNNSM) is a major initiative of the Government of India and state governments to promote ecologically sustainable growth while addressing India's energy security challenges. It also constitutes a major contribution by India to the global effort to meet the challenges of climate change. On launching of India's National Action Plan on Climate Change on 30 June 2008, it had emphasized a graduated shift from economic activity based on fossil fuels to one based on non-fossil fuels and from reliance on non-renewable and depleting sources of energy to renewable sources of energy, specifically to develop solar energy as a source of abundant energy to power our economy and to transform the lives of our people.

The objective of the solar mission is to create conditions through rapid scale-up of capacity and technological innovation to drive down costs towards grid parity. The mission anticipates in its three phases to grid cost achieving grid parity for solar energy and to install 20 GW of grid-connected solar power by 2022 and parity with coal-based thermal power by 2030 (ref. 6). It recognizes that there are a number of off-grid solar applications particularly for meeting the rural energy needs, which are already cost-effective and provides for their rapid expansion. India is endowed with vast solar energy potential. Hence, both technology routes for conversion of solar radiation into heat and electricity, namely solar thermal and solar photovoltaic (PV), can effectively be harnessed providing huge scalability for solar energy in India. It also provides the ability to generate power on a distributed basis and enables rapid capacity addition with short lead times. In addition, without effective storage, solar power is characterized by a high degree of variability in space and time. In India, this would be particularly true in the monsoon season. Therefore, demarcation of potential solar energy zone is important for investment in this sector. Solar imperative is both urgent and feasible to enable the country to meet long-term energy needs.

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Digital solar energy atlas is essential to locate solar energy conversion systems such as solar PV or thermal power plants[7]. A monthly solar radiation map on spatial scale is demand of the present time to locate solar energy conversion systems to produce natural and eco-friendly energy. Conventionally, these maps are constructed from high density network of pyranometers. In India, a sparse network of 45 pyranometer stations is presently operating through government agencies. The Ministry of New and Renewable Energy is also in the process of setting up a proposed network of 121 Solar Radiation Resource Assessment (SRRA) stations. The interpolation from such sparse network produces large errors (60–70%) due to large uncertainties of intermittent diurnal cloud cover, cloud types and atmospheric turbidity in cloudless skies[8,9]. Moreover, high maintenance costs and lack of availability of real-time data are major impediments. Several estimation models have been developed based on temperature amplitude, sunshine hours or cloud cover and combination of temperature, humidity, rainfall, but these require site and season-specific calibration of coefficients and thus difficult to extrapolate. Moreover, such models do not explicitly consider the role of atmospheric constituents such as air molecule, aerosol, water vapour, ozone and cloud. The use of remote sensing observations from geostationary satellite sensors that have high temporal sampling frequency (multiple passes every day) is ideal to capture spatio-temporal variability of surface insolation for those regions where regular measurements from sparse radiation network and their availability are not consistent till date. Moreover, satellite-derived hourly insolation is considered equivalent to ground station measurements at a distance of 25 km (ref. 10). The basic objectives of this study are to quantify the potential of assured solar energy over India, delineate its zones and its availability over different land use categories using multi-year diurnal observations from Indian geostationary meteorological satellite.

Data used

Satellite data

Kalpana-1 was launched in 2002 by Polar Satellite Launch Vehicle, which is the exclusive meteorological satellite in the INSAT system. The satellite consists of Very High Resolution Radiometer payload with a Data Relay Transponder (DRT) to provide meteorological service. This radiometer consists of one broad VIS (0.55–0.75 mm), one WV (5.7–7.1 mm) and one thermal IR (10.5–12.5 mm) bands with spatial resolution of 2000 m for VIS band and 8000 m for WV and thermal IR bands. The introduction of INSAT Meteorological Data Processing System (IMDPS)[11] provides both 'full-globe' and 'sector' data products in all the three bands at half-an-hour interval at 8 km spatial resolution in an automated mode. The dimension of each band at each acquisition is 807 rows × 808 columns for Asia Mercator sector product[12].

Instantaneous insolation was generated using spectrally integrated radiative transfer scheme and three-layer cloudy-sky model with cloud-top albedo, temperature, atmospheric water vapour from VIS, thermal IR and WV bands[13] and ancillary global data (eight-day aerosol, ozone). The K1VHRR data are available to registered users through Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) (http://www.mosdac.gov.in) on request basis. The daily integral of insolation data is available in hdf5 (hierarchical data format 5) format at 8 km spatial resolution with product code K1-VHR-DAILYINS. The daily insolation data for three years from 1 January 2009 to 31 December 2011 were used for the estimation of hot-spots of solar energy exposure over India.

In situ data

A network of INSAT-linked Agro-Met Stations (AMS) is located over different land use categories in the country[14]. The stations record the automated measurements of incoming and outgoing shortwave and longwave radiation components, multi-level weather quantities (air temperature, wind speed and relative humidity) at half-an-hour interval. These are transmitted through Yagi antenna to INSAT 3A DRT (Data-Relay Transponders) which then retransmit to Bopal Earth Station (BES) at Ahmedabad, India. The data are available in user friendly format at MOSDAC site. The half-an-hourly average incoming shortwave radiation data from 14 AMS stations (Figure 1)

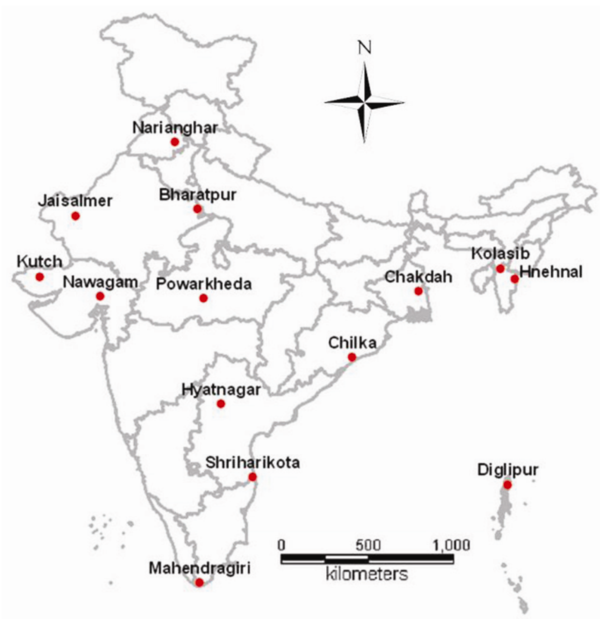

Figure 1. Study area with Agro-Met Station locations.

for the year 2011 (from 1 January 2011 to 31 December 2011) were used to evaluate solar energy potential estimated from Kalpana-1 VHRR observations.

Methodology

The extraterrestrial solar radiation reaching the top of the atmosphere (Rs_0) was computed using standard astronomical formulae that require day number in a year, time in a day, latitude and longitude[15]. This is also termed as potential insolation. The relative daily surface insolation (Rs/Rs_0) is defined as the ratio of the global (Rs) insolation actually reaching the Earth's surface on a given day and potential insolation (Rs_0)[16,17]. Thus, it is an indicator of atmospheric clearness[18,19]. The relative insolation was derived on daily basis. Then, the regional monthly means of relative insolation were computed for each month. The frequency of clear sky days was determined by summing the sequences when daily relative insolation crosses 0.6 (ref. 20). Here, clear days mean cloud and fog-free days. The monthly and annual fractions of clear-sky days were computed from the ratio of number of clear days and the total number of days in a month or year. The annual clear solar exposure was determined from summation of annual insolation weighted by annual fraction of clear days[21]. The overall flow of methodology is shown in Figure 2.

Results and discussions

Evaluation of satellite-based daily solar energy with in-situ data

The daily insolation for 2010 was compared with *in-situ* measurements from AMS at 14 locations for the monsoon months (July, August and September) and non-monsoon months (January and February). Table 1 shows the error statistics of satellite-based estimates on daily, weekly, fortnightly and monthly scales with respect to *in-situ* measurements.

The root mean square error (RMSE) of the estimates reduced from 0.67 Wm^{-2} to 0.47 Wm^{-2} in non-monsoon months and from 1.78 Wm^{-2} to 0.97 Wm^{-2} in monsoon months at daily, weekly, fortnightly and monthly scales. The RMSE in pooled datasets reduced from 1.25 Wm^{-2} (32.2%) for daily, 1.00 Wm^{-2} (24.9%) weekly and 0.78 Wm^{-2} (20.2%) fortnightly to 0.72 Wm^{-2} (18.2%) for monthly averages.

The yearly sum of solar energy at each AMS was compared with the satellite derived annual solar energy over AMS locations (Figure 3). The satellite-based solar energy showed underestimates as compared to those recorded by AMS. The RMSE of annual estimates of solar energy was 16.9% of mean of AMS data records.

Table 1. Comparison of satellite derived insolation with *in-situ* observations from AMS

Time scales	RMSE (Wm^{-2})	RMSE (% of measured mean)	MAE
Non-monsoon months (January and February, 2010)			
Daily	0.67	17.9	0.56
Weekly	0.56	15.1	0.47
Fortnightly	0.53	14.2	0.44
Monthly	0.47	13.0	0.39
Monsoon months (July, August, September, 2010)			
Daily	1.78	39.1	1.42
Weekly	1.42	30.2	1.08
Fortnightly	1.03	22.4	0.89
Monthly	0.97	19.2	0.86
Pooled (January, February, July, August, September, 2010)			
Daily	1.25	32.2	0.92
Weekly	1.00	24.9	0.72
Fortnightly	0.78	20.2	0.64
Monthly	0.72	18.2	0.61

RMSE, Root mean square error; MAE, Mean absolute error.

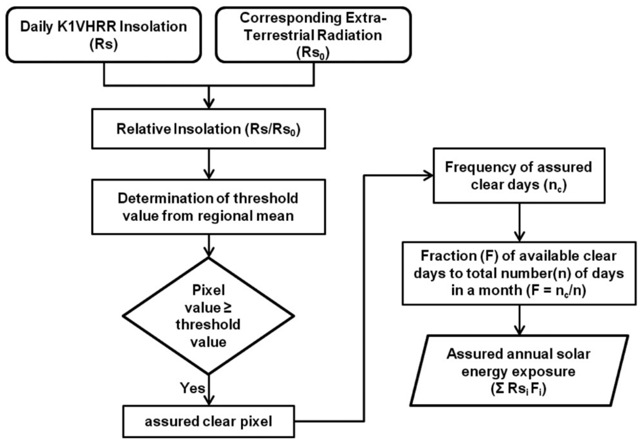

Figure 2. Overview of methodology adopted for determining assured annual solar energy exposure using daily K1VHRR insolation data.

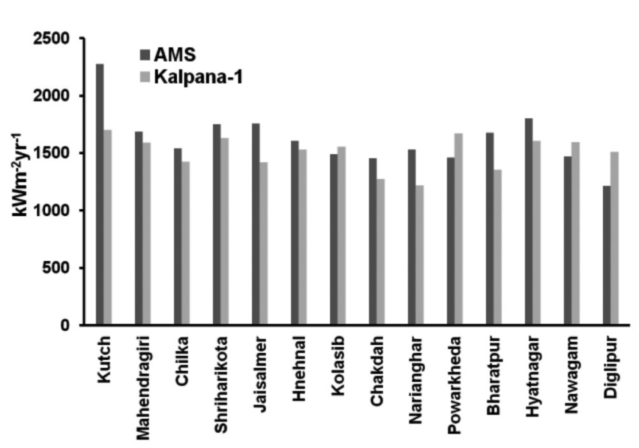

Figure 3. Comparison of yearly available solar energy recorded by AMS and spatial estimates derived from Kalpana-1.

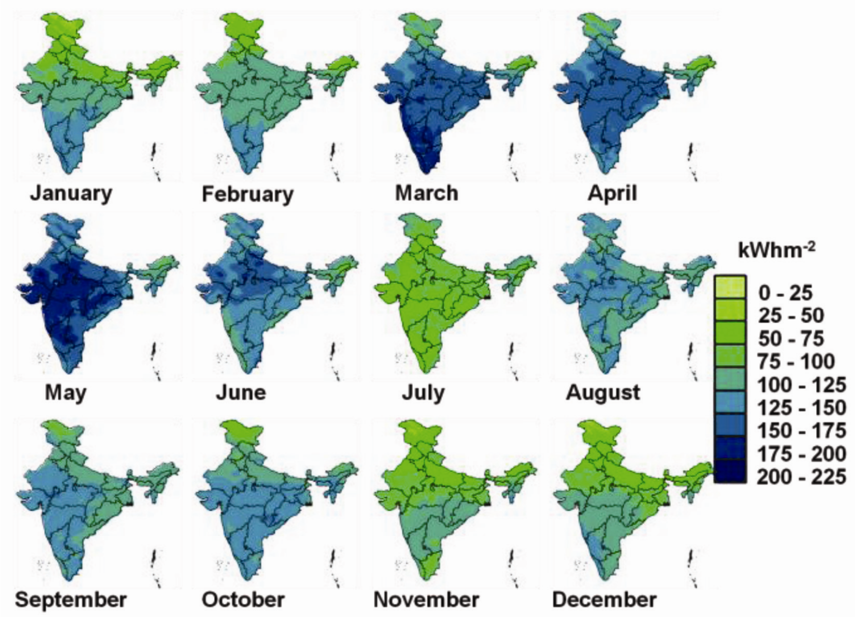

Figure 4. Three years (2009–2011) monthly mean solar energy over India.

The dissimilar foot-prints at which the energy is recorded and estimated (0.25 sq. km in the case of AMS and 64 sq. km for Kalpana-1) could be the major reason for this error. Moreover, the variability of cloud cover over 64 sq. km is more as compared to a point location[22]. The Kalpana-1 insolation product algorithm has an accuracy of 70–85% to detect clear and cloudy pixels. Moreover, it cannot easily detect thin cloud[12]. The annual variability of available solar energy over India is a result of persistent fog cover, clouds associated with western disturbances, the effect of intra-tropical convergence zone and the monsoon (south-west and north-east) cloud[13].

Monthly and annual solar energy over Indian landmass

Figure 4 shows the distribution of monthly solar energy averaged over three years (2009–2011). As summer approaches, the amount of solar energy reaching the surface increases during March to May. During monsoon months it is reduced due to cloudy conditions. In winter months, the foggy conditions in the Indo-Gangetic plains (25°N–32°N) reduce solar energy.

It is evident that during summer months more than 85% of the country receives solar energy above 175 kW h m^{-2} $month^{-1}$ with a peak (210 kW h m^{-2} $month^{-1}$) in May. The maximum solar energy is noticed in the western dry and central Indian plains (15°N–28°N). With the onset of south-west monsoon there is a remarkable decrease in solar energy towards the southern tip of India, where it reaches a minimum of 75 kW h m^{-2} and a maximum of 164 kW h m^{-2} within a month in the monsoon season. The reduction in solar energy continues till August. During October just after the withdrawal of south-west monsoon, a sudden rise in the solar energy is observed in all parts of the country, especially in central and western regions of India which receive solar energy up to 175 kW h m^{-2} $month^{-1}$. During winter months (November, December and January) the major part of the southern peninsular India receives solar energy above 100 kW h m^{-2} whereas northern India (parts of Punjab, Haryana, Uttar Pradesh, Bihar, Himachal Pradesh, Uttarakhand, Jammu & Kashmir, Assam and Arunachal Pradesh) receives solar energy less than 75 kW h m^{-2} $month^{-1}$ due to fog and cloudy conditions. During February, the received solar energy is up to 170 kW h m^{-2} on monthly basis over 80% of the country whereas western (Himachal Pradesh, Uttarakhand, Jammu & Kashmir) and eastern (Assam, Arunachal Pradesh) Himalayas continue to receive monthly solar energy below 75 kW h m^{-2}.

A prominent spatial pattern has emerged in the distribution of annual solar energy over Indian landmass, from the equator towards higher latitude. It is also observed that lower solar energy is available at higher altitudes such as in the Himalayan regions and some parts in north-eastern states of Assam and Arunachal Pradesh. Between the equator and the tropic of cancer the annual solar energy varies from 1500 to 2500 kW h m^{-2} wherein majority of Indian landmass receives solar energy above 1750 kW h m^{-2}. Except few pockets in Western and Central India, it shows a lower range from 1000 to 1500 kW h m^{-2} above the tropic of cancer. The year-to-year variation in the spatial distribution of annual solar energy for the three years, 2009–2011, is shown in Figure 5. The histogram of solar energy showed a high year-to-year variation. In 2009, it shows high frequency of pixels

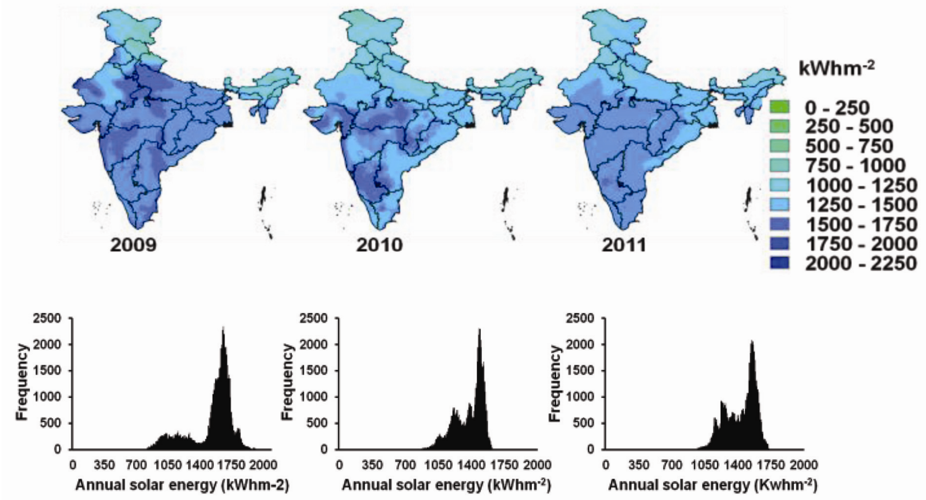

Figure 5. Spatial distribution of annual solar energy over Indian landmass.

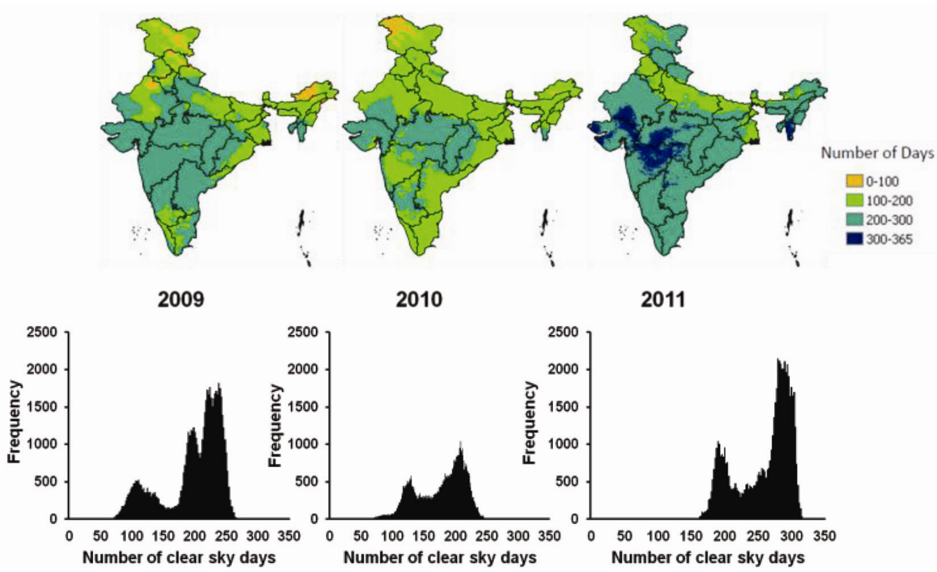

Figure 6. Year-to-year variability of spatial distribution of number of clear-sky days.

falling between 1500 and 1700 kW h m^{-2}. In 2010, the higher frequency of energy ranges from 1400 to 1600 kW h m^{-2} whereas in 2011, a little higher frequency in the 1100–1200 kW h m^{-2} range and maximum frequency in 1500–1750 kW h m^{-2} range are observed. The year 2009 being a drought year had less and infrequent cloud cover, leading to relatively high solar energy regime compared to normal monsoon years (2010 and 2011).

Annual clear-sky days

Figure 6 shows the spatial distribution of number of cloud and fog-free days in each of three years. The number of clear days varied from 200 to 300 in all the three years over the western and central India. Except 2010, this showed a slightly lower range (100–200 days) in those parts. In 2009 and 2011, almost 85% of the Indian landmass showed 200–300 clear-sky days.

In 2011, few pockets in Gujarat, Rajasthan, Maharashtra, Madhya Pradesh and Tripura showed more than 300 clear-sky days. The histogram shows a bimodal distribution for normal years (2010 and 2011). But a tri-modal trend is seen in the histogram of 2009. The frequency of 200–250 clear sky days was high (1000–2000) in the year 2009. In 2010, the frequencies of regional distribution of clear sky days in the classes 100–150 and 200–250 were comparatively low (500–1000) than those (1000–2400) in 2011. The overall frequency of regional distribution and number of clear-sky days were found to be low (100–200 days) over the Indo-Gangetic plain. This could be due to persistent fog and haze conditions during November, December and January in addition to influences by southwest monsoon clouds and weather disturbances. Consistent clear-sky days above 200 were observed over the western and central parts of India for all the three years.

Regional hot-spots of assured solar energy

The assured solar energy was computed using methodology as mentioned earlier for all the three years. The mean annual assured solar energy was estimated from three-year datasets. The assured annual solar energy is categorized into different zones such as very low (<1000 kW h m^{-2} yr^{-1}), low (1000–1500 kW h m^{-2} yr^{-1}), moderate (1500–2000 kW h m^{-2} yr^{-1}), high (2000–2500 kW h m^{-2} yr^{-1}) and very high (>2500 kW h m^{-2} yr^{-1}). The spatial distribution of these zones is shown in Figure 7. The zones with high to very high (2500–3500 kW h m^{-2} yr^{-1}) assured solar energy are identified as hot-spots. These fall in parts of western and central India including Chhattisgarh with promising pockets in Gujarat, Rajasthan, Madhya Pradesh, Karnataka and Tamil Nadu. The zones with lesser assured solar energy potential were seen over Indo-Gangetic plain where it varied from 1500 to 2500 kW h m^{-2} yr^{-1}. These zones were mainly affected by persistent cloud cover, fog and haze during January, February, July, November and December. In Western Himalayan range, the mountainous terrain receives low assured solar energy (1000–1500 kW h m^{-2} yr^{-1}) and the valley received relatively larger assured solar energy of 1500–2000 kW h m^{-2} yr^{-1}. In the north-eastern hill region, Mizoram and parts of Tripura receive higher assured solar energy to the tune of 1500–2500 kW h m^{-2} yr^{-1}.

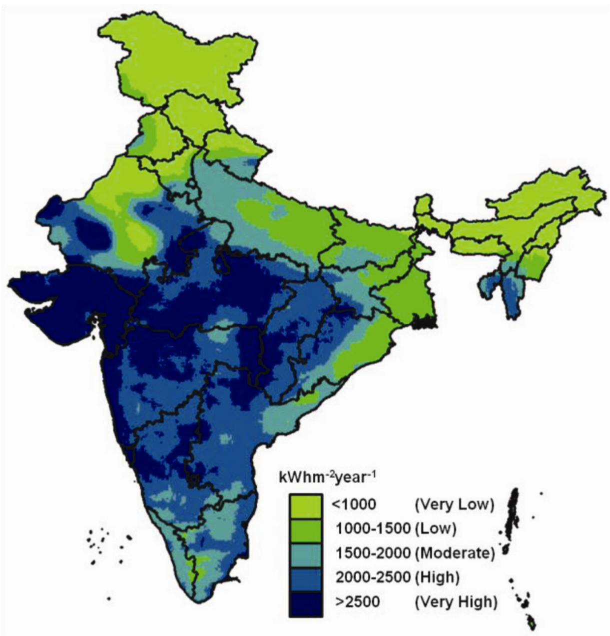

Figure 7. Hot-spots of assured solar energy exposure over India.

The total available assured solar energy was estimated over different land cover types in India. The wasteland, grassland and desert land approximately received 11.0×10^6 kW h of assured solar energy followed by the shrubs or bushes and savannah which received 1.72×10^6 kW h and 1.11×10^5 kW h respectively.

The share of (three-year, mean) solar energy over different land uses from the annual sum over Indian landmass is shown in Figure 8. Out of the total assured solar energy over Indian landmass, grasslands receive 39%, followed by desert (25%) land. The wasteland and shrub lands receive 21% and 14% of assured energy respectively. Though the solar hotspots in India were defined recently[8] by using coarser resolution (1° × 1°) SSE (Surface Meteorology and Solar Energy) data of NASA, the study lacked in estimation of assured solar energy potential over different land uses. The present assessment would facilitate to have decisions on site-selection for installation of new large scale solar-based power generation systems and also to compute roof-top solar energy potential in urban and rural India.

Conclusion

There is an immense need for the development of green energy technology to address the growing energy requirements of the country. Indian land mass receives one of the highest levels of solar energy in the world, which still remains untapped and underutilized. The present study helps in identifying solar hot-spot zones in India using high temporal resolution Indian geostationary satellite data. This information would be useful to the Ministry of New and Renewable Energy and other state agencies in selecting suitable sites for installing solar energy-based systems. The country receives annual assured global insolation up to 2500 kW h m^{-2} which could meet the escalating power demand of the country in a decentralized, efficient and sustainable manner. Moreover,

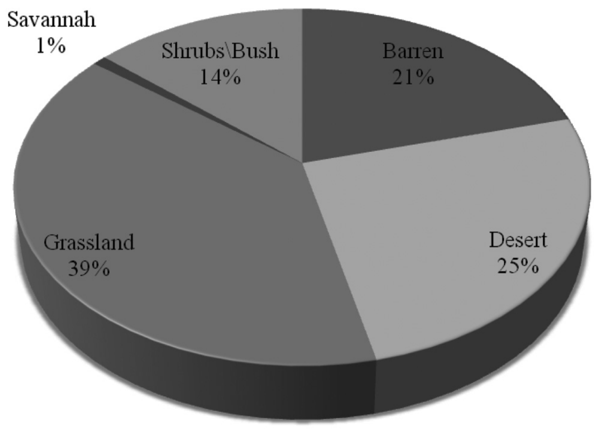

Figure 8. Share (per cent) of assured annual solar energy over different land cover types of Indian landmass.

sustainable development is the only way to prevent the climate change and use of renewable source of energy is a better alternative. Being a densely populated country with residential, agricultural and industrial priorities, availability of land for solar power plant is of serious concern in some parts. Therefore, roof-top solar power system plays important role. Given the three-dimensional building structures and associated varying shadows on neighbourhood depending on the sun position throughout a day, merging assured solar energy potential and 3D city-model from stereoscopic high-resolution imaging would be of immense help in the near future, especially in the perspective of new 'Smart City' plans of Government of India. The enhanced spatial resolution and observational capabilities of INSAT 3D at 1–4 km and GISAT at 56 m to 1.5 km in future would help in detailed mapping of solar energy. It is observed that the per capita electricity consumption is highest in Western India (approximately 1029.52 kW h yr^{-1}) followed by Southern and Northern regions[24]. Most of the identified solar hotspots are also in these regions, and hence solar power generation could reduce transmission losses due to its decentralized and distributed nature.

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