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Research paper

Satellite-based solar energy potential analysis for southern states of India

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ABSTRACT

Numerous efforts have been taken to exhibit scientific advancement in solar energy analysis. The current study attempts to demonstrate an approach for the solar resource variability analysis at a spatial scale in the southern states of India. This work utilized the satellite-derived modelled solar insolation datasets due to the global unavailability of in-situ meteorological data sets (especially solar radiation data). The visualization of solar insolation components including direct normal irradiance (DNI) and global horizontal irradiance (GHI) provided an opportunity to understand the energy configurations and its potential. An average DNI variation of 5.21 kWh/m² and GHI variation of 5.72 kWh/m² was observed. The ancillary analysis presented a detailed map for southern states of India at a grid resolution of 100 km x 100 km. Thereafter DNI and GHI distribution map for selected random points were estimated. The precise summary statistics stated that maximum and minimum values of DNI range from 3.72 kWh/m² to 5.59 kWh/m² with an average value of 5.18 kWh/m² and likewise maximum and minimum values of GHI ranges from 4.91 kWh/m² to 5.99 kWh/m² with an average value of 5.71 kWh/m². It was observed that the states of Karnataka and Tamil Nadu have a better prospect for further applications. The obtained results provided datasets for further analysis to comprehend the spatial distribution at a regional or national level. These will be very much useful for better energy planning for sound decision making.

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1. Introduction

The global crisis on conventional sources of energy has enforced each nation to deliberate on alternative energy resources (Ajayi et al., 2016). In recent years, energy demands for nations like India have amplified many folds due to speedy urbanization and industrial growth (Moonen et al., 2012). To cater to the rising energy demands India has set up an independent ministry for alternative energy resources (Thirumurthy et al., 2012). Solar energy and other clean energy are emerging and growing rapidly over the globe (Vinod and Singh, 2018). Solar energy can emit less carbon emission and also clean energy for our living environment (Kirmani, 2015). Greed has always been the best engine for the human race, but if it works. Solar energy has ample opportunity, which can be used in all the poor developing countries (Mishra, 2020). So researchers are expected to continue their work towards the improvement of all knowledge bases for future applications (Sharma, 2017). Several studies reports that there is an unbalanced distribution of the serious social and economic problems. It is critical to redistribute these resources density to

fully utilize the uninhabited areas (Sanjay et al., 2014). In order to achieve the desired goals, it requires ascertaining of renewable energy and water resources, for the sustainable development. The nation wants to improve its energy potential due to being fastest-growing economies in the world. Hence, the alternate source of energy like wind, solar, hydel etc. is an augmentation to energy potential and it will be very much helpful towards reducing environmental impacts (Hirano and Fujita, 2012). Therefore, it is required to identify the suitable locations for establishing the photovoltaic (PV) energy resources with respect to techno-economic and environmental feasibility (Rajput and Arora, 2017). Integration of Geographic Information System (GIS) tools along with the Remote Sensing technology (RS) with application of Multi-Criteria Decision Making (MCDM) technique plays an important role (Habib et al., 2020). Some attempts were made to utilize the Terra/ASTER imagery along with in-situ spatial data to examine the potential of multi-spectral remote sensing for urban planning to provide an important addition to conventional methods of monitoring the urban environment. Chrysoulakis (2002). A study on solar potential of Himachal Pradesh, which lies in western Himalayan Indian state were performed with the help of Artificial Neural Network (ANN) based global solar radiation

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(GSR) prediction model to assess solar potential of any location (Yadav and Chandel, 2015). Beyond these a spatio-temporal urban sprawl and land consumption patterns were explored in the Himalayan region with the help of multi-temporal satellite images to report urban growth on temporal scale for suitable urban planning methods (Diksha and Kumar, 2017).

There is requirement to map and analyse the solar energy generation potential of any region to stabilize the competing and upcoming energy demands. Earlier researches have explored and employed the geospatial technology to provide a worthy inputs to the energy sector (Kumar, 2019). Several under-developed countries including India is experiencing issues of energy deficit due to increase in energy requirements (Redweik et al., 2013), industrial expansion, increased growth rate of population, increasing cost of energy imports, inappropriate organization of energy resources, lack of better implementation energy policies (Inman et al., 2013). Initially, several nations were dependent on conventional energy resources, but to fuel up better future developments in the energy sector, several countries are trivially switching to non-conventional energy resources (Shi et al., 2015). Though, India despite having very large coal reserves, it is still facing acute problem of resources, which are consequently failing domestic coal production, retarding the rapid pace energy demand for economic growth (Meisen et al., 2006). The critical challenges faced by several sectors have created a quest to look for alternative energy resources for securing the proper pace towards development. During recent years, the world is standing at crossroads of the economic, social, and environmental requirements, where every nation disagrees with one another. It is very difficult to escape from the resultant scenarios raised due to socio-economic difficulties. Consequently, a new model was required to be presented, but it should not be based on casual socio-economic indicators. Subsequently, a new perspective was required. In this regard, research conducted by Lucia and Grisolia (2019) suggested three different indicators derived from an engineering approach of irreversibility. A brief study on the hotspots of the solar potential of India was also conducted by Ramachandra et al. (2011). This work identified the feasible solar hotspots over vast geographical extends to compensate with escalating energy demand in a decentralized, efficient, and sustainable manner. It was focused on the assessment with the variability of solar resource potential in India, which was derived from high-resolution satellite-derived insolation data. Solar energy generation potential estimation for Indian states comprising Gujarat, Andhra Pradesh, and Telangana was conducted by Harinarayana and Jaya Kashyap (2014). Research on urban solar energy potential with a statistical estimation method for suitable built rooftop was conducted by Karteris et al. (2013) to identify the actual potential of solar insolation for a complex urban framework. Yang et al. (2014) conducted precise research regarding the application of solar technologies builds up environments for solar-powered residential complexes. Irfan et al. (2020) have investigated for assessment of energy dynamics caused by biomass energy. Various researchers have supplemented the work to know about interlinkages among economic growth, energy consumption, and carbon emission for multi-country (Waheed et al., 2019). Some research reported regarding solar photovoltaic modelling and simulation as an optimal energy solution for upcoming energy demands (Vinod and Singh, 2018). Dondariya et al. (2018) conducted work related to solar rooftop solar PV performance simulation for Indian region. Work on performance analysis for rooftop PV system in the eastern part of India was conducted by Sharma and Goel (2017). The study to assess the availability factor of the PV power plant was conducted for investigating the availability of PV in the Revulapally, Mahbubnagar district of Telangana State, India by Kumar et al. (2018). An investigation to map the district-wise solar

power potential for concentrating solar power (CSP) and centralized solar photovoltaic (SPV) technology for India was attempted by Mahtta et al. (2014). Martín et al. (2010) and Polo et al. (2015) presented work related to mapping of the solar resources for concentrating solar power (CSP) and for grid-connected photovoltaic (PV) technology with the use of satellite-derived and GIS-based inputs. A study by Ramirez et al. (2015) presented an integrated spatial and energy planning as a powerful tool to meet the current renewable energy. These alternate energy resources have a better perspective to provide solutions for long-standing energy problems being faced (Perez et al., 2009). In the same context, the present tries to focus towards the analysis of previous approaches used study of energy-related projects with the usage of satellite remote sensing for solar energy assessment towards energy infrastructure planning (Jesch, 1980). Satellite remote sensing techniques have become an integral part of the spheres of our daily lives (Chenni, 2011).

Modern Indian cities are observing a unique pace of urban development catalyzed by the economic stimulus provided by a booming economy. Rapid urbanization often results in an inadequate expansion in different regions (Diksha and Kumar, 2017). There are various mechanisms, which are responsible for development and growth in different areas (Hirano and Fujita, 2012). This work tries to discuss the philosophical and methodological considerations for analytics (Tripathy and Kumar, 2019). Usually, solar energy sources are capable to facilitate the efficient energy services with almost zero-emission (Sharma and Harinarayana, 2017). As it is a well-known phenomenon that the solar insolation and atmospheric conditions vary across various locations with varying efficiency, so it has been a fascinating area of research for the study of solar insolation in terms of direct normal irradiance (DNI) with global horizontal irradiance (GHI), methodologies to analyse the DNI and GHI distribution, and techniques for spatial data analysis including processing for identification of potential regions.

The solar insolation is one significant parameter for solar energy research but the values of solar insolation are inaccessible for most of the regions due to the absence of in-situ solar insolation gauging instruments or meteorological stations. Modelling, simulation and analysis of the solar photovoltaic system is a vital part of the process before installation and commissioning of any PV system at any geographical location, which helps to understand the behaviour and characteristics in real climatic conditions of that particular location. Consequently, it is crucial to identify some alternate method for solar insolation analysis at any geographic region with several climatic variables.

Application of remote sensing-based technology for energy resource assessment (Santos et al., 2014). It described on a global scale, the latitudinal gradients of insolation occurs due to geometry of the earth and its rotation & revolution around the sun but at regional or local scales, it is being influenced by terrain (relief) as the major factor. Alrwashdeh (2018) discovered the study for computing solar radiation at the earth surface with the usage of meteorological and satellite data. A study on solar resource assessment using GIS & remote sensing techniques solar resource assessment using GIS & remote sensing techniques utilized remote sensing data to assess the solar energy potential was not a completely new idea (Adelaja et al., 2011). The procedure followed was based on the method used previously by some authors for calculating the PV potential in Europe and Africa but with some modifications in the model. Research on solar energy potential assessment using GIS was conducted (Ramachandra, 2007; Ramachandra et al., 2011) assessed the spatio-temporal availability of solar resources. GIS along with Remote Sensing (RS) was used for planning the resources on spatial and temporal scales introduced the requirement of applying spatial estimation approach for global solar radiation with geostatistics for

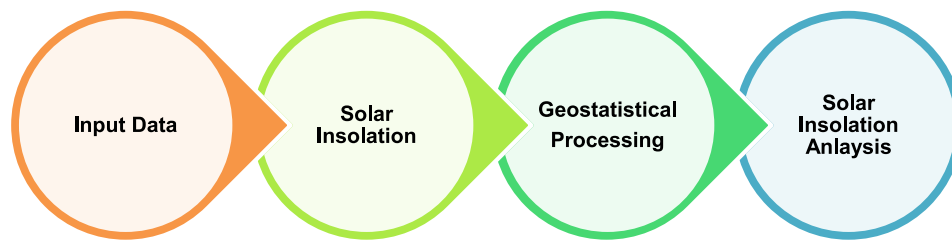


Fig. 1. Schematic workflow diagram.

continuous mapping of solar radiation on a spatial scale. This operational progress will focus on the application of energy for an urban sector with the help of urban remote sensing datasets. It is well-understood fact that unchecked urbanization has led to an escalation in electricity demands due to rapid depletion of fossil fuels. Although in the earlier studies, solar energy potential maps for India have been prepared based on information on solar irradiation, but detailed spatial variability analysis at the local or regional level have not been performed. To achieve these, traditional knowledge suggests us to study the spatial distribution of solar insolation with precise details. These will also aid to identify the sites with high energy potential. So, a detailed database for the spatial distribution of solar insolation was required to analyse the design, development & installation of solar systems at any geographic locations. Customarily, we used ground-based measurements for quantification and analysis of solar insolation but many of the time, it was difficult to have the datasets for every location.

Any projects based on solar insolation are location-sensitive and it has more geographical dependency due to the scattered nature of solar insolation. Also, a thorough understanding of spatial and temporal behaviour of global solar insolation on the surface of the earth will of great importance for the design and development of solar dependent projects. There was a very limited number of ground measurements with inaccurate information for analysis of spatial variability of solar insolation. Incidentally, a remote sensing-based solar energy analysis database will serve as potential tools for numerous applications. So, the current analysis presented a detailed map for southern states of India at a grid resolution of $100 \text{ km} \times 100 \text{ km}$. The spatial distribution analysis of annual direct normal irradiance and global horizontal irradiance datasets were performed with archive data for the year 2013. These particular set of data was used due to scarcity of ground-truth data for the complete region. These results will augment towards an enhanced understanding of the spatial complexity of solar energy potential at a local or regional scale, where it is required to consider the geographical variability considering policy-making requirements. These will also supplement towards knowledge base for energy shortages in the forthcoming smart cities in these regions. The energy generation along with reduced carbon emissions at potential solar hotspots regions are required to be understood for evaluating the prospects of achieving the long-term energy targets considering the techno-economic and organizational aspects of the available technologies. The work expects to analyse and assess the solar energy potential for the selected regions of the southern part of India with the application of remote sensing technique. This study proposes a technique to diagnose the solar energy potential of the southern part of India. The objective of the work was to understand the spatial distribution of solar insolation for a detailed study of the accessible amount of solar insolation for future energy harvest and these can be utilized further for forthcoming energy demands of the energy sector.

2. Material and methods

Analysing potential sites at a selected region of southern India will help in identifying the areas suitable for tapping solar energy. Analysing the amount of solar energy reaching the earth's surface is essential for solar potential assessment. Solar radiation data based on satellites provide higher spatial and temporal coverage of regions compared to surface-based measurements. Solar potential of the selected Indian region has been attempted with satellite-based direct normal incidence and global horizontal irradiance datasets for complex terrains. Solar maps can be generated further to represent regional and temporal resource availability within the study area.

The key perspective of the work intends to analyse solar insolation datasets acquired from various sources to serve the requirements of various user groups. A comprehensive workflow for the approach employed in this work has been presented in Fig. 1. The work includes two components, where the first part intends to acquire the available open archive solar insolation datasets and later part includes geostatistical processing of the acquired datasets for precise spatial variation analysis. These main stages encapsulate the tasks taken to (1) obtain and preprocess the required dataset, (2) to estimate annual solar radiation, (3) to perform geostatistical processing on the acquired datasets, (4) to analyse statistically processed datasets for identification of suitable regions from random points for energy harvest.

2.1. Study area

The current work was intended to be carried out at the southern part of India as a study area. The study tries to include the major states of southern India including Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, and Telangana (*erstwhile Andhra Pradesh*), and also the Union Territory Pondicherry.

But as Union Territory Pondicherry has a very little land cover, therefore it was not considered for the current study towards further analysis. Therefore only regions of Telangana, Andhra Pradesh, Kerala, Karnataka, and Tamil Nadu states were considered for the study. Fig. 2 explains the location of different states. These selected states were chosen due to a reason that these exhibits characteristics of almost all natural topography, flora-fauna, and climate conditions, and these also offer a wide range of diverse characteristics, which are generally desired for solar energy analysis. The mentioned pilot study area covers varied topography with varying elevation ranging in the states of Andhra Pradesh, Karnataka, and Tamil Nadu.

2.2. Datasets used for the study

The present work utilized the sample points generated with open-source datasets, reference imagery from Google Earth, and meteorological parameters datasets like *direct normal incidence*, *global horizontal irradiance*, *wind datasets*, *temperature*, *relative humidity*, *atmospheric pressure*, and *rainfall*. The shapefiles of south

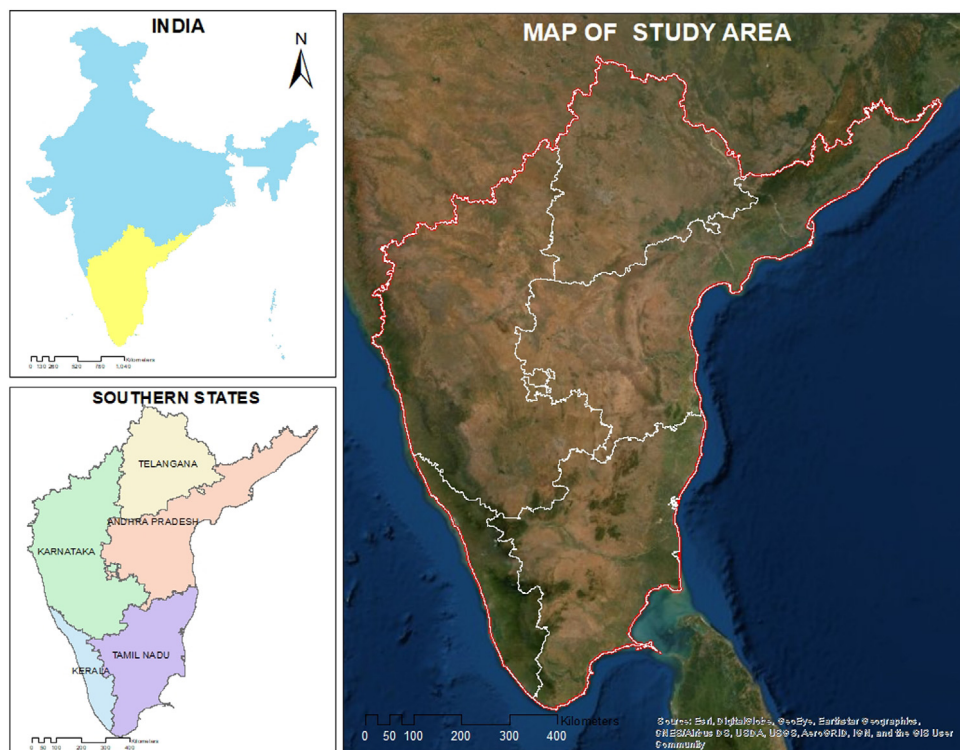


Fig. 2. Location of the study area.

Indian state were assimilated as the first input to the ArcGIS interface. It is a pre-understood phenomenon that the incoming solar radiation at any geographical on the terrestrial surface is dependent on factors like surrounding topography, albedo and forest canopy. Moreover, variability due to elevation, surface orientation arising due to slope and aspect and the shadow cast resulting due to topographic features (*creating a strong local gradient for solar insolation including direct normal incidence and global horizontal irradiance*) are some other factors, which are being affected. Generally, the traditional methods for assessing solar insolation any location (a) in-situ ground measurements through instruments mounted on the ground platform, (b) deriving required parameters from weather satellites, and (c) numerical modelling of several weather prediction models.

However, the present work accomplished with annual solar insolation data generated at a grid of $10 \text{ km} \times 10 \text{ km}$ from weather satellite (METEOSAT) observation datasets. These raw data sets were acquired from open-source data archives database maintained with the National Renewable Energy Laboratory (NREL-<https://www.nrel.gov/>). The 15 years of the hourly datasets for the period of 2000 to 2014 are freely available through a bilateral partnership between the United States and India, These data quite resourceful for accelerating the development of solar energy projects in both the nations.

2.3. Software's/tools used

- ESRI ArcGIS 10.x tool was used for geodatabase creation and geo-data analysis.
- ERDAS 201x was used for preliminary to advanced image processing.

2.4. Methodology for analysis

Researchers in remote sensing technology simultaneously use a blend of observation and theory for understanding the impact

of the problem. Traditionally, it included identification of the appropriate approach for precise geo-data analysis. The analytical method provided a method for enhanced geo-data analysis with the help of several mathematical and statistical models or algorithms to provide better results. Thus, this research work was augmented with the analytical and observational framework of data analysis. The brief methodology for remote sensing-based solar energy potential analysis framework is being summarized in Fig. 3.

It presents a sequence of steps for solar energy potential analysis to comprehend the spatial distribution of solar insolation all over the study area. The spatial distribution of annual solar insolation was spatially interpolated with the best accessible geostatistical method. The acquired datasets of solar insolation were interpolated with the Radial basis function (RBF) method for the study area. Geostatistical interpolation method exclusively regularized spline function for predicting solar insolation values at unknown locations. Various input parameters along with shapefiles were used to create a base geodatabase for further analysis Thereafter significant boundaries at the state level were earmarked to analyse the solar insolation's values. This precise analysis at the state level exhibited thorough information about the availability of solar radiation for selected regions of southern India.

2.5. Methodology for geostatistical analysis of solar insolation with radial basis functions (RBF)

An annual average of the solar insolation was computed through geostatistical interpolation techniques to create raster surface to exhibit the spatial distribution of solar insolation over the study area. These were was visualized as a layer to provide a visual look of the distribution. Usually, inverse distance weighting (IDW) method of interpolation is being applied for computing values for unknown locations of the raster surface (Şentürk and Çepni, 2018). But, in this method of IDW interpolation (Ecology,

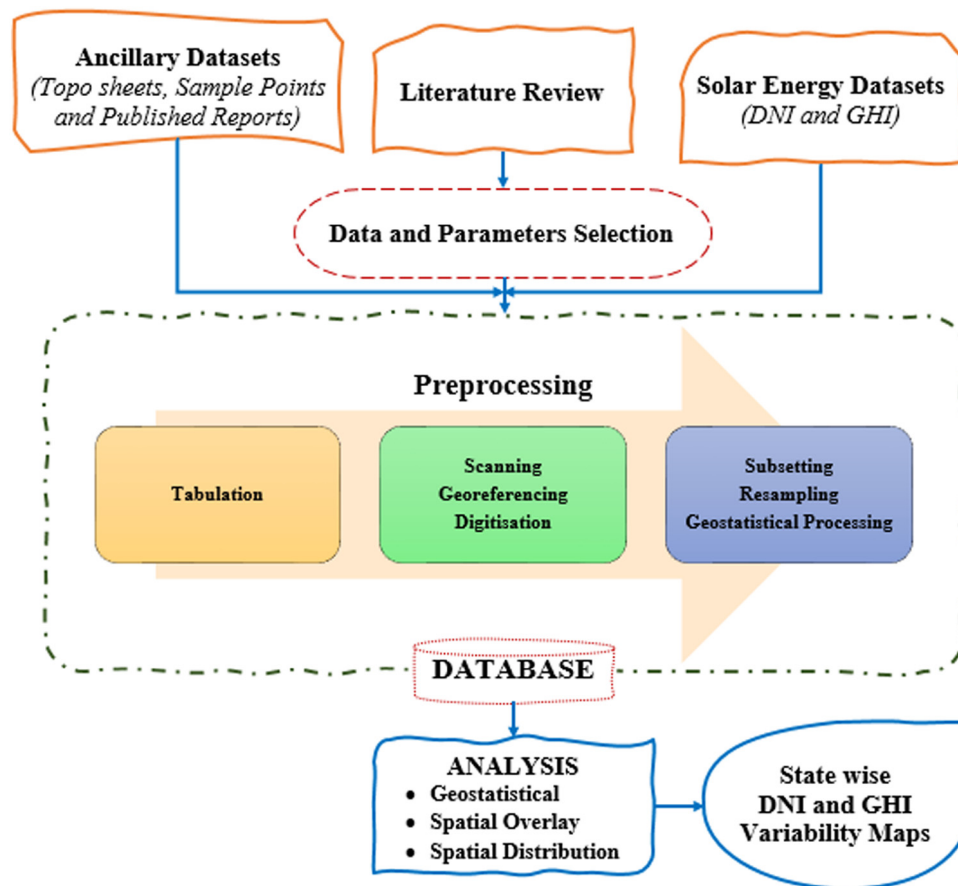


Fig. 3. Brief methodology framework for solar energy potential analysis.

2004), weights are proportional to the inverse distance value between sampled and un-sampled location. Here proportionality varies with the power to which the distance is raised and is referred to as the distance coefficient. But the current work was tried with radial basis function (RBF) interpolation for generating the smoother raster surface, as this interpolation method works on approximation theory for constructing high-order accurate interpolants from unstructured data with high-dimensional spaces possibilities. It is often spectrally accurate and stable for large numbers of nodes even in high dimensions. It uses one of five basis functions to create an exact interpolation surface through the processing of each measured sample value. The smooth search neighbourhood is available in the inverse multi-quadratic function, as this function operates with higher parameter value for generating smoother surface.

3. Results and analysis

3.1. Solar insolation with radial basis functions (RBF)

Raster surfaces generated through RBFs interpolation were used to visualize the spatial distribution of solar insolation at regional or local level analysis. The accessibility of solar energy resource at several geographical locations will advance our understanding of emerging urban energy requirements for analysis of the solar insolation at any gridded location.

3.2. Analysis of solar insolation for gridded locations

The area enclosed by southern states of India (including Tamil Nadu, Pondicherry (Union Territories), Karnataka, Andhra Pradesh,

Telangana and Kerala respectively) were gridded into $100k \times 100k$ m to analyse the spatial distribution of DNI & GHI over the year as per the schematic shown in Figs. 4 and 5. Fig. 4 exhibits the annual variations of direct normal irradiance (DNI) at each gridded location and similarly Fig. 5 illustrates the annual variations of global horizontal irradiance (GHI) at each gridded location. The variation of DNI at gridded location ranges with a low of 3.71 kWh/m^2 to a high of 5.79 kWh/m^2 likewise the annual variations of GHI ranges from 6.12 kWh/m^2 to 4.82 kWh/m^2 . Also, it can be observed that there is a moderate variation of solar insolation over the region. The DNI variations map exhibits that there were high amount of DNI values at central, north, and south-east portion (i.e. at grid numbers 2, 6, 31, 33, 44, 55, 39–42, 46–49, 54–57), there were lower DNI values at south-west region (i.e. covering grid numbers 1, 4, 8, 13, 18, 25, 60–62, 70–72 and similarly eastern part including grid numbers 5, 10, 12, 16, 22, 29, 30, 34, 37, 43, 44, 50–52 displays moderate DNI values (as shown in Fig. 4).

Fig. 5 exhibited that there a availability of the higher solar GHI values on an annual basis at the central and south-east part (i.e. at grid numbers 2, 6, 11, 17, 14, 15, 20, 21, 26, 27, 28, 33–35, 39, 40–42, 46–49, 54–57). Similarly, the regions in south-west and north including grid numbers 1, 4, 8, 9, 13, 18, 25, 85, 86 have relatively lower solar GHI values. Eastern region encompassing grid numbers 52, 60–62, 69–73, 76, 77, 80, 81, 84, 88, 89 indicates a fairly good GHI values. Moreover, Fig. 6 shows the annual trends of spatial variations for GHI and DNI. It can be observed that DNI has an average variation of 5.21 kWh/m^2 along with an average variation of GHI as 5.72 kWh/m^2 .

From above-illustrated attempt, it can be narrated that a remote sensing-based approach can serve as a vital tool for a

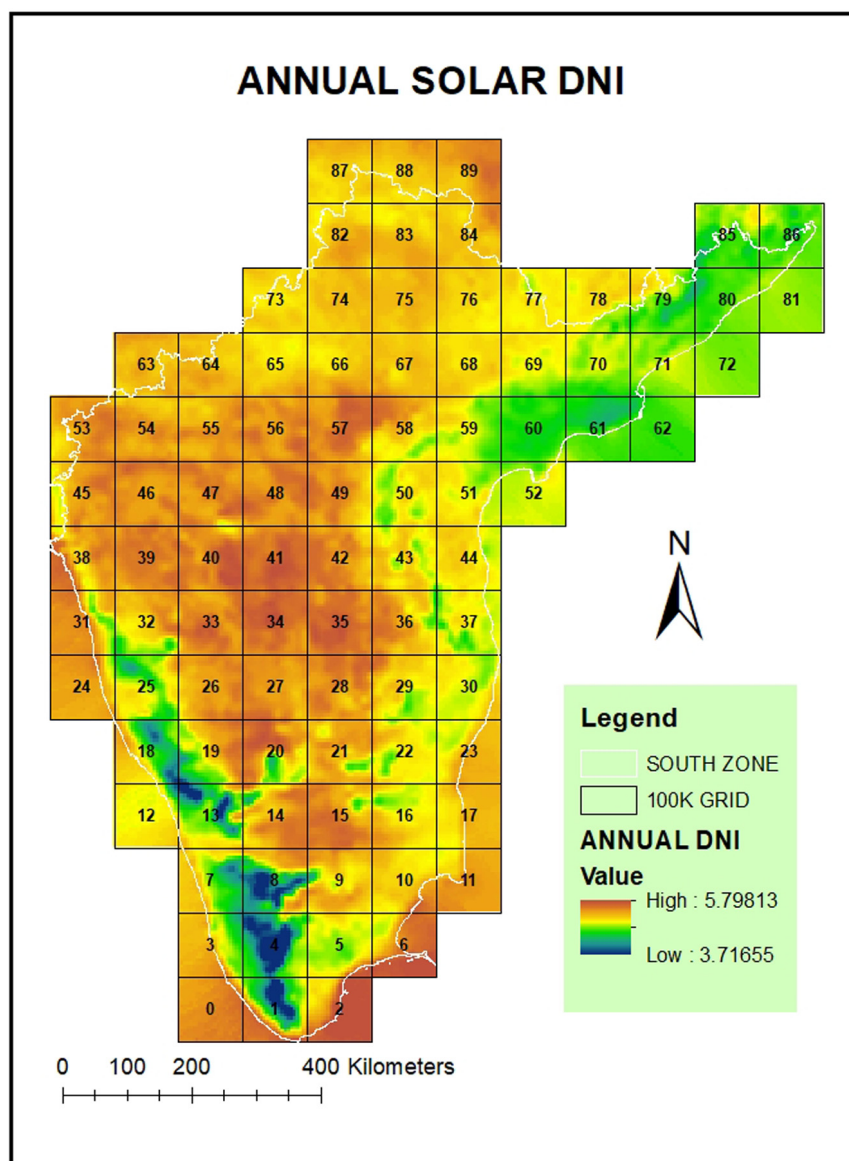


Fig. 4. Annual variations of direct normal irradiance (DNI) at each grid location.

better understanding of available solar energy potential at any geographical location for detailed analysis. Subsequently, these comprehensively analysed results can be useful in mitigating future energy requirements from different sectors.

3.3. Variation of solar insolation over selected southern state of India

As stated in the earlier sections, the current segment analyses the variation of solar insolation over selected southern state of India with the application remote sensing-based approach. In this context, a strategic approach has been attempted to analyse the regional or local spatial variation of solar insolation in terms of DNI and GHI to understand the energy potential for optimum utilization. In this regard, the present study tries to analyse the spatial distribution of solar insolation variations in terms of DNI and GHI for the desired analysis. As shown in Fig. 3, only states of Telangana, Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu were considered for this study.

(a) Variation of solar insolation in Telangana state

The state of Telangana is positioned in the Northern region of the selected study location. It consists of the various soil types

comprising chalks, red sandy soils, dub bass, deep red loamy soils, and very deep black cotton soils, and these are capable to facilitate plantation of mangoes, oranges and flowers in the said region. This state has a semi-arid area with a mostly hot and dry climate. Summer season commences from March and shows a peak in May with an average high-temperature range of 42 °C (108 °F). The monsoon arrives in June and it lasts until September month with about precipitation of 755 mm (29.7 in.). A dry, mild winter flinches in late November month and it persists until early February month with a slight humidity beside average temperatures within the range of 22–23 °C (72–73 °F).

The said area was gridded with 100 km x 100 km (as shown in Fig. 7) to analyse the variability spatial DNI & GHI across the state. Fig. 7 exhibits the annual variations of DNI and at each gridded location. It exhibits an annual variation of DNI ranges within 4.83 kWh/m² to 5.60 kWh/m² and GHI ranges from 5.44 kWh/m² to 5.99 kWh/m². It can be observed that there is a reasonable variation of solar insolation over the region. The DNI variations as shown in Fig. 8 exhibited that there was a high amount of GHI at grid numbers 0, 1, 2, GHI values at grid numbers 8, 13, 16, 18 have lower values and correspondingly grid numbers 7,

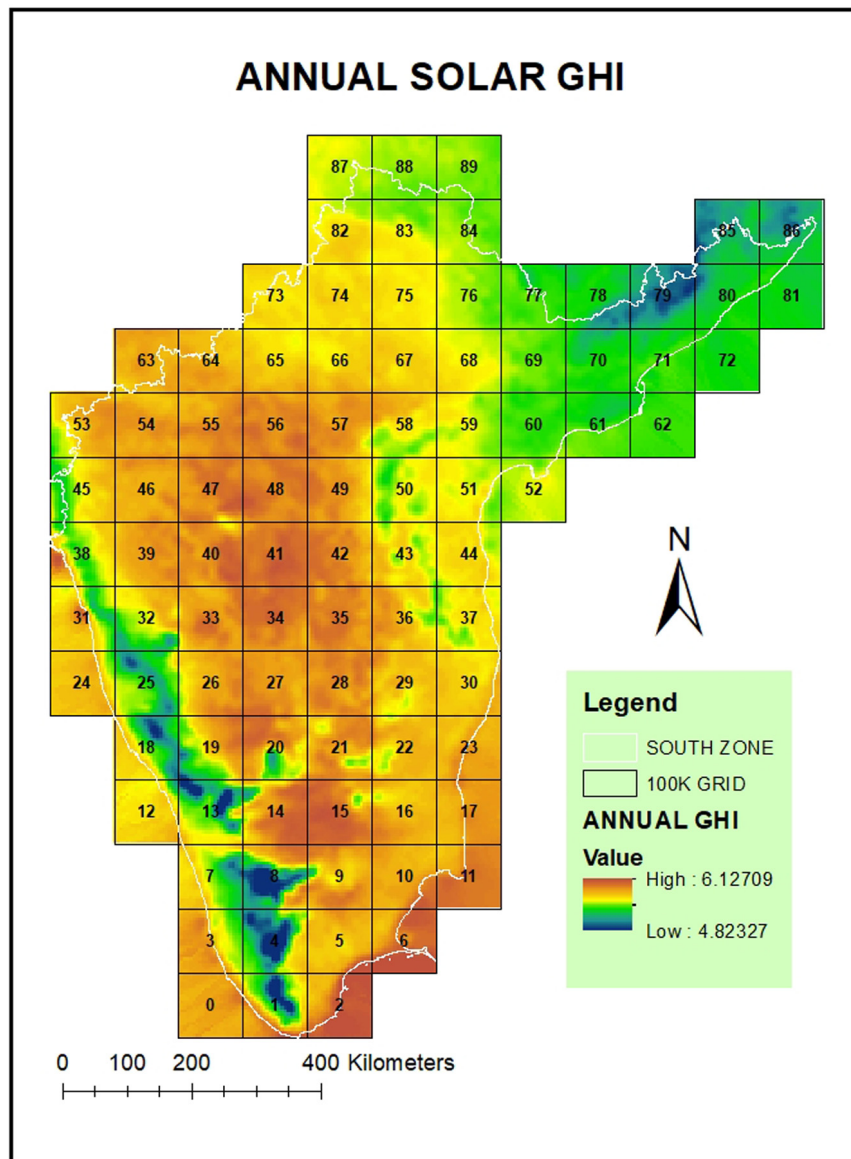


Fig. 5. Annual variations of global horizontal irradiance (GHI) at each grid location.

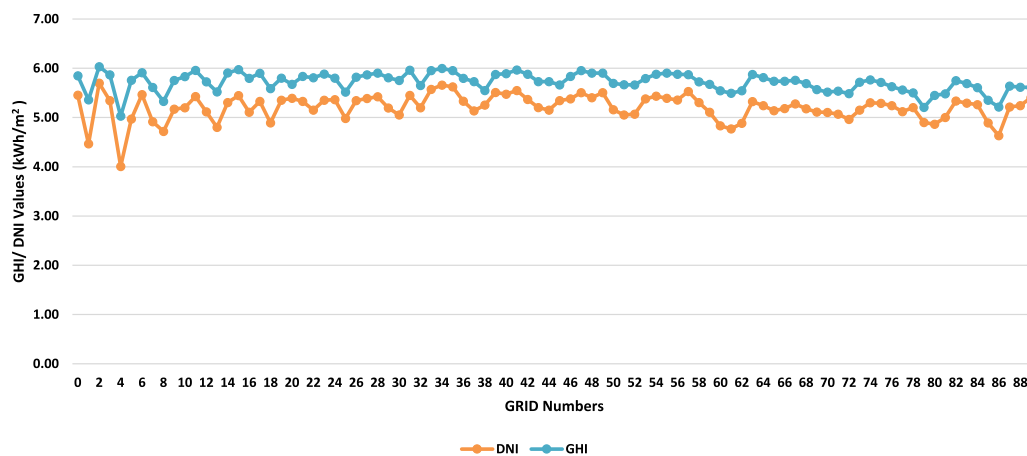


Fig. 6. Annual trends of direct normal irradiance (DNI) along with global horizontal irradiance (GHI).

11 displays moderate GHI values. Grid numbers 0, 1, 2 as shown in Fig. 7 exhibited the higher solar DNI values on an annual basis.

Similarly, the other grid numbers including 8, 13 were found to have relatively lower solar DNI values. Grid numbers 14, 15 in

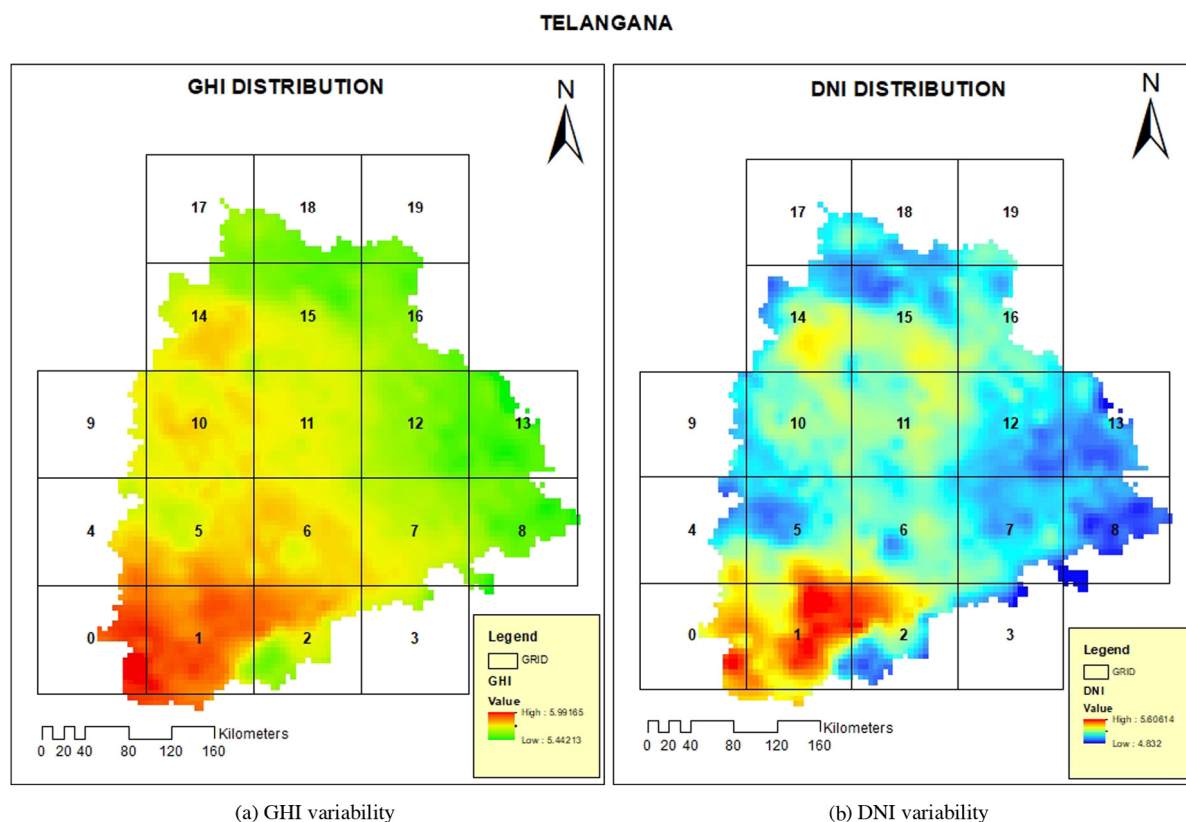


Fig. 7. Solar insolation variability in Telangana State.

Fig. 7 signifies a fairly good. Apart from these grid number 2 shows the dual behaviour with partially high and low GHI & DNI values, which infers that some portion of the grid has ambient amount partial solar insolation.

(b) Variation of solar insolation Andhra Pradesh State

Geographically, Andhra Pradesh is full of multi-dimensional topography ranging from the seashores of Bay of Bengal assisting varied ecosystems, the rich variety of flora and fauna to the hills of the Eastern Ghats and Nallamala Hills. The Eastern Ghats act as a major splitting line in the state's geography. The plains of the Eastern Ghats form the Eastern coastal plains, which is mostly comprised of the delta regions being formed by the Godavari, Krishna, and Penna rivers. Lambasingi (or Lammasingi). A village in the Visakhapatnam district of Chintapalli Mandal is situated at an elevation of 1000 m above sea level and it is the only place in South India, which has snowfall and is also nicknamed as Kashmir of Andhra Pradesh. The forest in the state of Andhra is mostly divided into four major biotic provinces as Deccan Plateau, Central Plateau, Eastern Highland, and East Coastal Plains. Depending on the geographical region, the state of Andhra Pradesh has a considerably varying climate with Monsoons as a major player in influencing the climate of the state. The summer season lasts from March to June with the season for tropical rains from July to September. During these months only, the state gets heavy rainfall from the southwest monsoon. Almost one-third of the total rainfall in the state occurs due to the northeast monsoon. October and November observe low-pressure systems and tropical cyclones forms in the Bay of Bengal along with the northeast monsoon bring rains to the southern and coastal regions of the state. Winter seasons of the state include the months of November, December, January, and February. But due to longer coastal belt in the state, winters are not very cold. Generally, winter temperature ranges from 12 °C to 30 °C. The

summer temperatures are generally higher than the rest of the state along the coastal plain, with a temperature range of 20 °C and 41 °C (Harinarayana and Jaya Kashyap, 2014).

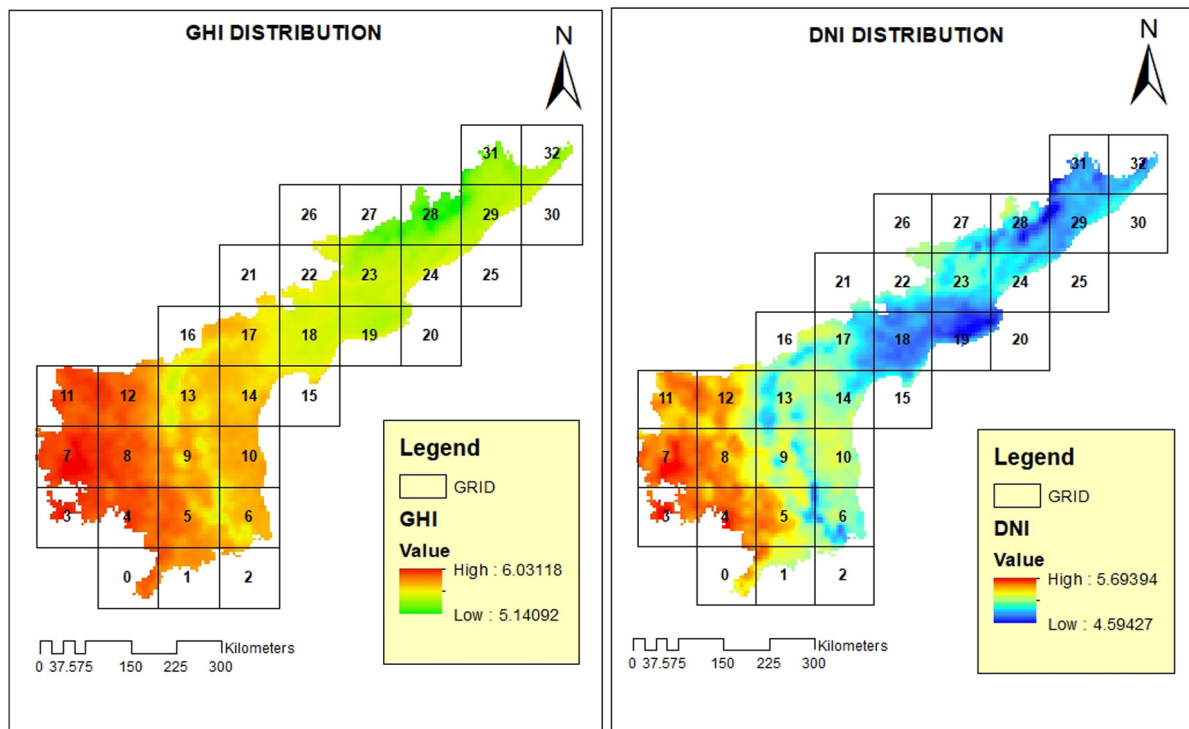
The mentioned area is shown in Fig. 8 with 100 km × 100 km grid analyses the spatial variability distribution of DNI and GHI across the region. Fig. 8 exhibits the annual variations of DNI and GHI at each gridded location. It exhibits an annual variation of DNI ranges within 4.59 kWh/m² to 5.69 kWh/m² and GHI ranges from 5.14 kWh/m² to 6.03 kWh/m². It can be observed that there is an adequate variation of solar insolation over the region. The DNI variations as shown in Fig. 8 exhibits that there was a high amount of DNI at grid numbers 3, 4, 5, 7, 8, 11, 12, DNI values at grid numbers 18, 19, 28, 29, 31, 32 have lower values and similarly grid numbers 6, 10, 14 displays moderate DNI values. Grid numbers 4, 5, 8, 11, 12, 15 as shown in Fig. 8 exhibited the higher solar GHI values on an annual basis. Similarly, the other grid numbers including 28, 29, 31, 32 were found to have relatively lower solar GHI values. Grid numbers 18 in Fig. 8 shows fairly moderate GHI values.

(c) Variation of solar insolation in Karnataka State

The state of Karnataka is located along in the south-western expanse of India containing three principal geographical zones of the coastal region of Karavali, the hilly Malenadu region covering of the Western Ghats and the Bayaluseeme region encompassing the plains of the Deccan plateau. Meteorologically, the state is separated into three zones namely coastal, north interior and south interior, thus it is being influenced by four seasons. The winter season consists of January and February is followed by the summer season during March and May, the monsoon season in the middle of June and September and the post-monsoon season during October till December (Kumar, 2019).

The complete area was gridded with grids of 100 km x 100 km (as shown in Fig. 9) to analyse the variability of the spatial

ANDHRA PRADESH

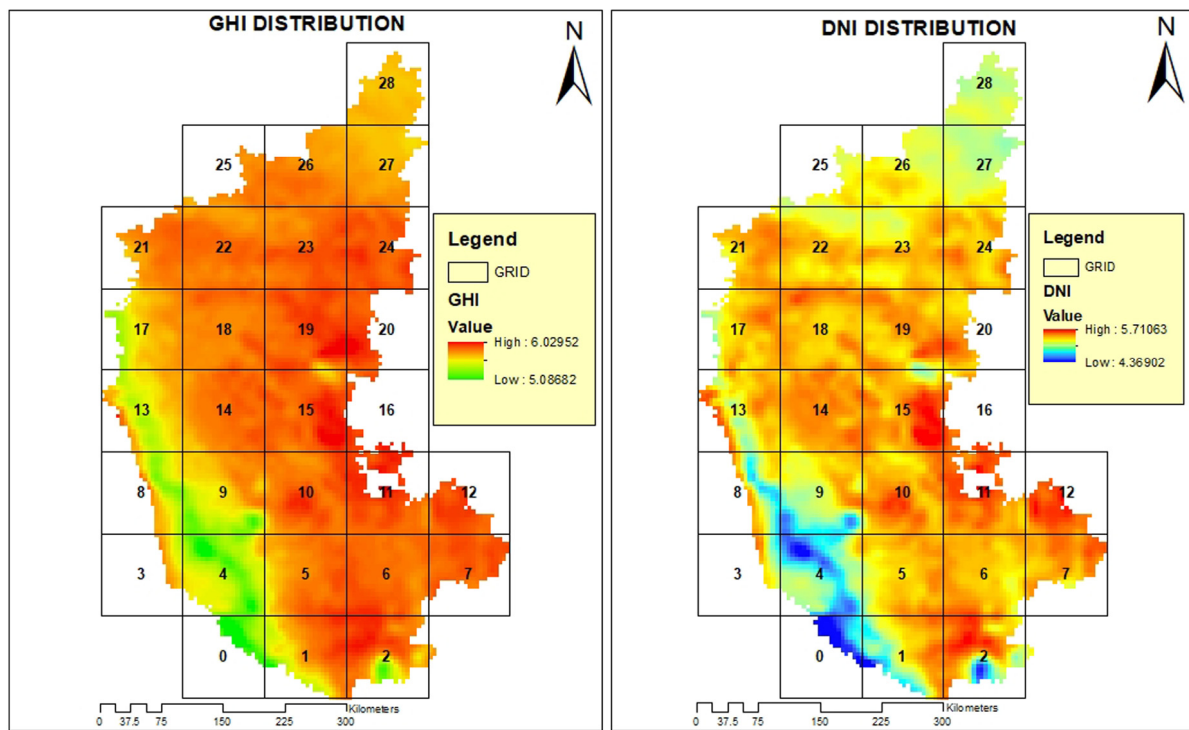


(a) GHI variability

(b) DNI variability

Fig. 8. Solar insolation variability in Andhra Pradesh State.

KARNATAKA



(a) GHI variability

(b) DNI variability

Fig. 9. Solar insolation variability in Karnataka State.

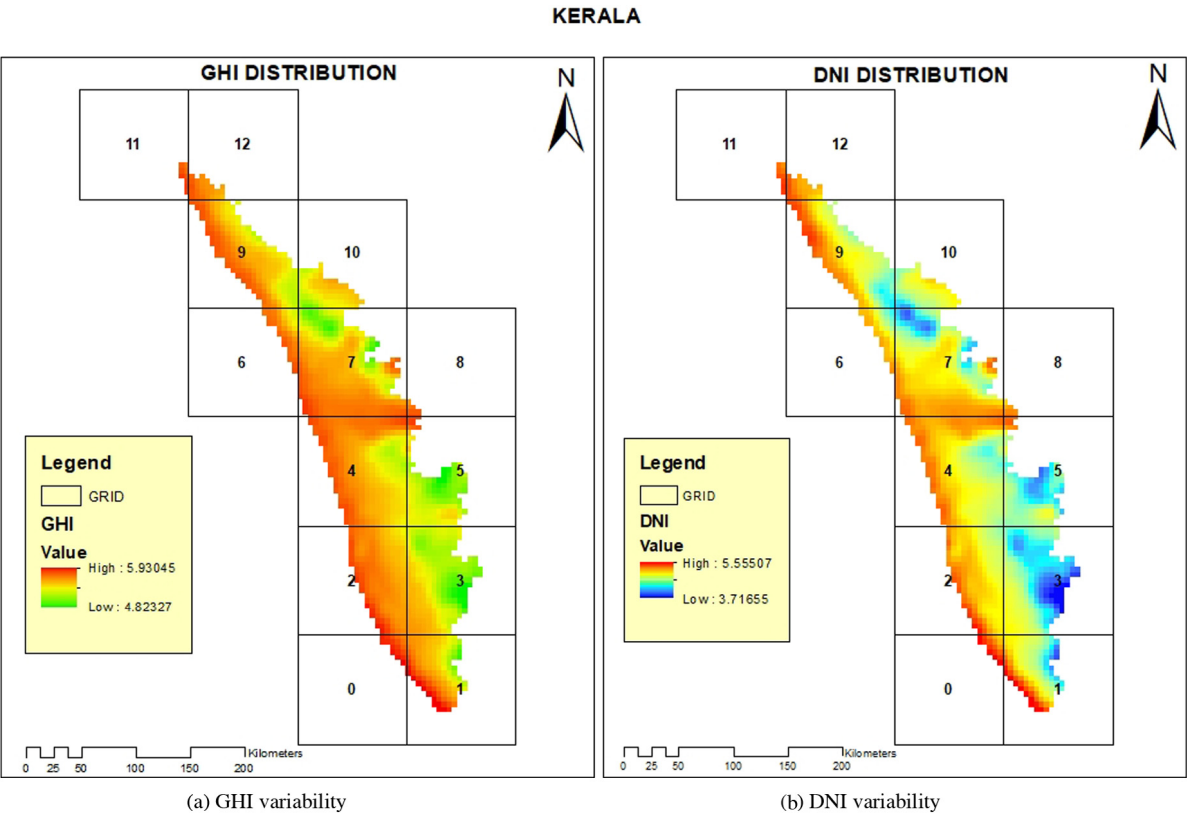


Fig. 10. Solar insolation variability in Kerala State.

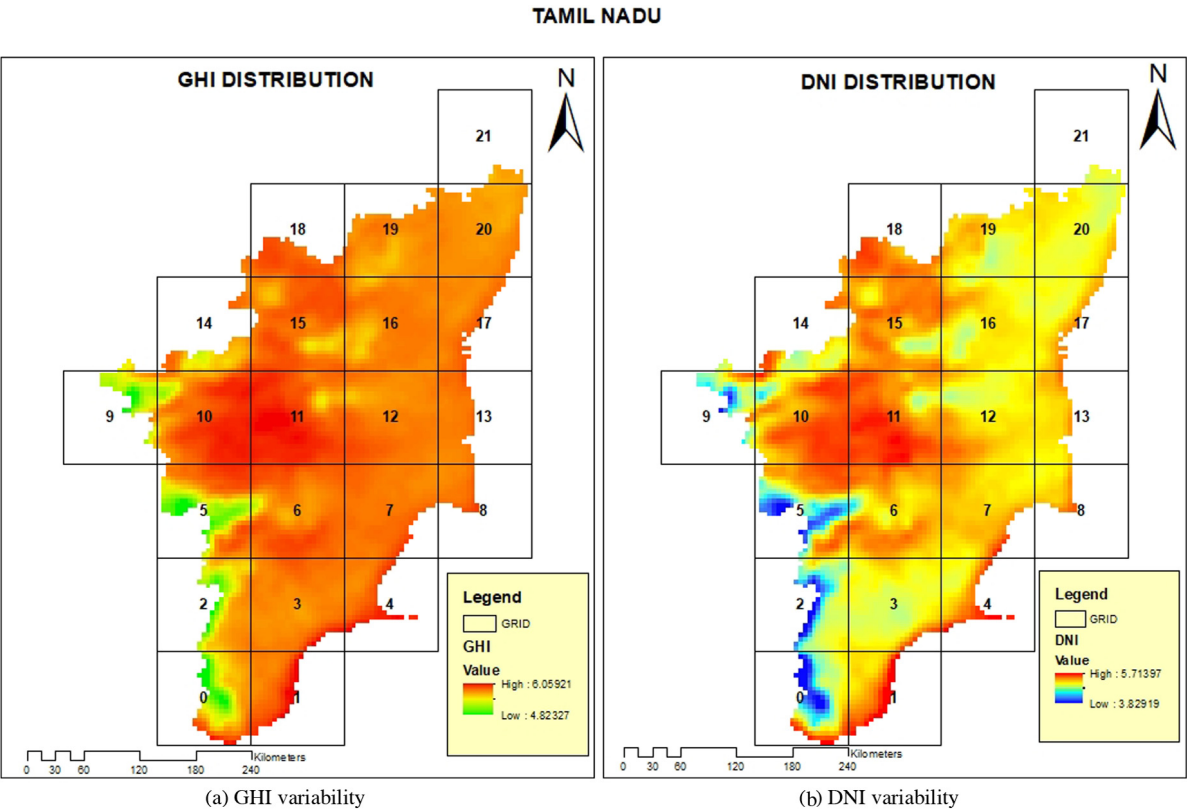


Fig. 11. Solar insolation variability in Tamil Nadu State.

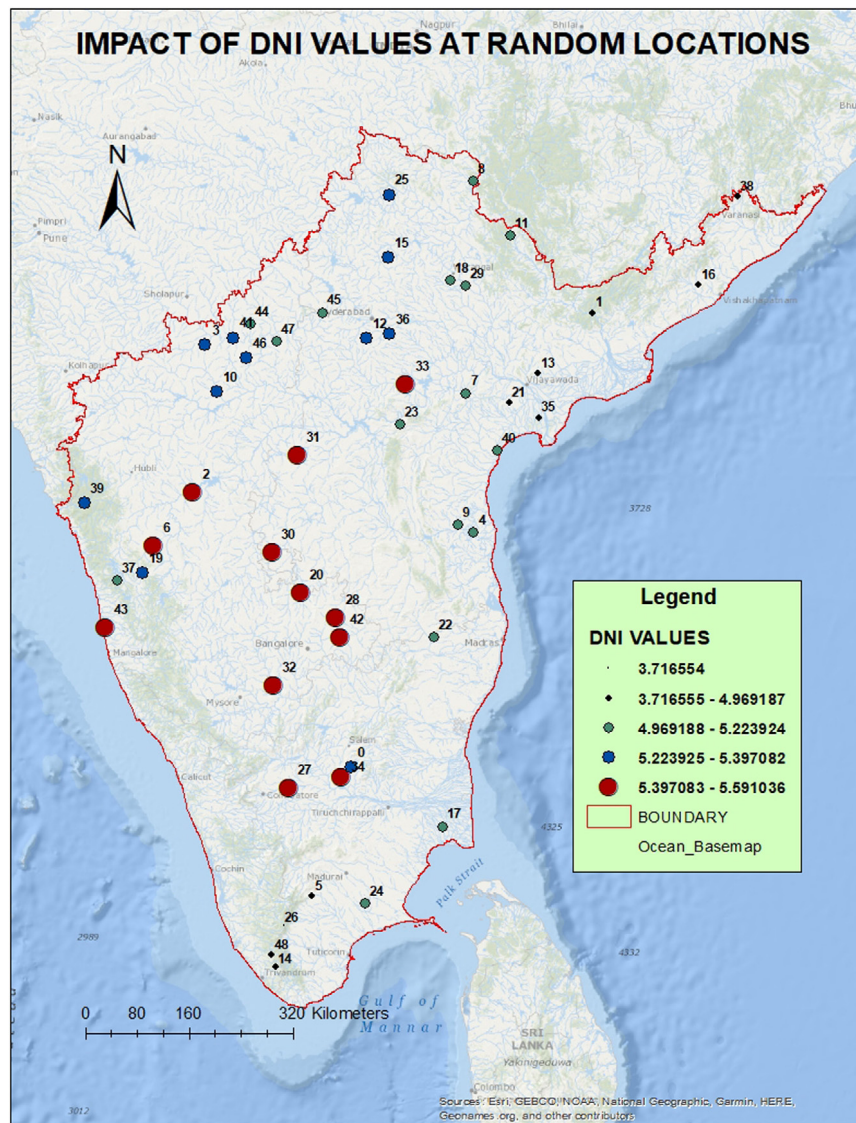


Fig. 12. Location of random points (to be used for variability analysis) along with intensity of DNI values.

distribution of DNI and GHI through the region. Fig. 9 exhibits the annual variations of DNI and GHI for each of the gridded location. It exhibits an annual variation of DNI fluctuating from 4.36 kWh/m^2 to 5.71 kWh/m^2 and GHI ranges from 5.08 kWh/m^2 to 6.02 kWh/m^2 . It can be observed that there is a moderate variation of solar insolation over the region. The DNI variations as shown in Fig. 10 exhibits that there was a high amount of DNI at grid numbers 2, 7, 10, 11, 12, 14, 15, 18, 19, 22. DNI values at grid numbers 0, 4, 9 have lower values and similarly, grid numbers 25, 26, 27, 28 displays moderate DNI values. Grid numbers 1, 2, 5, 6, 7, 10, 11, 12, 14, 15, 18, 19, 21, 22, 23, 24, 26 as shown in Fig. 9 exhibited the higher solar GHI values on an annual basis. Similarly, the other grid numbers including 0, 4, 13 were found to have relatively lower solar GHI values. Grid numbers 27, 28 in Fig. 9 indicates a fairly good value of GHI.

(d) Variation of solar insolation in Kerala State

The state of Kerala is lodged between the Western Ghats and the Lakshadweep Sea. The state is mostly influenced by the humid equatorial–tropical climate. Physically, the state can be divided into three climatically distinct regions including the eastern highlands; rolling hills, and the western lowlands; rugged and cool mountainous terrain, the central midlands; coastal plains.

The complete area was sub-divided into a grid of $100 \text{ km} \times 100 \text{ km}$ (as shown in Fig. 10) to analyse the variability in the spatial distribution of DNI and GHI through the region. Fig. 10 exhibits the annual variations of DNI and GHI for each gridded location. It exhibits an annual variation of DNI ranges within 3.71 kWh/m^2 to 5.55 kWh/m^2 and GHI ranges from 4.82 kWh/m^2 to 5.93 kWh/m^2 . It can be observed that there is enough variation of solar insolation over the region. The DNI variations as shown in Fig. 11 exhibits that there was a high amount of DNI at grid numbers 1, 2, 4, 7, 9. DNI values at grid numbers 3, 5 have lower values and similarly, there is no grid with moderate DNI values. Grid numbers 1, 2, 4, 7, 9 as shown in Fig. 10 exhibited the higher solar GHI values on an annual basis. Similarly, the other grid numbers including 3, 5 were found to have relatively lower solar GHI values. There were no grids in Fig. 10 with moderate solar insolation values.

(e) Variation of solar insolation in Tamil Nadu State

The state of Tamil Nadu is also referred to as the home of many natural resources. The western, southern and the north-western parts of the state are hilly and these are very much rich in vegetation. The Western and the Eastern Ghats meet at the Nilgiri hills. The Western Ghats traverses through entire western

Table 1
Summary of annual solar insolation at random locations.

Point number	GHI (kWh/m ²)	DNI (kWh/m ²)
2	5.91	5.33
3	5.41	4.97
4	5.93	5.50
5	5.87	5.37
6	5.75	5.21
7	5.72	4.96
8	5.85	5.45
9	5.66	5.09
10	5.56	5.17
11	5.74	5.22
12	5.90	5.40
13	5.57	5.19
14	5.78	5.31
15	5.52	4.82
16	5.32	4.43
17	5.74	5.31
18	5.47	4.94
19	5.79	5.11
20	5.66	5.22
21	5.70	5.27
22	5.91	5.48
23	5.58	4.89
24	5.79	5.18
25	5.59	5.09
26	5.81	5.06
27	5.69	5.25
28	4.91	3.72
29	5.98	5.46
30	5.93	5.55
31	5.64	5.17
32	5.93	5.52
33	5.93	5.48
34	5.98	5.59
35	5.80	5.42
36	5.99	5.47
37	5.54	4.83
38	5.77	5.29
39	5.51	5.15
40	5.35	4.89
41	5.61	5.36
42	5.67	5.05
43	5.84	5.30
44	5.92	5.51
45	5.78	5.50
46	5.78	5.22
47	5.69	5.13
48	5.88	5.39
49	5.76	5.20
50	5.38	4.54
Mean	5.71	5.18
Minimum	4.91	3.72
Maximum	5.99	5.59
Range	1.08	1.87

Table 2
Summary of the state-wise solar energy potential.

Sl. No	State (s)	GHI (kWh/m ²)		DNI (kWh/m ²)	
		Minimum	Maximum	Minimum	Maximum
1.	Andhra Pradesh	5.14	6.03	4.59	5.693
2.	Telangana	5.44	5.99	4.83	5.60
3.	Karnataka	5.08	6.02	4.36	5.71
4.	Tamil Nadu	4.82	6.05	3.82	5.71
5.	Kerala	4.82	5.93	3.71	5.55

The whole area was divided into a grid of 100 km × 100 km (as shown in Fig. 11) to analyse the variability in solar insolation distribution of DNI and GHI across the region. Fig. 11 exhibits the annual variations of DNI and GHI at each gridded location. It exhibits an annual variation of DNI within range of 3.82 kWh/m² to 5.71 kWh/m² and GHI range from 4.82 kWh/m² to 6.05 kWh/m². It can be observed that there is an adequate variation of solar insolation over the region. The DNI variations as shown in Fig. 12 exhibits that there was a high amount of DNI at grid numbers 10, 11, 15, 18. DNI values at grid numbers 0, 2, 5, 9 have lower values and similarly were no grids with moderate DNI values. Grid numbers 1, 3, 4, 6, 7, 10–20 as shown in Fig. 11 exhibited the higher solar GHI values on an annual basis. Similarly, the other grid numbers including 0, 2, 5, 9 were found to have relatively lower solar GHI values.

(f) Solar insolation analysis at random points

Some selected random points were generated to assess the spatial variation of solar insolation at these selected locations in the southern part of India. These points were randomly generated in the study area to suggest a better analysis method for a comprehensive analysis of the region.

Moreover, auxiliary objective of this work was to identify a scheme for analytical estimation of solar insolation values at unknown discrete geographical locations, where ground measurements of solar insolation in terms of DNI and GHI is not available. Accordingly, a set of 50 random points were generated (as shown in Fig. 12) and these points were further used for detailed analysis (*excluding one point as this generated point falls outside the study region*). These randomly generated points were overlaid over the DNI and GHI distribution map of the study area. Subsequently, these points were used to extract values of DNI and GHI for further spatial distribution analysis across the region. Table 1 summarizes the comprehensive summary of annual solar insolation for each random points to understand the aggregate the solar insolation values across the whole region. Summary statistics reported that maximum and minimum values of DNI lies within the range of 3.72 kWh/m² to 5.59 kWh/m² with an average value of 5.18 kWh/m², similarly maximum and minimum values of GHI varies from 4.91 kWh/m² to 5.99 kWh/m² with an average value of 5.71 kWh/m². It can be observed that there is insignificant variation of solar insolation over the region.

Furthermore, the spatial variation of solar insolation over the region was attempted, and hence in this regard the calculated solar insolation values in terms of DNI and GHI at the regional level were summarized for future sustainable energy improvement, management and planning.

Table 2 summarizes the potential of solar energy being estimated for each state so that the same can be used for further applications towards sustainable development.

4. Conclusion

The main focus was to quantify the availability of energy potential at regional or local level. A framework was developed to understand the localized availability of solar energy resources for

rim of Kerala, and these are effectively blocking most of the rain-bearing clouds from southwest monsoon from entering to the state. The eastern parts are predominantly fertile coastal plains with the northern parts as an amalgamation of hills and plains. The south-central and central regions of the state are mostly arid plains and these are rain scanty regions compared to the other regions (Meisen et al., 2006). Tamil Nadu falls under a region of low seismic hazard except for western border regions. The state is customarily dependent on monsoon rains and thus it is prone to droughts occurred due to failure of monsoons. The state exhibits climate of dry sub-humid to semi-arid. The state has two distinct cycles of rainfall patterns, first caused by the Southwest monsoon ranging from June to September, with strong southwest winds and another is influenced by the Northeast monsoon with dominant northeast winds. Duration ranges from October to December.

further associating to other open archive databases. The reported analysis presented a detailed strategy for study the regional or local variability of solar resource potential for implementation of environmental friendly technology. This work has demonstrated a simplified method to measure the solar insolation for further detailed modelling and simulation towards the precise numerical simulation of regional or national energy requirements at a real-time basis. The study revealed that there was a spatial shift of the accessible energy along the study area but the southwestern region of the area had ample potential regions of solar insolation. The study accounts that Andhra Pradesh and Tamil Nadu has a wide potential of solar energy, which can be exploited for several applications. Beyond that, a detailed analysis of 50 random points was performed for the region to generate a solar energy distribution map for the pilot study area. The statistical summary reported that DNI values range within 3.72 kWh/m² to 5.59 kWh/m² with an average value of 5.18 kWh/m² and GHI values ranges from 4.91 kWh/m² to 5.99 kWh/m² with an average value of 5.71 kWh/m². The amount of solar insolation will play a key role in understanding a broad range of natural processes at a landscape scale. As it enables to analyse the geographic area to model physical and biological processes occurring due to solar energy. The recent satellite remote sensing-based solar energy assessment will significantly contribute to the enriched energy supply in smart cities. These derived resource availability spatial geodatabase will in the local or regional energy management. Furthermore, it would assist in enriched decision making in an analytical and logical framework to achieve the inspiration of 'Solar India' in the field of urban remote sensing for better energy planning for the transfer of knowledge towards further research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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