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Mathematics-based investigation of solar energy potential and solar radiation mapping

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Abstract: The transition to renewable energy sources, particularly solar energy, is of paramount importance in mitigating climate change and ensuring sustainable energy solutions. This study presents a mathematics-based investigation into the solar energy potential of a specified geographical region through solar radiation mapping. By employing mathematical models and geographical information systems (GIS) techniques, the research aims to accurately assess the solar energy availability and inform optimal photovoltaic system installations. The study begins by collecting solar radiation data, considering factors such as geographical location, time of day, season, and cloud cover.

These data are then integrated into mathematical models that simulate the interaction between sunlight and the Earth's atmosphere. By employing established radiative transfer equations, the study accounts for atmospheric effects, such as scattering and absorption, to provide a precise representation of solar radiation reaching the Earth's surface. Furthermore, geographical information systems are utilized to create solar radiation maps for the investigated region. These maps visualize the spatial distribution of solar energy potential, highlighting areas with the highest solar radiation levels

The investigation extends beyond simple solar radiation mapping. The study delves into the mathematics behind optimizing solar panel tilt angles and orientations for various times of the year. This dynamic approach ensures that solar panels are positioned optimally to capture the maximum amount of sunlight throughout the year, enhancing energy yield. In this mathematics-based investigation offers valuable insights into the solar energy potential of a specific region through rigorous solar radiation mapping and mathematical modelling.

Keywords: Mathematics, solar energy, solar radiation, mapping, renewable energy, geographical information systems (GIS).

1. INTRODUCTION

The escalating concerns over climate change and the finite nature of fossil fuels have spurred a global shift towards renewable energy sources. Among these, solar energy stands out as a promising solution due to its abundant availability and minimal environmental impact. Harnessing solar energy efficiently requires a comprehensive understanding of its potential in specific geographical regions.

This paper introduces a mathematics-based investigation focused on evaluating solar energy potential and creating solar radiation maps. By utilizing mathematical models and advanced geographical information systems (GIS) techniques, the study aims to provide accurate insights into the solar radiation patterns of a designated area. Solar radiation mapping plays a pivotal role in quantifying the solar energy a region can harness.

Such maps enable the identification of optimal locations for solar installations, ensuring maximum energy output while minimizing costs. The investigation involves collecting solar radiation data, considering parameters such as latitude, longitude, time of day, and atmospheric conditions. These data are integrated into mathematical models that simulate the interactions between solar radiation and the Earth's atmosphere, accounting for scattering, absorption, and other atmospheric effects.

Geographical information systems facilitate the creation of solar radiation maps, visualizing the spatial distribution of solar energy potential. This visual representation aids in the identification of areas with high solar potential, allowing stakeholders to make informed decisions about solar power infrastructure development. Moreover, the study delves into optimizing solar panel tilt angles and orientations, considering seasonal variations to maximize energy capture. In essence, this research bridges the gap between mathematics, geography, and sustainable energy development.

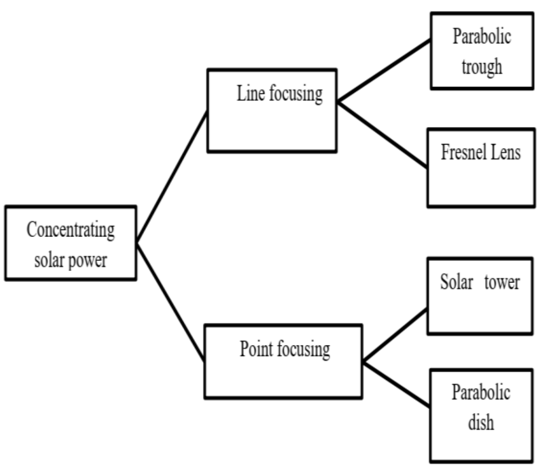

Figure1.2:Types of concentratingsolarpowerplants

By quantifying solar energy potential and offering insights into its utilization, this investigation contributes to informed decision-making and paves the way for a more resilient and sustainable energy future. All sustainable power sources are for the most part gotten from the sun. Sun powered energy-based advancements are ecologically advantageous, and everybody ought to be urged to utilize them to meet their energy needs to keep up with the biological system's general equilibrium. The amplest and equally appropriated energy source on earth is sun powered radiation. India is experiencing a severe energy shortage, which is impeding its industrial growth and economic development.

The percentage share of installed capacity in India is depicted in Figure 1.1.

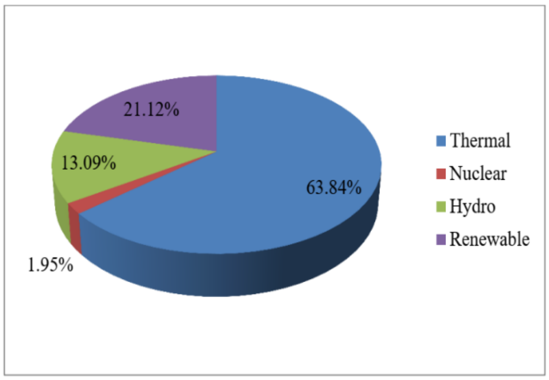

Fig.1.1:shareof installedcapacityfromdifferentsources

Table1.1:Installedcapacity in India

Source	**Installedcapacity(GW)**
Thermal	221.76
Nuclear	6.78
Hydro	45.48
Renewable	73.35
Total	**347.37**

Nevertheless, the solar industry requires supportive policies for its continued expansion. According to the International Energy Agency (IEA), solar energy (photovoltaic and thermal) could meet the majority of the world's electrical energy demand by 2060. In 2035, renewable energy sources could increase by at least 60 percent and possibly double. And by 2060, renewable energy could provide four times as much energy as it does now. By 2060, solar energy could be the world's largest source of primary energy, according to Schandl (2016). At the upper environment, the planet gets 1,74,000 terawatts (TW) of sun oriented radiation. The excess 30% is consumed by mists, seas, and bodies of land, though just around 30% is reflected back to space . Most of individuals on earth live in areas with day to day insolation averaging 150-300 Watt/m2, or 3.5-7.0 kWh/m2.

Problem statement

The utilization of solar energy as a sustainable and renewable source of power is gaining momentum in the face of growing environmental concerns and the need for cleaner energy alternatives. However, accurately assessing the solar energy potential of a specific geographical area and effectively mapping solar radiation patterns remain significant challenges. These challenges arise due to the complex interplay of various factors such as geographical location, climate conditions, topography, and the intricate mathematical relationships governing solar radiation.

Motivation

The motivation behind conducting a mathematics-based investigation of solar energy potential and solar radiation mapping stems from the pressing need to transition towards sustainable and renewable sources of energy. the motivation behind conducting a mathematics-based investigation of solar energy potential and solar radiation mapping lies in addressing energy, environmental, economic, and societal challenges while working towards a sustainable and greener future.

Contribution

The contribution lies in enabling informed renewable energy planning, sustainable infrastructure design, and environmental preservation through accurate solar energy potential assessments and radiation mapping. the contribution of mathematics-based investigations of solar energy potential and solar radiation mapping is multifaceted, spanning energy, environment, economics, technology, and society. It accelerates the shift towards a more sustainable and resilient future while addressing some of the most pressing challenges of our time.

Literature review

A large number of uses in meteorology, designing, rural sciences — especially for soil physical science, horticultural hydrology, crop displaying, and assessment of yield evapotranspiration — as well as in the wellbeing area, in research, and in many fields of the inherent sciences — all rely upon information on sun-based radiation at ground level.

- Coming up next are only a couple of instances of the large number of utilizations: engineering and building configuration, (for example, cooling and cooling frameworks); plan and utilization of sunlight based warming frameworks; age of sun oriented power and sun oriented fueled vehicle races; climate and environment expectation models; vanishing and water system; assessment of harvest water needs; observing plant development; infectious prevention; and skin-malignant growth research. This section presents an inside and out investigation of various past examinations that are relevant to estimating and displaying sunlight based radiation.

Todevelop mathematicalmodeltoassesssolarradiationonhorizontalsurface

In Jeddah, Saudi Arabia, Sebaii et al. (2010) calculated global, direct, and diffuse solar radiation on horizontal surfaces.

- A number of parameters were obtained from the Saudi Ministry of Defense and Aviation, Meteorology and Environmental Administration in order to validate various radiations. The calculated and measured values of Solar Irradiation were compared. Regarding testing accuracy, the mean bias error (MBE), root mean square error (RMSE), and the mean percentage error (MPE) were analyzed further. The values of r2, RMSE, and MPE were found to be within the allowable range, indicating a reasonably decent correlation between measured and calculated values of H (horizontal radiation).
- Nguyen and Pearce (2012) estimated potential photovoltaic yield using the open source Geographical Resources Analysis Support System (GRASS) and the r.sun program. The diffuse and reflected components of the clear sky and real-sky global irradiance/irradiation on horizontal or inclined surfaces were estimated using the r.sun model beam. A case study utilizing the devised algorithm was conducted on a North American region. It was determined that r.sun provides a partially open-source, relatively low-computing-intensive, but still high-handling-capacity method for modeling solar energy for the planning of large-scale photovoltaic systems.
- Marwal et al. (2012) estimated monthly mean daily global solar radiation for Jaipur, Rajasthan, by comparing correlation functions using six empirical correlations. Angstrom-Prescott linear

correlation and modified functions such as quadratic, cubic, exponential, logarithmic, and power function of relative duration of sunlight hours were used as correlations.

- The India Meteorological Department (IMD) provided monthly mean daily global solar radiation and monthly mean daily sunshine duration for Jaipur from 1987 to 2002. Using the statistical parameters coefficient of determination, mean bias error (MBE), and root mean square error (RMSE), observed and predicted values of monthly mean global solar radiation were compared. The coefficient of determination was greater than 80% for each correlation, indicating that all correlations fit the data adequately; however, the cubic correlation had the highest R2 value (85.51%) and the lowest MBE and RMSE values.
- Khan and Ahmed (2012) calculated the global solar radiation using the clear sky radiation in Yemen. Using multiple regression analyses, this study investigated the applicability of clear sky radiation to predict and express the average measured values of solar irradiance on a horizontal surface in Yemen. On the roof of the department were installed Eppley pyranometers, a pyrheliometer, integrators, and printers for observing various forms of irradiations. Using these parameters, equations representing the two seasons, winter and summer, were also constructed. Using t-statistics, it was demonstrated that the results were efficient and reliable.
- Rajput et al. (2014) estimated solar radiation at Allahabad, Uttar Pradesh, and also discussed the potential of solar energy estimation and utilization using the Angstrom equation. Approximately 63 percent of the year is comprised of sunshine, as observed. In June and August or January and October of a given year, the value of diffuse solar radiation was nearly identical, whereas the monthly mean global solar radiation per day on a horizontal surface fell significantly after May. The Clearness Index was calculated, and it was determined that the sky above Allahabad was almost always clearer than 60%, with the exception of the months of June, August, and September, when it ranges from 50% to 60%, but July, when it falls below 50%.
- Ouali and Alkama (2014) introduced a new model of global solar radiation based on Bejaia (Algeria) meteorological data. The meteorological parameters (ambient temperature, air pressure, relative humidity, and precipitation) were measured at an Oregon Scientific Meteorological station, and the global solar radiation data.

MATERIALS AND METHODS

*R.SUN*MODEL

C programming is used to implement the r.sun model in the GRASS GIS open source environment. As previously described, r.sun is a complex and flexible solar radiation model completely integrated within the open source environment of GRASS GIS.

MODELPARAMETERS

LTF is the primary parameter influencing solar radiation in the r.sun model. The procedure suggested by Louche et al. (1986) to determine the linke turbidity factor as a function of direct normal irradiance is as follows:

Where mA represents the relative air mass, I represents the solar beam irradiation received at the earth's surface, and I0 represents the solar beam irradiation penetrating the earth's surface.

SoDa (Solar radiation data) services were consulted for LTF values. This resource provides monthly LTF climate values for air mass 2.

$$I = I_o . \in . \exp(-\delta_R . m_A . T_L)$$

ThereforeT_L(Linke turbidityfactor) canbefoundoutusingbelow relation

$$T_L = \frac{\ln I_o - \ln I + ln\in}{m_A \delta_R}$$

SOLARIRRADIATIONFORHORIZONTALSURFACE

According to the methodology proposed by Hofierka and ri (2002), the extra-terrestrial solar irradiation is calculated using equation (3.3), which is a function of I0 (solar constant) and (extra-terrestrial irradiation).

This correction factor is applied to the calculation of extra-terrestrial irradiation due to the eccentricity of earth's orbit and the fact that the distance between the sun and earth varies throughout the year.

SOLARRADIATIONMEASURINGINSTRUMENTS

The expression "sun powered radiation" is utilized to depict the bright and close infrared (apparent and close noticeable) energy that the sun transmits. Inside the expansive band scope of 0.20 to 4.0 m, the numerous frequency runs that make up the districts are utilized to characterize them. Infrared radiation transmitted from the environment is alluded to as earthbound radiation . The parts of sun oriented and earthbound radiation are recorded beneath, alongside an unpleasant thought of their frequency ranges:

- UV beams: 0.20 to 0.39 m
- 0.39 to 0.78 m Noticeable
- 0.78 to 4.00 m in the close infrared
- 4.00 - 100.00 m in the infrared

Most of earthbound, or long wave, radiation is contained in the reach from 3.5 to 50 m, while more than the vast majority of sun powered, or shortwave, radiation at the world's surface is contained in the area between 0.3 to 3.0 m . The force of sunlight based radiation outside the world's climate is around 1353 watts/square meter.

The Sun based Consistent is the estimation of the mean earth-sun distance at the highest point of the climate. On the outer layer of the earth, the immediate pillar radiation will be around 1000 W/m2 around early afternoon on a crisp morning . While area (counting scope and height), season, and season of day all affect the accessibility of energy, overcast cover and other meteorological factors, which change with spot and time, have the best effect.

PYRANOMETER

The frequency scope of a pyranometer, a type of actinometer used to gauge sunlight based irradiance on a level surface, is from 0.3 m to 3 m . It is expected to recognize the sun orientedradiation motion thickness (W/m2) from the side of the equator above. Average pyranometers needn't bother with ability to work. The frequency scope of the sun powered radiation that arrives at the outer layer of the planet is about 300 to 2800 nm. Irradiance estimations will be created with fluctuating degrees of otherworldly awareness relying upon the sort of pyranometer used . By definition, the response to "bar" radiation should shift with the cosine of the point of rate to be estimated for irradiance.

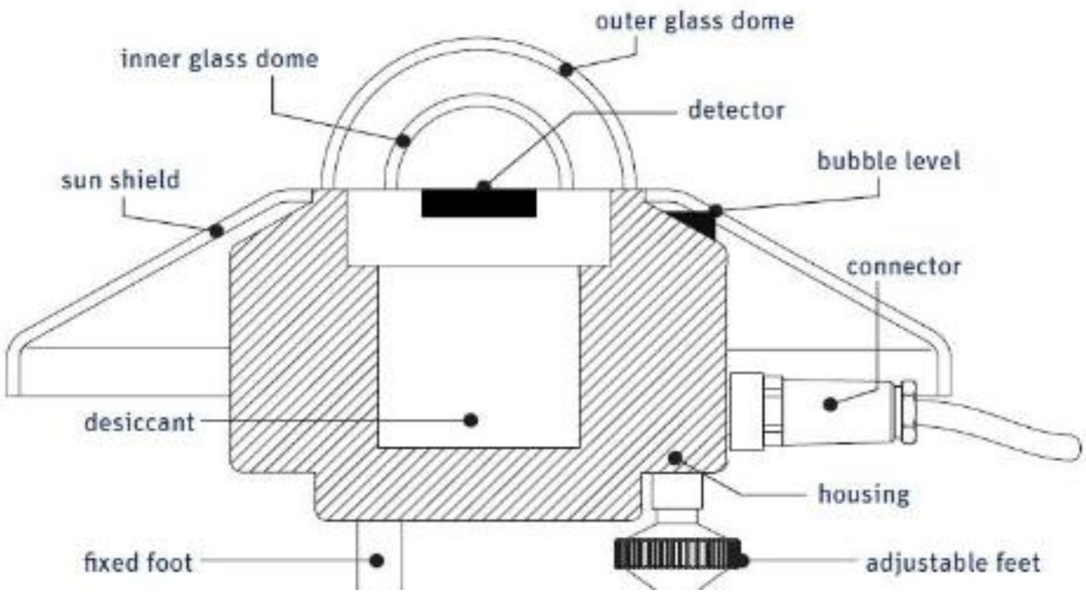

FIGURE3.1 SCHEMATICDIAGRAMOFPYRANOMETER

This ensures a full response when the sun sparkles straightforwardly on the sensor (ordinary to the surface, sun at peak, 0° point of rate), a zero reaction when the sun is at the skyline (90° point of frequency, 90° pinnacle point), and a reaction of 0.5 when the sun is at a 60° point of occurrence. In this way, a pyranometer should have a "directional reaction" or "cosine reaction" that is near the best cosine trademark.

PYRHELIOMETER

An instrument that actions pillar radiation is known as a pyrheliometer. The sensor plate is arranged at the lower part of a cylinder whose pivot is lined up with the way of the sun's beams, as opposed to a pyranometer. The sensor surface is successfully safeguarded from diffuse radiation thus.

Most of pyrheliometers utilized for ordinary estimations depend on the thermopile impact and, in such manner, are tantamount to pyranometers . They are precisely disparate in that they should follow the sun to gauge just direct daylight and avoid diffuse light. In actuality, direct sun oriented radiation is estimated by mounting the instrument on a central mount that is fueled by power and used to follow the sun. A collimator tube with a round cone point of around 5 is set over the sensor to take out the diffuse part .

Different issues with pyrheliometer estimations incorporate the gap point, circum sun powered commitments, and global positioning framework imprecision. The failure to appropriately depict the sun oriented circle and the limited elements of the instrument parts make it almost challenging to settle the initial two issues . Accuracy following and sensor direction are both exceptionally helpful by and by. The utilization of remedial elements isn't just work escalated yet in addition fairly whimsical. An extra technique for getting the immediate daylight part on an even surface is to utilize a shade ring. To accomplish this, deduct the diffuse (concealed) perusing from the worldwide (unshaded) perusing.

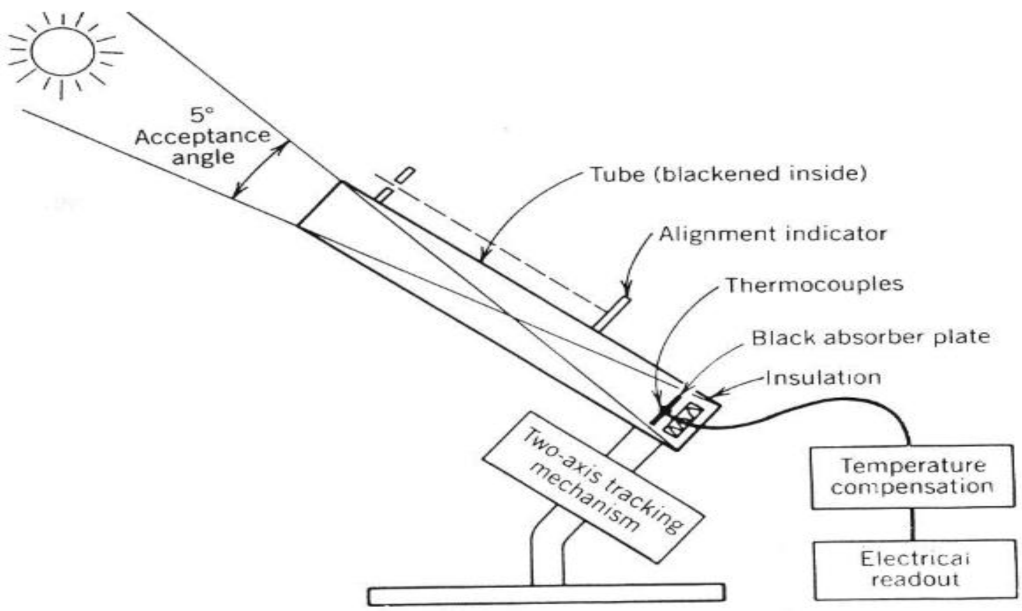

FIGURE3.2 SCHEMATICDIAGRAMOFPYRHELIOMETER

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Results and discussion

The equations of the r.sun model were utilized to develop software for evaluating the various components of solar irradiation, including direct irradiation, diffuse irradiation, global irradiation, and direct normal irradiation. The software was developed in the C programming language and will assist in determining the solar irradiation of any location. This software will be of great assistance in determining the parameters that must be determined prior to constructing a solar plant, such as the linke turbidity factor, solar irradiation, sun shine hours, etc.India's solar atlas was created using the software that was developed. Comparing measured and calculated values for various types of irradiation from 2006 to 2013 served as an additional validation step From 2006 to 2013, IMD values were regarded as the measured value. The r.sun model devised in this study was used to design a 1 MW solar photovoltaic (PV) and solar thermal power plant for Udaipur. The designed plant's techno-economic performance was also evaluated in terms of LCOE, repayment period, and internal rate of return. This chapter discusses the specific outcomes of mathematical modeling for assessing solar irradiance, the design of solar plants, and the techno-economic evaluation of the designed system.

Table3.1geographical featuresof thelocationsunderstudy

Location	L beatitude(N)	Lo magnitude(E)	Altitude(m)
Location1	13.08	80.27	6.7
Location2	9.92	78.12	101
Location3	11.34	77.72	183
Location4	10.79	78.70	85
Location5	9.41	78.70	2
Location6	8.71	77.76	47

GLOBALSOLARRADIATIONANDCLIMATICDATAIN LOCATION 6

Area 6 gets 3.4 to 5.9 kWh/m2 of worldwide sunlight based radiation in the colder time of year, 5.1 to 6.2 kWh/m2 in the pre-rainstorm, 4.6 to 6.0 kWh/m2 in the south-west storm, and 1.9 to 5.2 kWh/m2 in the post-storm. This region frequently has a warm and damp environment. Averaging 24 to 35 degrees Celsius in the late spring (Walk to June) and 21 to 33 degrees Celsius the remainder of the year. 35.4 mm of downpour falls every year by and large. Precipitation is at its greatest during the upper east rainstorm (October to December), arriving at a pinnacle of 232.8 mm in November. The city's overall dampness changes from 69% in the colder time of year to 89% in the post-storm. In the pre-fall and early south west storm season, the pneumatic force ranges somewhere in the range of 1009 and 1012 millibars, while in the pre-spring and early premonsoon, it is 1012 millibars.

GEOGRAPHICAL CHARACTERISTICS OF TAMIL NADU'S LOCALES

Tamil Nadu, one of India's two most southern states, is situated between scopes 8 N and 13 N and longitudes 76 E and 81 E. Table 3.1 gives the scope and longitude of the different review areas. As can be noticed, the few spots' scopes range from 8.71 N to 13.08 N and their longitudes from 77.72 E to 80.27 E. From 2 meters in Ramanathapuram to 183 meters in Disintegrate, the height differs.

Location	**beatitude(N)**	**magnitude(E)**	**titude(m)**
Location1	13.08	80.27	6.7
Location2	9.92	78.12	101
Location3	11.34	77.72	183
Location4	10.79	78.70	85
Location5	9.41	78.70	2
Location6	8.71	77.76	47

Table3.3globalsolarradiationandclimaticdataoflocation2

While different measurements have a negative relationship with worldwide sun powered radiation throughout the colder time of year, it tends to be shown that encompassing temperature has a positive connection with it. Worldwide sun radiation associates emphatically with encompassing temperature and gaseous tension during the pre-rainstorm season. It tends to be expected that when sun based radiation increments, nearby air pressure and consequently encompassing temperature increase.

There is areas of strength for a connection between relative stickiness and surrounding temperature during the south-west rainstorm season. The stickiness proceeds to climb and the temperature begins to fall as the south-west storm season reaches a conclusion. Weighty precipitation describes the post-rainstorm season. During this time, the moistness is high and the air temperature is very low. This might be found from the relationship study, which shows that temperature, trailed by different elements, has a generally low association with worldwide sun based radiation though precipitation and dampness have a decent regrettable connection.

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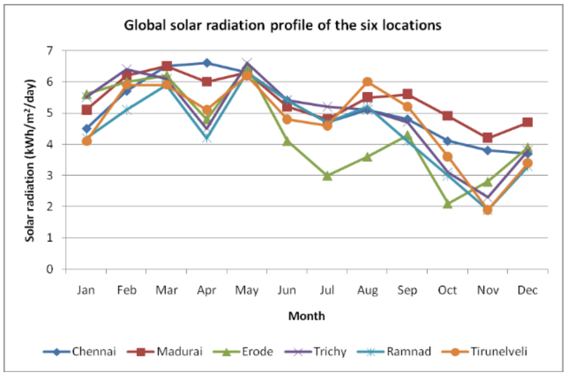

Season	Month	Global SolarRadiation (kWh/m2/day)	AmbientTemperature (C)	Relativehumidity (%)	Windspeed(m/s)	Atmosphericpressure(mbar)	Precipitation(mm)
Winter	January	5.1	26.4	71	1.4	1013	3.5
	February	6.2	27.2	64	3.1	1013	18.8
Premonsoon	March	6.5	30.0	61	2.7	1012	174.0
	April	6.0	31.5	65	3.1	1009	161.2
	May	6.3	31.3	69	4.3	1007	122.0
South-westmonsoon	June	5.2	31.6	61	4.2	1006	18.7
	July	4.8	32.1	53	3.9	1006	6.9
	August	5.5	31.8	59	3.3	1007	43.0
	September	5.6	31.6	61	2.7	1008	139.7
Postmonsoon	October	4.9	28.9	77	2.4	1010	240.1
	November	4.2	26.2	85	2.7	1010	377.9
	December	4.7	26.1	82	2.8	1013	246.0

FIGURE3.2GLOBALSOLARRADIATION PROFILEOFTHESIXLOCATIONS

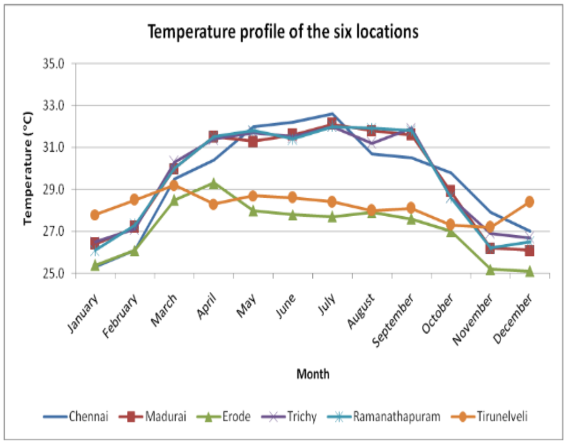

FIGURE3.3TEMPERATUREPROFILEOFTHESIXLOCATIONS

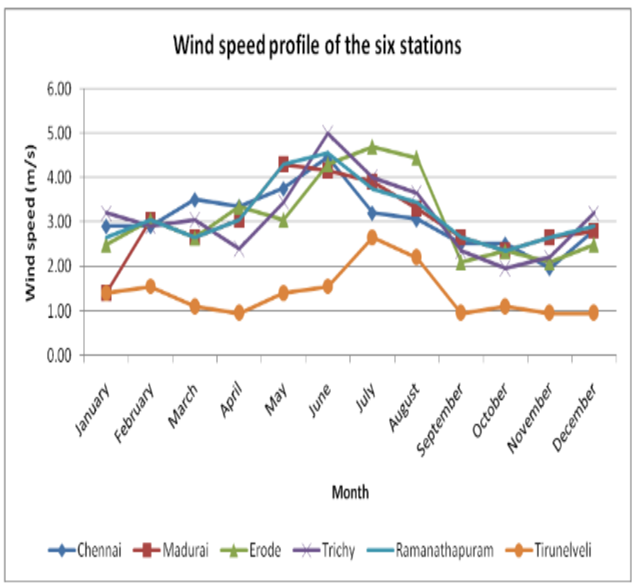

FIGURE3.4 WINDSPEEDPROFILE OFTHESIXLOCATIONS

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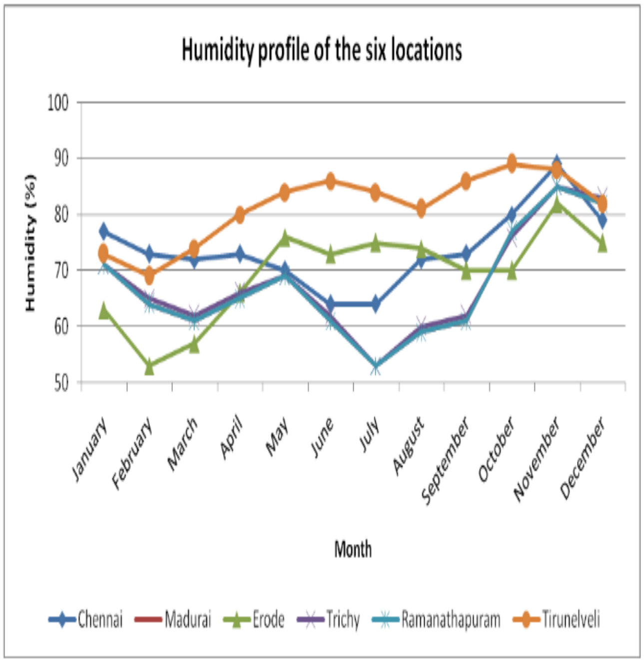

FIGURE3.5 HUMIDITYPROFILE OF THE SIXLOCATIONS

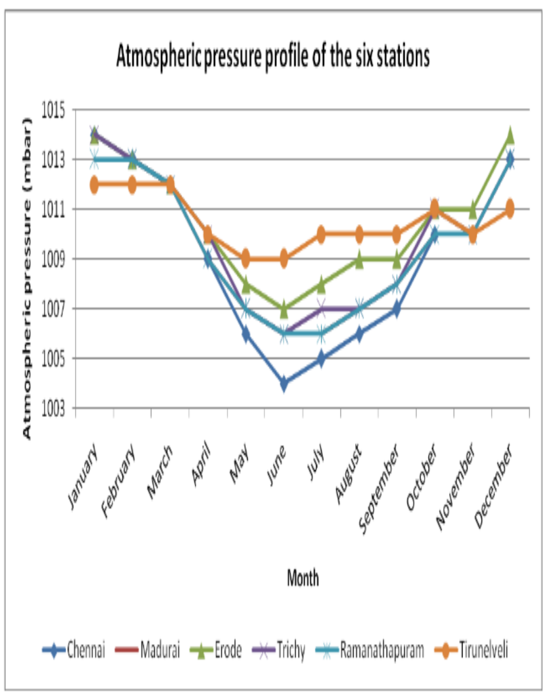

FIGURE3.6 ATMOSPHERICPRESSUREPROFILEOFTHESIXLOCATIONS

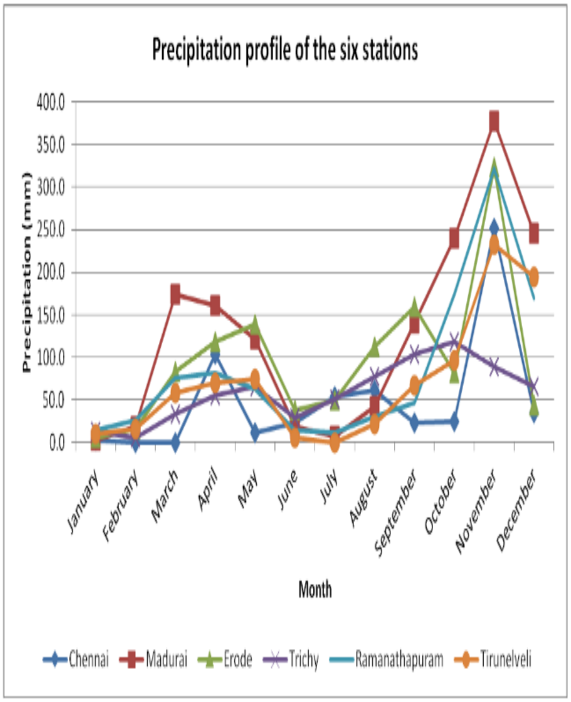

FIGURE3.7 PRECIPITATIONPROFILEOFTHESIXLOCATIONS

The discoveries of the relationship examination led between the factors for the four seasons at Area 2 are displayed as a connection grid in Tables 3.13 to 3.16.

Discussion

Presently, the majority of Indian industries rely on conventional energy sources (fossil fuels) to satisfy their energy needs. Fossil fuels are scarce, polluting, and continually becoming more expensive. As the global supply of fossil fuels dwindles, there is a pressing need for pure, affordable renewable energy sources to meet rising energy demands. There must be alternatives to the use of nonrenewable and polluting fossil fuels. Solar energy is one alternative energy source. Solar energy is the greatest carbon-free energy source currently accessible. The earth receives more energy from the sun in one hour than it consumes in an entire year.

This research has been conducted to present and validate mathematical models of solar radiation mapping. In addition, the technical and economic viability of solar systems, such as the solar photovoltaic system and solar parabolic trough system, are evaluated.

Using the r.sun clear sky model, the above research produced solar irradiation maps (Global component, diffuse component, direct component, and direct normal component) for India under clear sky conditions. The generated maps revealed India's vast solar energy potential. The maximum diffuse irradiance under a clear sky is 1.45 kWh m-2day-1, while the minimum is 0.05 kWh m-2day-1. The range of India's global irradiance is between 6 and 7.15 kWh m-2day-1. Direct irradiation has a maximum potential of 6 kWh m-2day-1 and a minimum potential of 4.5 kWh m-2day-1. The majority of the country obtains an average of 6.8 to 8.4 kWh m-2day-1, as indicated by the DNI mapping for clear sky conditions.Validation was carried out utilizing IMD data and statistical analysis. MBE and RMSE have very low and acceptable values, proving the veracity of the r.sun model for India. This identification of solar potential would unquestionably aid investors in making investment decisions for future solar power plant projects. In addition, this will assist in offsetting greenhouse gas emissions and achieving a low-carbon economy in India.

Conclusion

For an SPT-type thermal power plant, the solar field requires four solar collector assembly loops, with sixteen collector assemblies per loop. The solar field is capable of collecting 4.2 MW of solar energy in the form of heated thermic fluid, which is then transferred to the power block via the heat transfer fluid Therminol VP-1. In the solar field, heat transfer fluid circulates at a rate of 18 kg second-1. This heat is conveyed to the steam generator, which generates steam at 375 C and 103 bar pressure. This high-pressure, high-temperature steam is used in a steam turbine to generate 1 MW of electricity. The SPT facility required an aperture area of 7,452 square meters.

In its first year of operation, the SPT power plant can generate 3,383 MWh year-1 (electrical units) at a capacity factor of 38.62%. A 1 MW solar PV facility was also designed. With a capacity factor of 28%, the SPV plant's land requirement was determined to be 5.18 acres.

Financial indicators like IRR and Payback period were calculated for SPV and Solar thermal power plant. The payback periods for solar PV and solar thermal plants are 7.27 and 3.91 years, respectively. The internal rate of return (%) for solar photovoltaic and solar thermal plants was 14.88% and 28%, respectively.

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