November 2024

EC WORKING PAPER WP 03

# Mapping Solar Rooftop Potential in Chennai using GIS


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Mondal, S, Muralidharan, R, Seshadri, S, and Tambe, N (2024). Mapping Solar Rooftop Potential in Chennai Using GIS. The Energy Consortium Indian Institute of Technology Madras Working Paper No. 03. Available at:

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# Executive Summary

The energy demand worldwide is growing exponentially with electrification of transport, heating, and industrial activities. Addressing this climate crisis requires finding solutions that meet net-zero carbon targets. Among different renewables, solar energy has been proved to be the cheapest and most accessible renewable. India, with its vast geography and high solar insolation, has set ambitious renewable energy targets, aiming at installing 175 GW of renewable energy capacity by 2022, with 40 GW dedicated to rooftop solar systems under Phase II of the Rooftop Solar Programme.

Tamil Nadu, with a cumulative installed solar capacity of 17.67 GWp, stands fourth in the country. The state contributes 8,145.53 MW to the country's aggregate solar potential. It has achieved significant success in encouraging domestic rooftop solar installations, and the Tamil Nadu Energy Development Agency (TEDA) has installed 59.28 MW of domestic rooftop solar PV. In the financial year 2023-2024, Tamil Nadu added 1,994.62 MW of renewable energy capacity to the grid, while 201.88 MW were from rooftop solar. Chennai, the capital of Tamil Nadu, has a rooftop potential of 138 million square meters, capable of generating 1.38 GW of solar power, which would power 500,000 households.

The study maps the rooftop solar potential using Geographic Information Systems (GIS) and utilizes high-resolution satellite imagery with building footprints and Digital Elevation Models to assess suitable rooftops for solar installations while it analyses key parameters like solar irradiance, roof aspect, and slope for providing a comprehensive solar potential map.

The results of the analysis indicate that there is a substantial potential for solar energy generation in Chennai with a calculated solar irradiance of 81.39 kWh/m²/day and an electricity generation potential of 70 kWh/day from a 100 m² rooftop. The total suitable rooftop area in Chennai is about 140,674,391.4 m² with an annual electricity generation potential of 35,936 GWh. The payback period is 20.8 months and the return on investment is 57.8%. Further, widespread rooftop solar adoption in Chennai could lead to a significant reduction of carbon emissions, about 23.18 metric tons of $CO_2$ per 10 kW installation.

Chennai is trying to move towards net-zero carbon emissions through rooftop solar, but faces issues such as high upfront costs, a long process for approval, public misconceptions about the efficiency of solar, environmental issues such as lead and cadmium, and financial delays by agencies such as TANGEDCO and TEDA. These factors make installations unaffordable for middle-class families, and the net metering policy caps residential rooftop solar at 50% of its potential. Strategic interventions in the form of grid-connected systems, smart grids, and technological advancements can contribute to energy security and economic viability.

Public-private partnerships and community solar programs can democratize access to clean energy by allowing low-income households to participate. Chennai has a potential to become a smart city in India by utilizing GIS-based mapping to estimate solar potential, optimize rooftop space, and integrate renewable energy into urban infrastructure. However, to overcome financial, regulatory, and technical challenges, it is required to have more subsidies, easier policies, low-interest loans, and public awareness campaigns. Strategic planning and technological innovation can increase solar capacity, contributing to Tamil Nadu's renewable energy goals and India's net-zero carbon future.

# 1.Abstract

With growing global energy demand, the need for sustainable solutions brings into focus the role of renewable energy—in particular, solar power — if net-zero is to be achieved. Solar energy is not only the most easily accessible but also the cheapest renewable source; therefore, developing countries such as India have a special interest in it, especially because high solar insolation falls on most areas of its landmass.

This study uses Geographic Information Systems (GIS) for estimating the potential for solar rooftops in Chennai, Tamil Nadu. Tamil Nadu has huge installed solar capacity and high solar potential, yet the large upfront cost, inconsistent policy environment, and technical concerns limit the adoption of rooftop solar. The estimated rooftop area in Chennai is about 138 million square meters, holding a capacity to generate 1.38 GW of solar power—enough to light up some 500,000 households. Besides this, high solar insolation and hot and humid climate make this city very conducive for solar energy generation.

This study focuses on identifying suitable rooftops for solar installations in Chennai using high-resolution satellite imagery, building footprints, and Digital Elevation Model (DEM). The analysis considers factors such as solar irradiation, roof slope, and aspect to create a detailed solar potential map. This map serves as a valuable tool for strategic planning and development of renewable energy infrastructure in the city.

Major limiting factors to its implementation include space constraints in densely populated urban areas, a lack of general public awareness, and shading from neighbouring structures. It also needs huge reforms at the policy level and greater consumer awareness, which can be achieved through technological innovations. The GIS-based assessment will, therefore, can significantly enhance Chennai's solar capacity, supporting Tamil Nadu's renewable energy targets while promoting sustainable urban development and reducing the city's carbon footprint.

Keywords: Solar energy, GIS, solar rooftop potential, DEM, renewable energy, net zero, solar irradiation, sustainable urban development.

# 2.Introduction

The rising global energy consumption, driven by the electrication of transport, heating, and industry, has led to a signicant rise in energy demand. To tackle the climate crisis and meet net-zero goals, solar energy stands out as the most affordable and accessible option among renewables.

India has signicant solar energy potential due to its geographical diversity and high solar insolation received in many parts. The country has about 62.5% of the geographical area receiving an annual average direct normal irradiance (DNI) of over 5.0 kWh/m²/day (Ministry of New and Renewable Energy, India Solar Resource Maps, 2013). The country aims to install 175 GW of renewable energy by 2022, out of which 40 GW is the target for rooftop solar systems under Phase II of the Rooftop Solar Programme. According to a report prepared by the Ministry of New and Renewable Energy, as much as 124 GW of solar rooftop potential exists in residential, commercial, and industrial buildings.

The aggregate solar potential of Tamil Nadu is 17.67 GWp, ranking 4th in the country, based on the cumulative installed solar capacity of 8,145.53 MW. The Tamil Nadu Energy Development Agency (TEDA) has also implemented 59.28 MW in domestic rooftop solar PV to promote renewable energy in the state. During 2023-2024, a total of 1,994.62 MW of renewable energy capacity was added to the grid; out of this, 201.88 MW is from rooftop solar. The Ministry of New and Renewable Energy has sanctioned 10 MW to TANGEDCO under the grid-connected Rooftop Solar Programme.

Chennai, being the capital city, lies in the hot and humid climate zone with huge potential for solar energy generation. The estimated total rooftop potential area is about 138 million square meters, capable of generating 1.38 GW of solar power, sufficient to power 500,000 households. Though Chennai holds immense potential, it has some limitations, such as high initial costs, inconsistent policies, a lack of awareness, and space-like multi-story residential buildings with limited roof area and shading from neighbouring structures, which further complicate installations.

This study aims to identify and map the potential for solar rooftop installations in Chennai using Geographic Information Systems (GIS), using high-resolution satellite imagery, building footprints, and digital elevation models to determine the most suitable rooftops for solar panel installations, considering factors such as solar irradiation, aspect, and slope. Through detailed solar potential mapping, this study will provide data analysis and insights to support strategic planning and the development of solar power infrastructure, aligning with Chennai's renewable energy goals and its commitment to achieving a net-zero carbon future.

# 3.Literature Review

**Solar energy potential in India:**

Solar energy is, in particular for developing countries, the most feasible environmental and economic source of renewable energy. India has set the target of achieving 100 GW of solar capacity by 2022, including 40 GW of grid-connected rooftop solar installations. As of January 1, 2017, the country had already achieved a cumulative installed capacity of 9.23 GW for grid-connected solar power (MNRE, 2017). Photovoltaics, or solar cells, convert sunlight directly into electrical energy, and it can be integrated into the building skin, i.e., roofs and facades (Gutschner et al., 2002).

Rooftop solar installations allow electricity generated by photovoltaics (PV) systems on residential, commercial, institutional, and industrial buildings to be either fed into the power grid at regulated feed-in taris or used for self-consumption by the building. In this context, the Ministry of New and Renewable Energy has initiated a programme on 'Development of Solar Cities' and identified 60 cities to become 'Renewable Energy Cities' or 'Solar Cities' with the aim to meet a minimum of 10% of their projected demand of conventional energy at the end of 5 years through a combination of augmentation in supply from renewable energy sources and energy efficiency measures like smart street lighting etc.

To address the growing challenges of resource-constrained urbanization in India, the "Smart Cities Mission" has identified 98 cities to advance their goals using information and communication technology (MoUD, 2015). Among the key pillars of Smart Cities: 'Smart Energy' plays a crucial role in reducing the dependence on non-renewable energy (Sharma et al., 2018). However, despite its promising potential, large-scale rooftop solar adoption in India faces several signicant barriers.

According to (Gupta et al., 2020), major obstacles include high initial capital costs, regulatory and policy obstacles (Sharma et al., 2019), and technical problems with grid integration (Kumar et al., 2018). There is also a shortage in consumer awareness and acceptance, further reducing the rate of adoption (Sharma et al., 2019)

**Solar energy potential in Tamil Nadu and Chennai:**

Solar energy is one of the prominent sources of sustainable power in Tamil Nadu, contributing significantly to the nation's renewable energy development. The state has a high solar insolation and has 300 clear sunny days in the year with an average solar irradiation of 1266.52 W/m² (Aravindan et al., 2019). Currently, the indicative power evacuation capacity for the connectivity of solar power plants is expected to be 11.10 GW.

The Tamil Nadu Energy Development Agency (TEDA) provided district-wise data and information on rooftop solar photovoltaic systems, stating a basic cost of INR 5,90,000 for a 7kW system and INR 7,83,000 for a 10kW system, both including a 5-year comprehensive maintenance contract (TEDA, 2018). The Tamil Nadu Vision 2023 outlined the state's strategic infrastructure development plan, including a solar energy target of 5,000 MW. In 2019, the Ministry of New and Renewable Energy set a revised target for Tamil Nadu to achieve 9,000 MW of solar energy capacity (TEDA, 2019).

In the second phase of the Grid-Connected Rooftop Solar Programme, the Ministry of New and Renewable Energy (MNRE) approved 10 MW for TANGEDCO. TANGEDCO designated TEDA as the State Implementing Agency to procure rooftop solar PV systems for residential consumers under the MNRE Phase II Grid-Connected Rooftop Solar Programme. Currently, TEDA has enabled the installation of 9.84 MWp of rooftop solar PV systems, directly benefiting around 2,359 households. However, the program's goal of reaching 12 MW by July this year remains unachieved. Efforts have been made to achieve the sanctioned 10 MW capacity by 2024 before the scheme expires in 2026. Up until FY 2024, the program was supported with up to a 40% subsidy from MNRE (TEDA, 2021).

Like many other regions in southern India, Chennai City experiences a tropical and hot climate. Solar insolation in the city averages 5–7 solar radiations per hundred square meters per day, depending on the region, providing approximately 5 to 6 kilowatt-hours per square meter per day with sun availability for about 300 days a year. The temperatures in Chennai vary from 20°C to 42°C. Flat rooftops have significant potential, making the city particularly suitable for solar energy generation (Aravindan et al., 2019). An estimated rooftop area of around 138 million square meters could, if 20% of this area were utilized for solar installations, generate approximately 1.38 GW of solar power, enough to produce about 2,000 GWh annually. This amount of energy could power roughly 500,000 households (MNRE, 2019). Installing rooftop solar can lead to a reduction in electricity bills by about 30-50%, with a payback period for these installations ranging from 4 to 6 years.

The government is providing capital subsidies of up to 30% for residential solar installations with net metering policies being issued (Hossain, 2018). Solar energy has resulted in a reduction of approximately 1 ton of $CO_2$ emissions per year per 1 kW of installed solar capacity (EPA, 2019). In Chennai, high urban density and limited rooftop space present significant challenges, severely restricting the availability of suitable areas for rooftop solar installations in densely populated urban regions (Mani et al., 2020). Additionally, regulatory issues at the municipal level, along with financial barriers and investment risks, further hinder the growth of rooftop solar installations (Sharma et al., 2019).

Advances in photovoltaic technology, such as more efficient panels and photovoltaic bifacial modules, enhance the performance of rooftop systems. Additionally, challenges related to grid integration can be addressed using smart grid technologies and energy storage solutions (Kumar et al., 2018). Innovative financing approaches, including rooftop leasing and community solar projects, can further expand the adoption of solar installations. Government subsidies and incentives, such as capital subsidies and net metering, may also encourage growth in this sector (Gupta et al., 2020).

**GIS Methodologies for Assessing Solar Rooftop Potential:**

Geographic Information System (GIS) is a very important tool when it comes to evaluating solar potential through the assessment of solar radiation, analysing the availability of the rooftop, and even incorporating other layers of data (Bansal et al., 2019).

They estimated rooftop solar photovoltaic potential by employing GIS mapping with high-resolution satellite imagery and digital surface models. They employed spatial analysis techniques to estimate the available rooftop area suitable for the installation of solar PV in urban settings.

The study also underscored that the assessment should give due consideration to building height, rooftop obstructions, and local climatic conditions. Further, (Kumar et al., 2018) discuss issues related to the assessment of rooftop solar potential in Indian cities using a GIS-based approach. They used spatial analysis tools to assess the rooftop spaces and analyse the amount of solar electricity that can be generated.

Their procedures incorporated LiDAR data to generate 3D models of buildings and urban morphology, aiding in the assessment of rooftop proles and shading conditions, which enhanced the precision of their solar power calculations. However, modern research often lacks comprehensive analysis and description of socio-economic factors that provide both short-term and long-term perspectives for specific locations.

Future research should focus on refining GIS-based rooftop solar models by enhancing data quality, improving real-time capabilities, and exploring the integration of rooftop solar with other renewable resources like wind or batteries. Additionally, incorporating socio-economic data, financing options, and higher-resolution solar potential metrics could significantly enhance the accuracy and applicability of these assessments (Gupta et al., 2020).

# 4.Aims:

This study maps rooftop solar potential in Chennai by using high-resolution satellite imagery, building footprints, and a Digital Elevation Model with the help of GIS. The overall map accounting for solar irradiation, roof aspect, and slope will help planners, policymakers, and investors to take decisions for the expansion of renewable energy infrastructure towards the achievement of renewable energy goals and commitment of Tamil Nadu to net-zero carbon future. This will fill gaps in detailed assessments, combined with actionable insights for rooftop solar adoption in crowded urban settings. The mapping will then be useful to stakeholders and act as a model for other cities in the country.

# Objectives:

- Identify Suitable Roofs: Analyse building footprints to determine which rooftops are suitable for solar installation, considering roof area, orientation, and slope using high-resolution satellite imagery.
- Evaluation of Solar Potential: Utilize GIS to model solar energy generation for each identified rooftop, estimating feasibility based on geographical and climatic parameters.
- Reduce Carbon Footprint: Estimate the potential reduction in carbon emissions by using rooftop solar, reflecting the environmental savings compared to fossil fuel-based energy consumption.
- Increase Energy Independence: Identify how local renewable energy solutions can enhance energy independence for Chennai’s residents and businesses, reducing their reliance on external sources.

# 5.Study Area: Chennai

Chennai is situated at 13.1°N latitude and 80.3°E longitude, providing ample sunlight over large rooftop spaces, which presents an opportunity to explore the city’s solar energy potential given its annual consumption of 14 billion kWh. Financial incentives for adoption are further supported by policies such as the Tamil Nadu Solar Energy Policy 2023 and the PM Surya Ghar Bijli Yojana scheme. The city’s high energy demand across residential, commercial, and industrial sectors makes it an ideal market for focusing on solar energy.

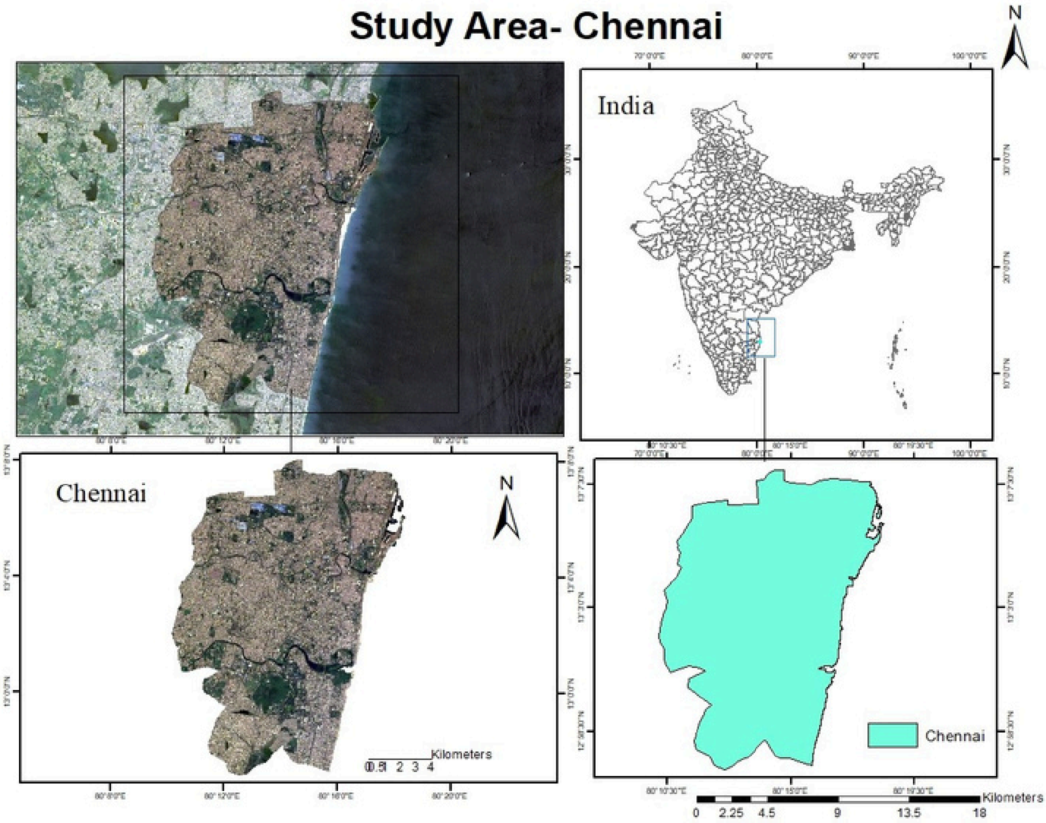



**Fig 1: Study area - Chennai**

# 6.Methodology

## 1.Data collection:

- **Mapping out line of Chennai:** It can accurately assess the potential of solar rooftops in Chennai by setting geographic boundaries using some of the GIS tools like DIVA-GIS. This tool provides free access to various global datasets like administrative boundaries and climate data. By incorporating the features provided, it gives a very fine scale representation of the administrative structure of the city and its physical features.

- **Digital Elevation Model (DEM) from ASTER GDEM:** A DEM is a 3D representation of terrain surface, created from elevation data without vegetation or buildings. It helps calculate slope, aspect, and shading, which affect solar radiation efficiency and rooftop solar panel efficiency. The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) is a collaboration between NASA and Japan's Ministry of Economy, Trade, and Industry. ASTER GDEM provides worldwide elevation data at a high resolution of 30 meters, which is highly required for detailed analysis of terrains. It provides high-resolution elevation data for topographical analysis, hydrological modelling, slope and aspect analysis, solar radiation estimation, infrastructure planning, natural resource management, and disaster management. The DEM in Chennai is crucial for mapping rooftop potential, identifying building height relative to terrain, establishing rooftop inclination, orientation, and assessing the impact of surrounding terrain and structures on solar exposure. The USGS Earth Explorer web application allows users to search, preview, and download geospatial data of any location on Earth and it require here for the analysis of solar rooftop potential in Chennai.

- **Building footprint from OpenStreetMap (OSM):** Building footprints are one of the basic requirements in urban analysis, including mapping rooftop solar potential. OpenStreetMap provides high-resolution geographic data covering almost all parts of the world with detailed building footprints, roads, landmarks, and natural features. It is useful for urban planning, GIS analyses, and transportation planning. This data type is community-driven, crowd sourced, and covers a wide range of regions. Data are available in XML, OSM, Shapefile, and GeoJSON formats. Resolution is likely to be high in urban areas, though the degree may vary depending on the accuracy and density of contributions. Among building footprint attributes are building height, material, use, levels, name, roof shape and material, and address. Data can be extracted using OSM Data Extracts, or Geofabric.

- **Solar radiation data from Global Solar Atlas:** The Global Solar Atlas is a World Bank Group initiative for universal provision of data on solar resources. It combines high-resolution solar radiation maps and data to quantify metrics like solar irradiance, solar power density, and cloud cover. Such data is critical in estimating the potential for solar energy in a region and in project planning. This data will be able to determine how much solar energy can actually be harnessed, thus optimizing its placement and efficiency of solar panels in Chennai.

## 2. Data processing:

The process of data processing involves a consistent coordinate system and projection, which depends on the geographic location and specifics of the study area. For Chennai, the WGS 84 coordinate system is predominantly used. UTM 44N is used in local studies due to its accurate distance measurements. Digital Elevation Models are necessary to understand the topography of the area and for solar radiation estimation. DEM data can be obtained from sources like the USGS Earth Explorer. Building footprint extraction is a critical step in identifying potential rooftop areas for solar installations. Building footprint data can be obtained from OpenStreetMap (OSM) or local municipal databases.

The Solar Analyst tool in ArcGIS can be used to estimate solar radiation potential based on slope, aspect, and shadowing effects. Solar radiation can be estimated on a monthly or annual basis to understand seasonal variations. The process involves importing satellite imagery, downloading DEM data, extracting building footprints from OSM or other local databases, processing DEM to calculate slope, aspect, and shading, reprojecting DEM to the required coordinate system, smoothing and filtering DEM to remove noise.

Building layer preparation and digitization of building footprints are done using ArcGIS tools, Attribute Table Management, and Digitization Techniques. Slope and aspect maps are generated to identify the tilt angle and direction of rooftops. Lastly, economic analysis is conducted to calculate potential energy generation, economic benefits for different building types, and payback periods for sustainable urban development.

- **Digital elevation model and building footprint map of Chennai:** DEM mapping of Chennai and its building footprint involves the importing of data from ASTER Global Digital Elevation Model and the administrative boundary shape file into ArcGIS software. All DEM data combined into one raster, which is relative to the geographic area of interest, using the tool "Mosaic To New Raster", then it is necessary to check the coordinate system to keep the two datasets in WGS 1984 UTM Zone 44N. If the coordinate systems do not match, the raster is projected using Arc Toolbox under Data Management Tools with the "Project Raster" tool. The next step is clipping the DEM into the exact boundary of Chennai by using the "Clip" tool available under Raster Processing in the Arc Toolbox. The final clipped DEM is checked for accuracy and gives an overview of the total elevation-covered area in Chennai. The building data footprint downloaded from OpenStreetMap is also clipped within the administrative boundary of Chennai. Adding data is done in a similar way to the DEM process, and both shape files are checked for accurate spatial analysis. These spatial data become very useful in urban and environmental planning, providing insight into the natural landscape and the urban fabric of Chennai. The clipping of the building footprint data extracted from OpenStreetMap by an administrative boundary, and then calculating the area through the attribute table. The DEM covers approximately 19,483.61 hectares, while that of the building's footprint is approximately 3,642.08 hectares.

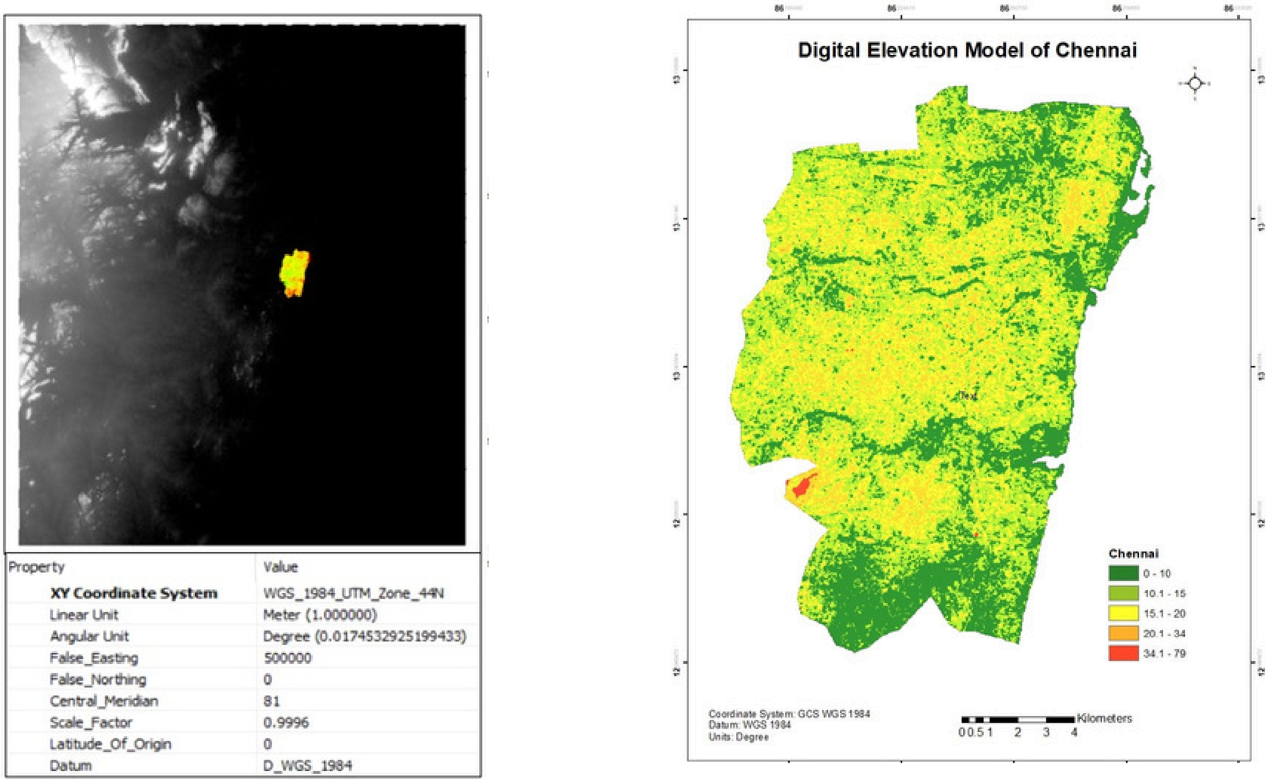



**Fig 2 : Mapping digital elevation model of Chennai**

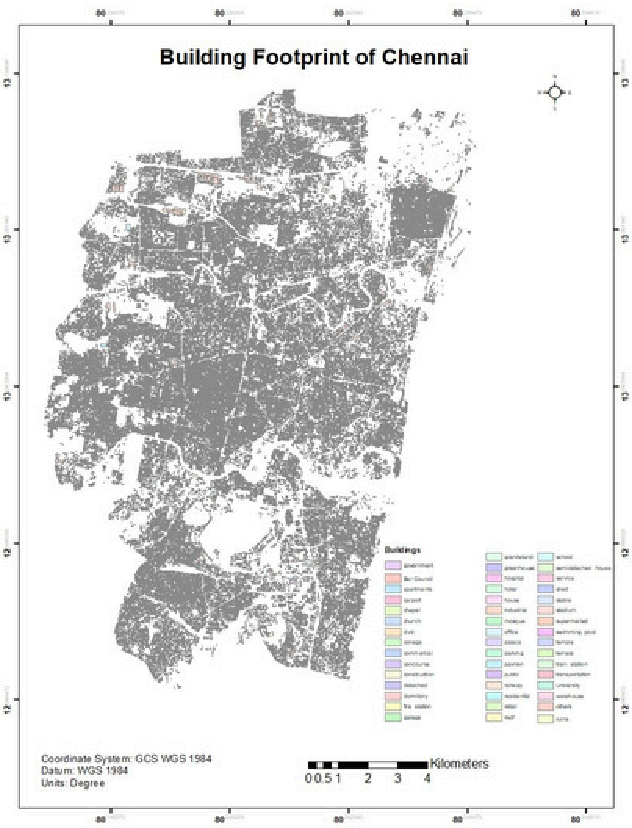



**Fig 3 : Mapping building footprints of Chennai**

## 3.Data analysis:

**a.Slope analysis:** One of the major factors that identify suitable rooftops in Chennai for installing solar panels is slope analysis. A rooftop's slope is very critical to the efficiency of a solar panel. The slope of a rooftop affects the efficiency of solar panels, and some optimal slope within a certain range optimizes capture. In Chennai, the optimum slope is around 10-20 degrees. To create slope in ArcGIS, add DEM layer, then go to Arc Toolbox > Spatial Analyst Tools > Surface > Slope; set the Input Raster to your DEM, the Output Raster to a new file, and Output Measurement to "Degree". Use the Slope Raster tool, Reclassify, and specify slope ranges with suitability for the solar panels like

- 0-5°: Less Suitable (value 1)
- 5-15°: Highly Suitable (value 2)
- 15-30°: Suitable (value 3)
- 30°: Unsuitable (value 4)

Finally, define the output raster name for the reclassed slope and create slope map. Using the attribute table, calculate a slope.

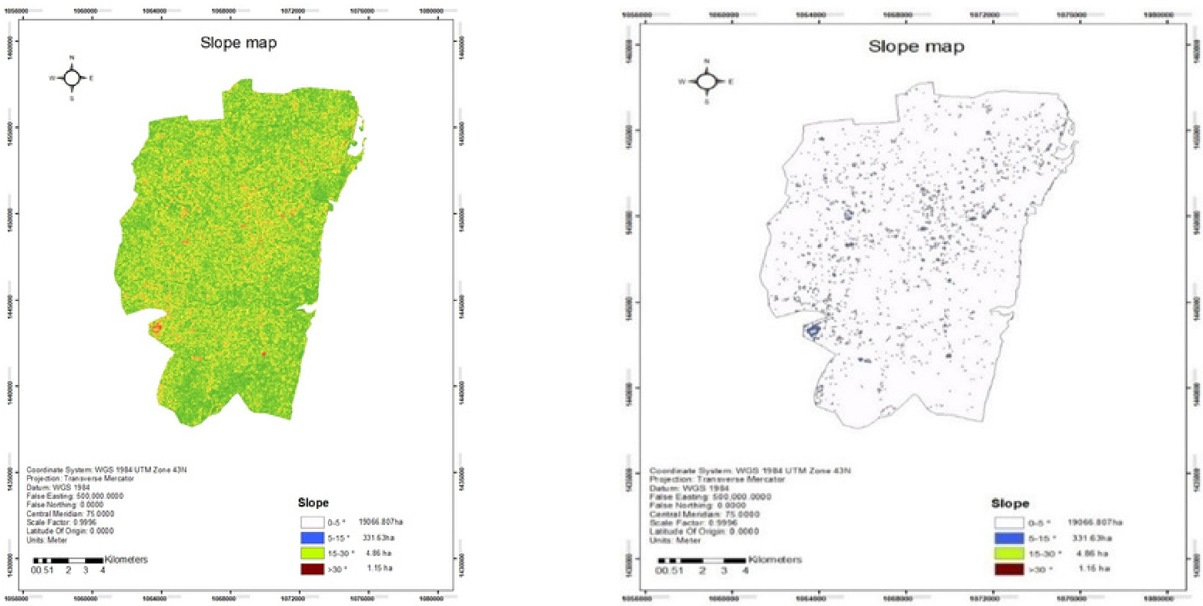


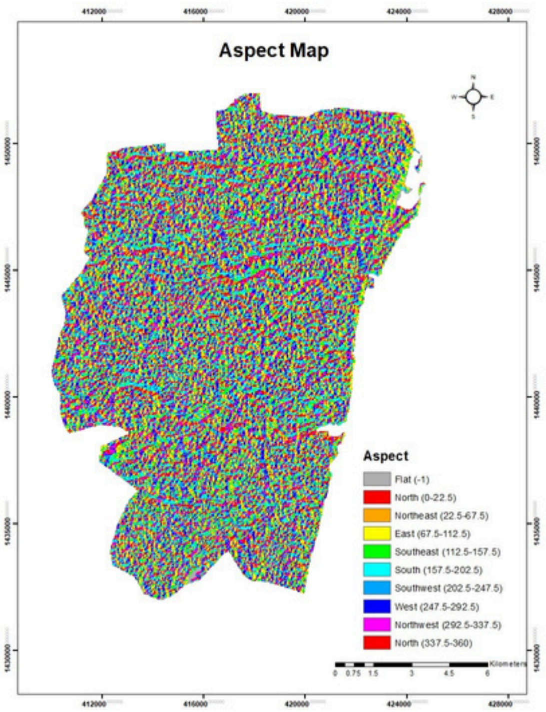

**Fig 4: Mapping of slope using DEM and reclassifying it for suitability analysis**

**b.Aspect analysis:** The aspect is a very critical element in analyzing the solar rooftop potential, as it predefines the amount of radiation that falls on any rooftop. In mapping for the solar rooftop potential using ArcGIS 10.8 for Chennai, the aim would go to determining the orientation of rooftops so as to find which ones are suitable for the installation of solar panels.

To create Aspect in ArcGIS, add DEM layer, to Arc Toolbox > Spatial Analyst Tools > Surface > Aspect. In output measurement, select "Degree". The aspect calculation formula is given in degrees ranging from 0°, pointing north, to 360° in the clockwise direction. To reclassify an aspect, use the Reclassify tool by selecting the aspect raster produced in the previous step. Then Save the reclassified aspect raster and make a map of rooftop-suitable orientations and calculate aspect using attribute table.

The reclassification ranges are guided by solar energy potential:

- 90° - 270°: Optimal (East to West, facing south)
- 0° - 45° and 315° - 360°: Less Optimal (Facing north)
- 45° - 90° and 270° - 315°: Moderate (Northeast and Northwest)
- In northern hemisphere, like Chennai, south-facing rooftops are optimal.



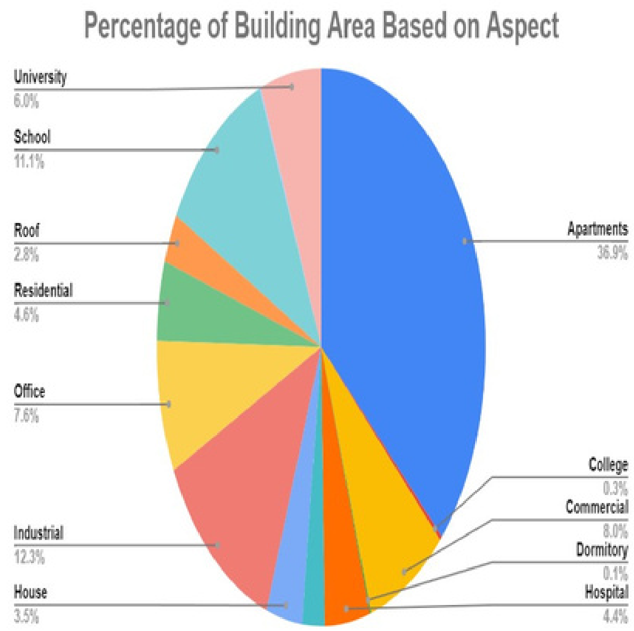




**Fig 5: Aspect map of Chennai and aspect categories distribution based on building area**

- **Suitability analysis of buildings based on optimal slope and aspect:**

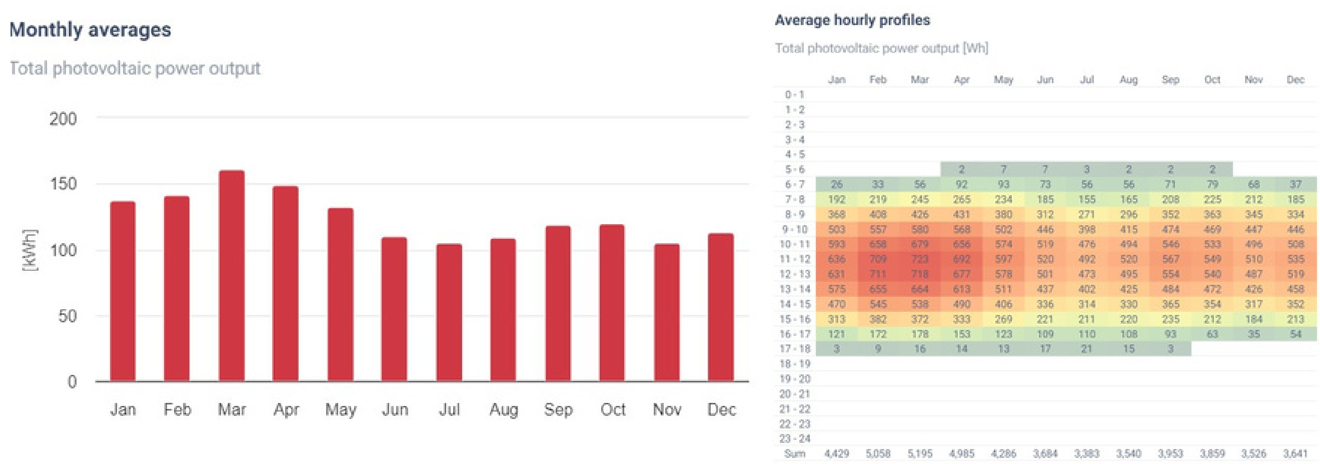
| Buildings | Sum of COUNT | Sum of AREA (sqm) | Slope analysis | | Aspect analysis | |
|---|---|---|---|---|---|---|
| | | | Sum of MIN (degree) | Sum of MAX (degree) | Sum of MIN (degree) | Sum of MAX (degree) |
| Apartments | 584 | 565408.4281 | 0.04 | 10.78 | -1 | 356.34777 |
| College | 4 | 3872.660466 | 2.70 | 7.06 | 258.6900 | 291.8014 |
| Commercial | 126 | 121988.8047 | 0.18 | 10.54 | 0 | 355.6012 |
| Dormitory | 2 | 1936.330233 | 1.06 | 4.24 | 45 | 235 |
| Hospital | 70 | 67771.55816 | 0.61 | 9.58 | 0 | 358.1523 |
| Hotel | 35 | 33885.77908 | 1.70 | 14.61 | 0 | 346.6075 |
| House | 56 | 54217.24653 | 0.037 | 9.72 | 0 | 341.5650 |
| Industrial | 195 | 188792.1977 | 0.43 | 9.56 | 0 | 356.1859 |
| Office | 121 | 117147.9791 | 0.43 | 23.88 | 0 | 357.2736 |
| Residential | 73 | 70676.05351 | 0.19 | 11.98 | 14.036242 | 353.2901 |
| Roof | 45 | 43567.43024 | 0.68 | 11.24 | 2.7263102 | 338.6293 |
| School | 175 | 169428.8954 | 0.273 | 10.73 | 0 | 356.6335 |
| Terrace | 2 | 1936.330233 | 0.80 | 3.74 | 153.43495 | 153.4349 |
| University | 95 | 91975.68607 | 0.74 | 8.78 | 0 | 356.4236 |
| **Grand Total** | **1583** | **1532605.379** | **9.929** | **146.50** | **472.8875** | **4456.9467** |

Table 1: Suitability analysis of buildings based on optimal slope and aspect

**Data output:** After discarding all highlighted rows in Aspect table final result is
• Acceptable Rooftops with slopes between 10° to 20°
• Total Area of suitable slope is 140.7712 ha
• Rooftops facing south (112.5° - 247.5°) which includes Southeast (112.5°-157.5°), South (157.5°-202.5°), Southwest (202.5°-247.5°)
• Total Area of suitable aspect -152.87 ha.
• Total suitable slope and aspect area- 35.0712 ha

**c. Solar radiation calculation:** The solar irradiation at Chennai is seasonal in nature. It varied from months, thus the average photovoltaic output changes depending on solar irradiance and angle of sun positioning to be within 100-160 kWh. The maximum value happened in March because it exceeded about 160 kWh whereas in June and July it's at minimum values because when it goes lesser than 100 kWh with monsoon cloud cover prevailed over this place.

As during monsoon season the output remains stable at approximately 120 kWh because Chennai's winter time is sunny. There exists a peak of the daily solar radiation in between hours of 9:00 am to 2:00 pm. Also during summer months that is, June, July, August, and September, due to steady output, which is from 9:00 am till 3:00 pm. So, the proper placement shall be done keeping in view the maximum possible exposure through the peak hours in dry seasons.




Average hourly profiles

Total photovoltaic power output [Wh]

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 1 | | | | | | | | | | | | |
| 1 - 2 | | | | | | | | | | | | |
| 2 - 3 | | | | | | | | | | | | |
| 3 - 4 | | | | | | | | | | | | |
| 4 - 5 | | | | | | | | | | | | |
| 5 - 6 | | | | 2 | 7 | 7 | 3 | 2 | 2 | 2 | | |
| 6 - 7 | 26 | 33 | 56 | 92 | 93 | 73 | 56 | 56 | 71 | 79 | 68 | 37 |
| 7 - 8 | 192 | 219 | 245 | 265 | 234 | 185 | 155 | 165 | 208 | 225 | 212 | 185 |
| 8 - 9 | 368 | 408 | 426 | 431 | 380 | 312 | 271 | 296 | 352 | 363 | 345 | 334 |
| 9 - 10 | 503 | 557 | 580 | 568 | 502 | 446 | 398 | 415 | 474 | 469 | 447 | 446 |
| 10 - 11 | 593 | 658 | 679 | 656 | 574 | 519 | 476 | 494 | 546 | 533 | 496 | 508 |
| 11 - 12 | 636 | 709 | 723 | 692 | 597 | 520 | 492 | 520 | 567 | 549 | 510 | 535 |
| 12 - 13 | 631 | 711 | 718 | 677 | 578 | 501 | 473 | 495 | 554 | 540 | 487 | 519 |
| 13 - 14 | 575 | 655 | 664 | 613 | 511 | 437 | 402 | 425 | 484 | 472 | 426 | 458 |
| 14 - 15 | 470 | 545 | 538 | 490 | 406 | 336 | 314 | 330 | 365 | 354 | 317 | 352 |
| 15 - 16 | 313 | 382 | 372 | 333 | 269 | 221 | 211 | 220 | 235 | 212 | 184 | 213 |
| 16 - 17 | 121 | 172 | 178 | 153 | 123 | 109 | 110 | 108 | 93 | 63 | 35 | 54 |
| 17 - 18 | 3 | 9 | 16 | 14 | 13 | 17 | 21 | 15 | 3 | | | |
| 18 - 19 | | | | | | | | | | | | |
| 19 - 20 | | | | | | | | | | | | |
| 20 - 21 | | | | | | | | | | | | |
| 21 - 22 | | | | | | | | | | | | |
| 22 - 23 | | | | | | | | | | | | |
| 23 - 24 | | | | | | | | | | | | |
| Sum | 4,429 | 5,058 | 5,195 | 4,985 | 4,286 | 3,684 | 3,383 | 3,540 | 3,953 | 3,859 | 3,526 | 3,641 |

**Fig 6: Monthly and hourly averages of solar radiation graph from Global Solar Atlas**

**Azimuth angle and sun paths for Chennai:’** The graph shows the sun's path across Chennai's sky, with East at 90°, South at 180°, and West at 270°. Understanding solar azimuth and elevation angles is crucial for optimizing solar panel orientation. The x-axis provides information on the solar azimuth angle, while the y-axis shows the solar elevation angle. Sun-path lines are represented at different times of the year, such as June Solstice, December Solstice, and equinoxes. The yellow-shaded area shows the time of day and year when solar elevation is high enough to generate significant energy, making it an active area for solar energy collection.

In Chennai, the optimal solar panel orientation is towards the south, as the sun remains in the southern half of the sky at an azimuth of 180°. Tilting the solar panel during the summer solstice would require positioning it at a higher elevation. The highest solar path is noon solely, where solar panels receive the most direct sunlight and energy output. Seasonal variations of the solar path require optimization of solar panel systems.

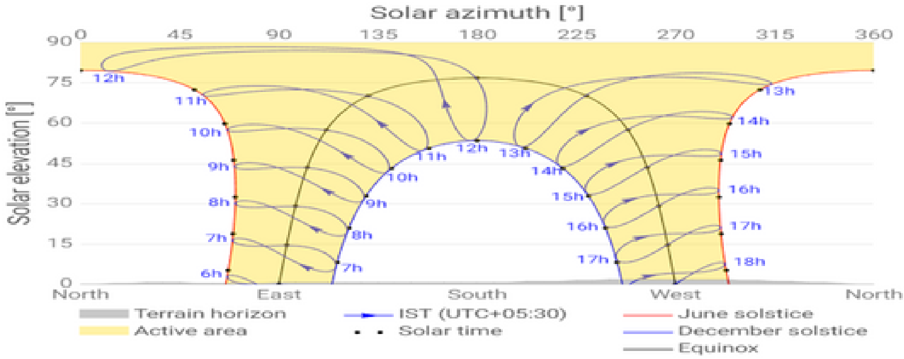



**Fig 7: Azimuth Angle and Sun Paths for Chennai from Global Solar Atlas**

**Solar radiation analysis:**

Solar radiation analysis can be can be done using the Area Solar Radiation tool located in the "Spatial Analyst" toolbox. It will conduct a solar radiation analysis by calculating parameters such as the amount of incoming solar radiation into a geographic area over a specified period using the input surface, time configuration, latitude, and calculation for multiple points. This tool outputs a raster displaying, in the attribute table, the amount of solar radiation received by every cell during a specified period. The raster can then be saved for further use in a map view of good orientations.

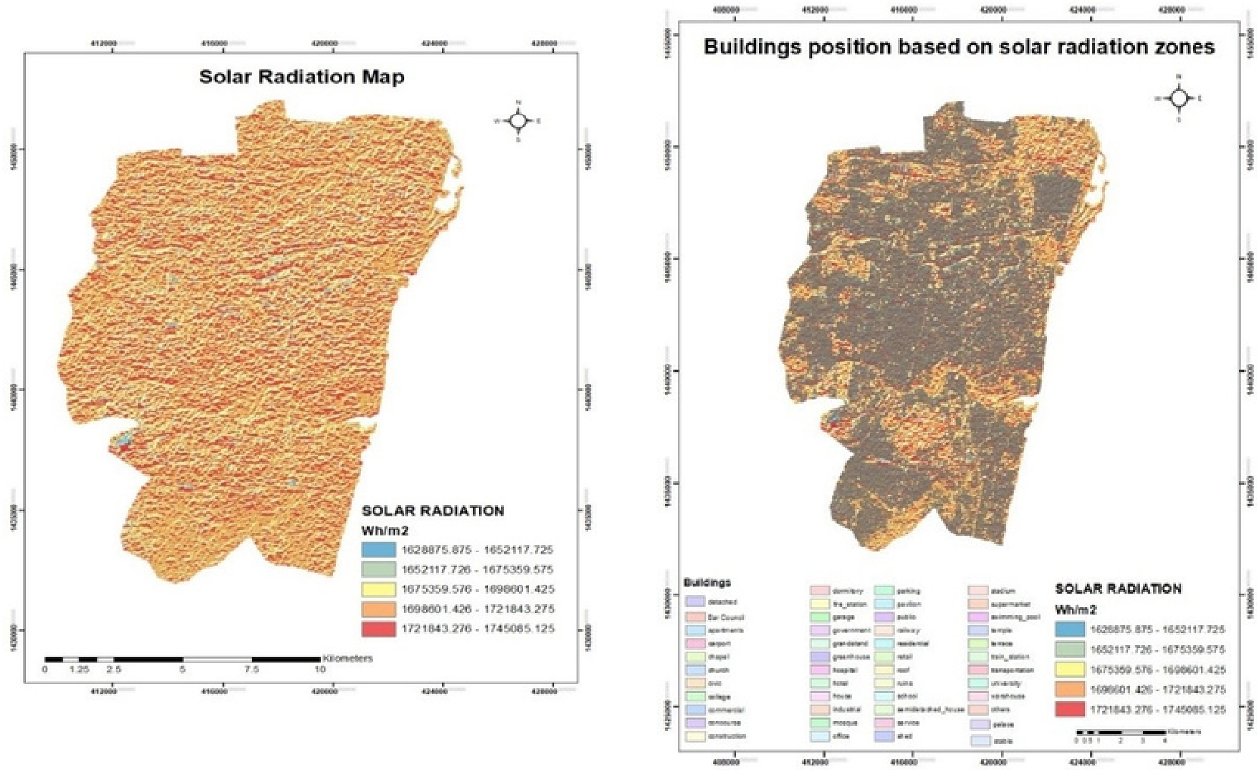



**Fig 8 : Solar radiation map**

| Buildings | Sum of COUNT | Sum of AREA (sqm) | Annual Solar Radiation | | Daily Solar Radiation | |
|---|---|---|---|---|---|---|
| | | | Sum of MIN (Wh/m2) | Sum of MAX (Wh/m2) | Sum of MIN (Wh/m2) | Sum of MAX (Wh/m2) |
| Apartments | 584 | 565408.4281 | 1659938.125 | 1740332.375 | 3916.909 | 5363.258 |
| College | 4 | 3872.660466 | 1714271 | 1723869.5 | 5100.128 | 5363.258 |
| Commercial | 126 | 121988.8047 | 1680224.875 | 1735908.75 | 3388.363 | 5622.003 |
| Dormitory | 2 | 1936.330233 | 1718286.375 | 1719304.25 | 4668.998 | 5421.904 |
| Hospital | 70 | 67771.55816 | 1701439.75 | 1732458.375 | 4482.702 | 5634.221 |
| Hotel | 35 | 33885.77908 | 1692789 | 1737972.25 | 3340.077 | 5632.980 |
| House | 56 | 54217.24653 | 1671085.375 | 1733656.5 | 4404.022 | 5632.980 |
| Industrial | 195 | 188792.1977 | 1649025.75 | 1737494.5 | 4658.726 | 5647.827 |
| Office | 121 | 117147.9791 | 1669303.625 | 1743840.125 | 2155.717 | 5623.086 |
| Residential | 73 | 70676.05351 | 1688808.625 | 1745004.5 | 3734.211 | 5618.813 |
| Roof | 45 | 43567.43024 | 1680950.75 | 1731227.125 | 4133.954 | 5638.405 |
| School | 175 | 169428.8954 | 1666327.375 | 1740700.875 | 4340.452 | 5644.602 |
| Terrace | 2 | 1936.330233 | 1720639.75 | 1724691.375 | 5175.141 | 5535.949 |
| University | 95 | 91975.68607 | 1697137 | 1738909 | 4392.403 | 5630.409 |
| Grand total | 1583 | 1532605.379 | 23610227.38 | 24285369.5 | 57891.8 | 78009.7 |

Table 2: Suitable Rooftops based on annual and daily solar radiation

# 7.Results

## Calculation:

### A. Annual solar radiation calculation:

The annual solar radiation is calculated by performing the summation of the total solar radiation value in Wh/m²/year over the building footprints. To extract suitable rooftops: the Extract by Mask tool will be used; the input raster will be the combined raster; input mask data will be building footprints; the output raster will be defined; then run the tool. There will be an estimation of the total potential of energy generated.

**• Suitable rooftops based on annual solar radiation:**

**1. Solar irradiance calculation**

**Formula:** $Q=H\times A\times \eta\times LF$

Where:

• Q = Total solar energy received (kWh/day or kWh/year)

• H= Average daily solar radiation (kWh/m²/day, e.g., GHI or DNI)

• A = Area of the rooftop or solar panel (m²)

• η = Efficiency of the solar panel (e.g., 0.18 for 18% efficiency)

• LF = Loss factor accounting for shading, dirt, etc. (e.g., 0.85)

• Total solar energy received (Q)= 1718.35 kWh/year ×100m²×0.18×0.85

=26290.755 kWh/m²/year

**2. Electricity generation calculation:**

- **Formula:** $E = Q \times \eta$ = 26290.755 kWh/m²/year ×0.85 =22347.141 kWh/Year

**3. Cost analysis**

- **Formula:** $C = E \times P$ (where cost of electricity 7 Rs. Per kWh)

  =156,429.987 Rs. /Year

**Overlay analysis:**

- Merge the re-classified slope, aspect and solar radiation raster's using the Raster Calculator tool.
- Generate the final suitability map representing areas highly suitable for solar panel installations.

| Buildings | Sum of COUNT | Sum of AREA (Sqm) | Sum of MIN (Wh/m2) | Sum of MAX ((Wh/m2) | Sum of RANGE ((Wh/m2) |
|---|---|---|---|---|---|
| Apartments | 584 | 565408.4281 | 3916.909 | 5634.388 | 1717.478 |
| Commercial | 126 | 121988.8047 | 3388.363 | 5622.003 | 2233.640 |
| Hospital | 70 | 67771.55816 | 4482.702 | 5634.221 | 1151.519 |
| Hotel | 35 | 33885.77908 | 3340.077 | 5624.889 | 2284.812 |
| House | 56 | 54217.24653 | 4404.022 | 5632.980 | 1228.958 |
| Industrial | 195 | 188792.1977 | 4658.724 | 5647.827 | 989.101 |
| Residential | 72 | 69707.88839 | 3734.211 | 5618.813 | 1884.602 |
| Roof | 45 | 43567.43024 | 4133.954 | 5638.405 | 1504.451 |
| School | 175 | 169428.8954 | 4340.452 | 5644.602 | 1304.149 |
| University | 95 | 91975.68607 | 4392.403 | 5630.409 | 1238.005 |
| Grand total | 1453 | 1406743.914 | 40791.824 | 56328.541 | 15536.717 |

Table 3: Overlay analysis of suitable Rooftops

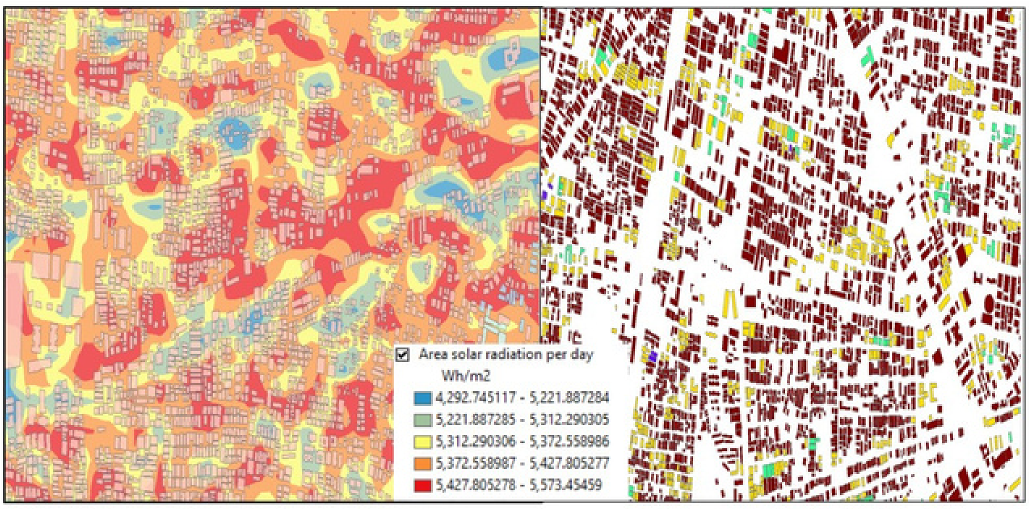



**Fig 9: Buildings based on overlay analysis**

## B. Daily solar radiation:

**1. Solar irradiance calculation**

$Q=H\times A\times \eta \times LF$ =5.32 kWh/day×100m²×0.18×0.85 =81.39 kWh/m²/day

2. Electricity Generation Calculation

$E=Q\times \eta$ = 81.39 kWh/m²/day ×0.85 =69.18 kWh/day ~ 70 kWh/day

3. Cost Analysis

$C=E\times P$ (where cost of electricity =7 Rs. Per kWh) = 490 Rs. /Day

=178,850 Rs. /Year

4.**Potential Electricity generation:**

| Description | Calculation | Result |
|---|---|---|
| Daily Electricity Generation | = 70 kWh/m²/day × 1,406,743.914 m² | 98,472,073.98 kWh/day |
| Yearly Electricity Generation | = 98,472,073.98 kWh/day × 365 days/year | 35,936,308,986.7 kWh/year |
| Convert to GWh/year | = 35,936,308,986.7 kWh/year / 1,000,000 | 35,936.31 GWh/year |
| Convert to GW/year | = 35,936.31 GWh/year / 8,760 hours/year | 4.10 GW/year |

Table 4: Potential electricity generation calculation

**4. Economic analysis:**

Under Grid Connected solar rooftop program, now PM Surya Ghar Bijli Yojana, Central Financial Assistance of 40% is available for Rooftop Solar systems (RTS) of up to 3 kW capacity (Up to 3 kW- Rs. 14588/- per kW) and 20% for capacity beyond 3 kW and up to 10 kW (Rs 14588/- per kW for the first 3 kW and thereafter Rs 7294/- per kW) and Above 10kW (Rs 94822/- fixed).

For the Group Housing Societies and Residents Welfare Associations, the CFA was restricted to 20% for RTS plants supplying power to common facilities. The provisioning of a higher CFA, through the National Portal, proportionate to the higher benchmark cost prescribed for North Eastern States and hilly States/UT has been requested by the Ministry.

**Cost analysis:** Based on the above data cost analysis of Chennai Solar rooftop potential will be following:

**Daily savings:**

- Daily energy generation = 70 kWh
- Cost of electricity per kWh = ₹7
- Daily savings = 70 kWh × ₹7/kWh = ₹490

**Monthly savings:**

• Monthly savings = Daily savings × 30 (average days in a month)
• Monthly savings = ₹490 × 30 = ₹14,700

**Total cost of the solar installation:**

• Installation cost per kW = ₹40,000
• Total installation cost without subsidies = 10 kW × ₹40,000/kW = ₹400,000

**Government subsidies calculation:**

• Subsidy for the first 3 kW: 3 kW × ₹14,588/kW = ₹43,764
• Subsidy for the remaining 7 kW: 7 kW × ₹7,294/kW = ₹51,058
• Total subsidy = ₹43,764 + ₹51,058 = ₹94,822

**Net Cost of the Solar Installation After Subsidy**

• Net cost = Total installation cost - Total subsidy = ₹400,000 - ₹94,822 = ₹305,178

**Payback Period**

• Payback period (in months) = Net cost / Monthly saving = ₹305,178 / ₹14,700 ≈ 20.8 months

**Annual ROI Calculation:**

• Annual savings = Monthly savings × 12 = ₹14,700 × 12 = ₹176,400
• ROI = (Annual savings / Net cost) × 100% = (₹176,400 / ₹305,178) × 100% ≈ 57.8%

### 5.Carbon footprint calculation:

Climate change is a global concern, prompting a shift towards renewable energy sources, particularly solar power. To encourage solar rooftop, use in cities like Chennai, it is crucial to calculate the carbon footprint of solar rooftops. This helps quantify CO2 emission reduction and accelerates the net-zero target. This information aids in policy decisions, public awareness, and future renewable energy projects. It also contributes to long-term sustainability by holding stakeholders accountable for their environmental impacts and contributing to global climate goals. Installing solar rooftops in Chennai can reduce carbon emissions by approximately 23,184 kg per year, or 23.18 metric tons, for every 10 kW solar installation.

| Daily Carbon Emission Reduction | Monthly Carbon Emission Reduction | Annual Carbon Emission Reduction |
| --- | --- | --- |
| • Daily energy generation = 70 kWh<br>• Carbon emissions per kWh from the grid = 0.92 kg $CO_2$<br>• Daily carbon reduction = 70 kWh × 0.92 kg $CO_2$/kWh = 64.4 kg $CO_2$ | • Monthly carbon reduction = Daily carbon reduction × 30 (average days in a month)<br>• Monthly carbon reduction = 64.4 kg $CO_2$ × 30 = 1,932 kg $CO_2$ | • Annual carbon reduction = Monthly carbon reduction × 12<br>• Annual carbon reduction = 1,932 kg $CO_2$ × 12 = 23,184 kg $CO_2$ |

Table 5: Carbon footprint calculation

# 8.Discussion

In Chennai, GIS mapping of rooftop solar potentials has been a great insight into the potential of harnessing solar energy within the city and transitioning into a more sustainable future. Irradiance data, electricity generation, cost analysis, and carbon footprint calculation indicate that rooftop solar systems have the potential to address a significant share of energy demand within the city. This, in turn, could mean energy independence and security, since the dispersion of energy production in solar rooftops cuts down on the risks related to energy imports and price volatility.

- **Potential solar energy generation:** The calculated solar irradiance is 81.39 kWh/m²/day, and the resultant electricity generation potential from a 100 m² rooftop in Chennai is 70 kWh/day, depicting high solar potential for the region. From 1406743.914 m² suitable rooftop area available in Chennai that would result in an enormous potential of approximately 35,936 GWh/year. This might give a generation capacity of 4.10 GW per year, which can considerably reduce its dependence on non-renewable sources of energy. This will ensure energy security because locally generated energy from solar rooftops displaces the risks that accrue from energy imports and price volatility.
- **Economic benefits:** Indicative cost analysis is very promising for a payback period of about 20.8 months and annual ROI of 57.8%. This makes rooftop solar installation financially viable for all categories of consumers and, therefore, an attractive investment opportunity. Reduced electricity bills on account of rooftop solar installations, coupled with subsidies offered by the government, encourage the usage of rooftop solar systems that become economically viable for long-term benefits to residents and businesses.
- **Carbon footprint analysis:** It emerges that city-wide rooftop solar adoption in Chennai will result in significant reductions of $CO_2$ emissions into the environment, approximately 23.18 metric tons of $CO_2$ per 10 kW installation. This surely aligns with the goal of Global Climate Action and hastens the movement of the city toward net-zero city emissions much earlier. In light of the above, moving away from fossil fuels will give Chennai an edge in leadership over other cities in India in terms of urban sustainability and climate action.
- **Role model for smart cities:** Chennai acts as a role model for other congested urban cities and smart cities in mapping out and implementing solar rooftop potential using GIS. Using the GIS technology effectively, cities can estimate the solar potential accurately, create optimal utilization of rooftop space, and draw strategies towards integrating renewable energy into the urban infrastructure. This approach will not only ensure energy self-sufficiency but also enhance the resilience of the urban power grid.

### Challenges:

The rooftop solar in Chennai is facing many challenges because of the limitations within the net metering policy. It is actually the cap installed under this policy that prevents the residential rooftop solar from reaching 50%, whereas overall approval process acts as a deterrent to the adoption of the same. These rooftop solar installations are not affordable for middle-class families with limited subsidies, with very high initial investments of ₹2,00,000 to ₹3,00,000. They cannot export the surplus electricity to the grid as they do not have infrastructure for higher tension consumers like industries, making them less inclined to invest in solar systems.

Heavy wheeling and additional charges also add to the financial burden, as the wheeling fees have increased over time, which further discourages potential solar investors. Public misconceptions regarding the efficiency of solar in cloudy or monsoon seasons have created barriers, and therefore, the adoption rates are lower among residential consumers. Environmental challenges from toxic materials existing in solar panels, such as lead and cadmium, require solutions for recycling-which are currently underdeveloped. TANGEDCO and TEDA, key agencies of solar projects in Tamil Nadu, are often plagued by various delays and face constraints on financial flows, which ultimately lead them to miss their target deadlines.

### Future solutions:

In Chennai, utilizing net metering for grid-connected systems allows residents and businesses to save money on electricity bills by selling excess energy back to the grid. However, to ensure energy security, smart grids and energy storage solutions are necessary to prevent grid instability. Policymakers must take proactive steps to promote solar energy adoption in cities, reducing carbon emissions and driving urban areas toward sustainable development. This involves integrating urban planning strategies that focus on preparing rooftops and green open spaces for solar energy, further enhancing sustainable growth.

Technologically, the perovskite solar cells are thereby transforming the solar landscape: increasing the panel efficiency, developing energy storage capabilities, and innovation in cooling technologies. Public-private partnerships are important in scaling rooftop solar adoption because they can nance and execute large-scale projects, democratizing access to clean energy. Chennai community solar programs allow multiple households or businesses to share the installation of solar power. This service can be sold to benefit larger society. Handholding at the local government and cooperative level could make it possible for even the poorest households to participate in this transformative solar initiative.

## 9.Conclusion

Chennai has immense potential for solar rooftop installation, with the capacity to generate about 4.1 GW of solar power. However, the growth of solar energy in the city is restricted by high upfront costs, inconsistent policies, lack of awareness among people and space limitations in multi-storied buildings. Enhanced subsidies, low-interest loans, and greater awareness are required to overcome such barriers.

The most important aspect would be regulation streamlining, particularly net metering policies, for wider adoption. Chennai can reach maximum solar capacity with potential mapping through advanced technologies like GIS and planning strategically to help Tamil Nadu meet its goals pertaining to renewable energy.

With enabling conditions set by government policies, technological change, and community-driven initiatives, Chennai has the chance to be a forerunner in sustainable urban development; large-scale solar energy adoption can reduce the carbon footprint of Chennai considerably and position it as a smart city contributing to India’s net zero goals.

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