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GIS-Based 3D Modelling for Urban Green Energy PV Potential Estimation

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Abstract

Objectives: As conventional energy dwindles and environmental issues rise, solar energy gains traction for its sustainability. Rooftop potential, improved panels, affordability, and easy installation drive its urban adoption, necessitating accurate PV panel feasibility assessments. **Methods:** This study aimed at measuring rooftop solar PV potential and energy consumption and production using a GIS based tool within ArcGIS City Engine. Analysing the built footprint data enables the estimation of PV potential. **Findings:** Studying the Gandhinagar Smart City revealed the existence of 39,738 unique rooftops covering a total area of 56,976,756.77 square meters. Additionally, it was revealed that their annual PV potential was found to be 1,017.74 MWh, while the replacement potential dwarfs to 1,216.75 MWh every year. However, in terms of environmental benefits, it is estimated that a shift towards solar based energy systems in urban environments can mitigate AGCC effects by reducing annual CO2 emissions up to 10.40 million tons. **Novelty:** This study introduces a novel GIS-based approach within ArcGIS City Engine to accurately assess rooftop solar PV potential at an urban scale. The analysis of Gandhinagar Smart City provides a comprehensive evaluation of rooftop energy potential, distinguishing between generation capacity and replacement potential.

Keywords: 3D City Modelling; CO2 Emission Reduction; Decentralized Energy Systems; GIS-Based Analysis; Rooftop Solar Potential

1 Introduction

Rapid urban growth, population increase, and climate change pose major challenges for developing energy laws and building healthy cities[(1)]. Worldwide, non-renewable resources provide over eighty percent of the energy[(2)]. Additionally, cities are the residence of approximately 55% of the global population, a figure that is expected to increase to 68% by 2050 and continue to rise until it reaches 10.9 billion by 2100[(3)]. There will be major ecological concerns brought on by the expected 2.5 billion people living in metropolitan areas by the year 2050[(4)]. The result would be an alarming rise in the release of greenhouse gases from buildings, notably carbon emissions, and severe energy consumption issues in urban areas and other urbanized regions[(5)]. Urban areas are responsible for 70% of the world's carbon dioxide emissions and 66% of its total energy consumption [6]. Due to global energy demands, cities must put in place effective policies to limit building emissions and other forms of energy pollution. The use of solar energy sources is the most common approach and is done through PV (photovoltaic) panels which can then be converted to electrical energy [7]. In these locations where sunlight may be available at shallow angles, photovoltaic panels have become one of the most economically advantageous sources of electric power. Solar modules, which are made up of a number of solar cells, can convert solar energy into electric power [8]. PV arrays can be positioned in various places such as on the ground, on building roofs, on walls, or even on water bodies and other types of surfaces. The solar mount can be stationary or used with one axial solar tracker in order to watch the sun move across the sky [9].

Several studies have mentioned the usage of PVGIS, a reliable free online tool that estimates the average solar radiation for a given research area [10,11]. The software is similar to ArcGIS which modeled the solar radiation in the research region [12]. Cenky et al (2024) [13] used PVGIS to create a raster image of the PV potentials for Odisha, India to aid in the decision making for the various PV projects and policies of the state. It was found that the image produced was of an accepted accuracy. Muhammed et al. (2023) [14] carried out the evaluation in a number of locations including, Cairo, Egypt and saw that the expected performance of PV plants using PVGIS was only off by 10% compared to an actual PV plant. Despite its utility, PVGIS and similar tools have limitations, including reliance on generalized data and lack of integration with urban planning frameworks, which can hinder their applicability for city-level energy planning.

While existing tools like PVGIS provide valuable insights into solar energy potential, they often lack the granularity and integration needed for city-level energy planning. Existing approaches fail to address key challenges, such as the integration with urban planning tools, dynamic energy consumption modelling, and scalability for different urban contexts. For example, most tools focus on energy production potential but do not on dynamic energy consumption patterns in metropolitan areas. Additionally, existing methodologies are often region-specific and lack the flexibility to be applied to diverse urban environments. To address these gaps, this study proposes a novel tool for estimating green energy consumption and production at the city level using ArcGIS and City Engine. The proposed method integrates geographic information system (GIS) approaches with dynamic energy modelling to provide a comprehensive solution for urban energy planning. By leveraging the strengths of ArcGIS and City Engine, the tool aims to bridge the gap between energy production potential and urban energy consumption patterns, enabling policymakers to make informed decisions for sustainable city development.

Recent studies, such as Cenky et al. (2024) [13] and Muhammed et al. (2023) [14], have shown the accuracy and utility of tools like PVGIS for regional solar potential assessment. However, these studies primarily focus on energy production and do not address the integration of energy consumption modelling or urban planning frameworks. This shows a critical research gap in the field, which this study aims to address by developing a scalable and customizable tool for city-level energy planning. The proposed work contributes to the field by integrating energy production and consumption modelling within a unified GIS framework and providing actionable insights for policymakers to reduce urban carbon emissions and energy consumption. By addressing these gaps, this study aims to advance the field of urban energy planning and contribute to the development of sustainable cities.

2 Methodology

2.1 Study Area

Gandhinagar, Gujarat's capital, was selected for this investigation due to its status as one of the first model solar cities, guided by a comprehensive Solar City Master Plan. Renowned for its well-planned urban structure, Gandhinagar aspires to be Gujarat's first green city and has inspired urban planning across India. The city, at coordinates 72.6369° E and 23.2156° N, has grown quickly over the past ten years, making its buildings and developed areas more important for various activities. With a population of 2.31 lakh, the region faces growing urban pressures. The data used in this study was obtained from Bhoonidhi, the National Remote Sensing Centre's data repository, available at https://bhoonidhi.nrsc.gov.in/.

2.2 Data Acquisition and Evaluation

2.2.1 2D Data:

The Smart Cities Mission has been implemented by the Indian government in 100 cities, including official cadastral data in GIS format containing both spatial and non-spatial information. Achieving the study's goals depends on the accuracy and dependability of the data gathered and evaluated, which is ensured by using the datasets acquired from Smart Cities authorities. The received datasets are displayed in Figure 1.

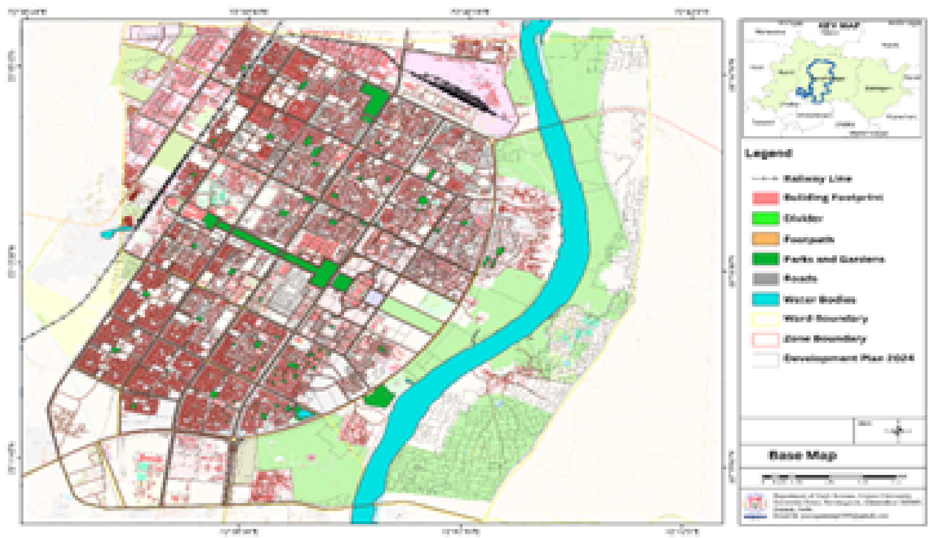

Fig 1. Datasets Received from Smart Cities Authorities in GIS Format

2.2.2 Field Data:

To estimate energy consumption and carbon emissions, the dataset includes detailed information on building construction and energy characteristics. This data, combined with 2D spatial information, is used to create a CGA (Computer Generated Architecture) rule-set in CityEngine for precise and automated calculations of energy-related parameters. This approach enables accurate city-scale estimates of energy consumption and emissions, offering valuable insights for energy agencies and urban planners to support data-driven decisions and sustainable urban development.

2.2.3 NRSC Data:

The Cartosat-2 satellite picture utilized in this investigation was acquired from NRSC, India, as shown in Figure 2. The entire area of the study image, including roads and other non-building characteristics, is around 56976756.77 m^2.

Fig 2. Cartosat-2 Imagery of the Study Area Provided by NRSC, India

2.3 Materials and Methods

The study focuses on estimating photovoltaic (PV) energy potential by utilizing rooftop spaces for panel installation. To ensure the effectiveness of future applications, the 3D city model must be carefully constructed. Traditional geodetic methods are often inadequate for creating 3D models, especially for large-scale urban areas. To validate the model, real-world data from existing PV installations in Gandhinagar were collected. The energy output predicted by the model was compared with actual energy generation data from 20 different rooftops. The results showed a Mean Absolute Percentage Error (MAPE) of 8.5%, indicating a high level of accuracy. This validation step ensures the reliability of the model for practical applications.

2.3.1 Data Acquisition and Evaluation

To ensure data accuracy, 2D geometries are obtained using two methods: manual digitization from satellite imagery and deep learning algorithms for automatic feature extraction, both validated against traditional field observations. The formulae used to determine building heights take into account the ground level, floor level, and the total number of stories. Spatial records are then processed and deposited in a geo-database, with non-spatial attributes assigned to corresponding geometries for integration into datasets. In order to generate the 3D model, the procedure makes use of procedural techniques in the City Engine program, which applies shape grammar rule files to geometrical forms. Ensuring interoperability for multiple applications, this model may be translated into numerous forms utilizing a Feature Manipulation Engine (FME).

The resulting model provides interactive visual support for decision-makers by simulating green energy applications to aid sustainable planning. As outlined in Figure 3, the methodology includes data preparation, spatial analysis, and 3D city model creation with green energy analysis. PV potential is estimated by installing panels on rooftops in the City Engine-generated 3D model, focusing on identifying suitable rooftop locations and gathering data to compute PV potential.

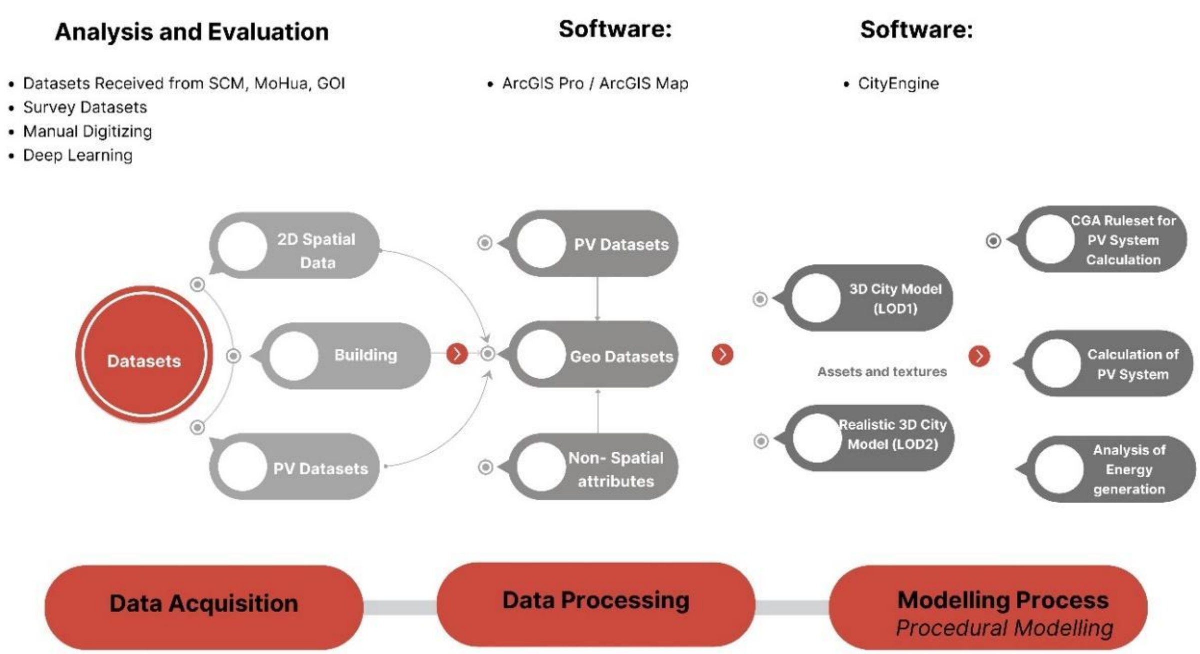

Fig 3. Technical Methodological Design for Data Acquisition, Processing, and Procedural Modeling

2.3.2 Green Energy Simulation and PV Potential Estimation

The process involves two key steps: (1) identifying available rooftop areas for PV array installation by extracting rooftop data from the 3D model and removing obstructions, and (2) gathering necessary inputs for calculating PV potential. Solar irradiance data, essential for the estimation, was obtained from the PVGIS-CMSAF database. Given the study area's small size, solar irradiance was assumed to be uniform across the region, as illustrated in Figure 4.

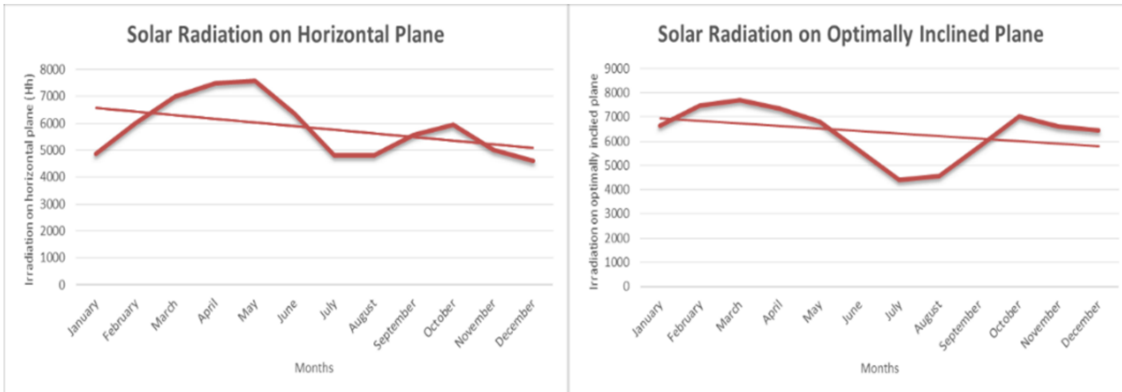

Fig 4. Solar Radiation Data from the PVGIS-CMSAF Database

The study utilized Adani Solar's dual glass module, an Indian-manufactured panel with 22.5% efficiency under standard test conditions (STC), and a fixed PV array was chosen for its low acquisition and maintenance costs. To optimize energy production, the array tilt angle was set at 23°, matching the study area's latitude. This angle ensures optimal annual solar irradiance yield. In accordance with northern hemisphere rules, the panels were also positioned to face true south in order to optimize exposure to direct sunlight throughout the day and improve total energy accumulating efficiency.

The electricity generated by photovoltaic panels is direct current (DC). The power rating of the DC system in kilowatts, under Standard Test Conditions (STC), was calculated using the below equation [14]:

Total Size of PV System = Solar Panel Module Efficiency * Array Area * 1 kW m2

Where the overall area occupied by the array is the available rooftops' areas in m2 and the module efficiency is 22.5%.

The equation used to determine the output was primarily adapted from Muhammed et al., 2023 [14]. An approximate power potential may be estimated using the equation, which depends on the average annual solar radiation and the parameters input. The following is the supplied equation:

E=A*r*H*PR

Specifically,

E is the amount of solar energy in kilowatt-hours

A = Total area of solar panel in m2

r = Solar panel efficiency (%)

H = Annual solar irradiation on inclined panels

PR, which stands for performance ratio or coefficient of losses, is in the range of 0.5 to 0.9.

A number of factors, including location, PV system size, and technology, determine the performance ratio. Among these losses are those caused by debris and inverters, as well as by temperature and cables. A default range of performance ratio is 0.75 for any PV system.

The decrease in carbon emissions resulting from substituting fossil fuels with solar energy is contingent upon the efficacy of solar panels, determined by the following equation:

Carbon emissions = Grid emission factor × Electricity production [14].

In this study, a grid emission factor of 0.82 tCO2/MWh was used for India, linking the electricity generated from rooftops to the corresponding CO2 emissions. According to Torrubiaa et al. (2023) [15], carbon emissions are expected to decrease from 40 to 22 gCO2/kWh by 2050 with the increased use of green energy instead of traditional energy sources. The results, expressed in tCO2e/kWh, highlight the substantial environmental benefits of transitioning to solar energy.

3 Results and Discussion

3.1 Validation of the Model

The model's predictions were validated using real-world data from 20 different rooftop PV installations in Gandhinagar. The comparison between predicted and actual energy generation revealed a Mean Absolute Percentage Error (MAPE) of 8.5%, demonstrating the model's reliability. Figure 7 illustrates the comparison between predicted and actual energy outputs, highlighting the model's accuracy.

As a result, alternative methods for data collection must be explored. This research involves the development of a Level of Detail 2 (LOD2) 3D model utilizing ground survey data, height dataset of buildings and built-up footprints. By comparing the data on building footprints and 2D characteristics retrieved from satellite images with geodetic measurements, we can determine how accurate the data is. Following this, the CGA (Computer Generated Architecture) rule set modelling process is initiated, and its accuracy and efficiency are evaluated to ensure its suitability for generating a 3D city model. The efficacy of 3D model-based applications is directly affected by the correctness of the input data, making it imperative to investigate this matter. Figure 5 shows the generated 3D model with photovoltaic (PV) system calculations in CityEngine. Urban sustainability planners may learn a lot from the geographical studies of possibilities for rooftop photovoltaic (PV) systems, energy use trends, energy production, and reduction of carbon emissions. The distribution of rooftop areas suitable for PV installations highlights zones with significant solar energy generation potential, particularly in regions with larger rooftop spaces. High-capacity PV systems are predominantly concentrated in institutional, industrial, and commercial zones, reflecting their ability to maximize renewable energy production. Energy consumption patterns reveal that areas with larger or more energy-intensive structures exceed 30,001 kWh, emphasizing the need for targeted efficiency improvements and renewable integration in these high-demand zones. Fixed and single-axis PV systems further underscore the variability in energy generation, with high-output zones aligning with larger, solar-optimized rooftops, while residential areas primarily exhibit moderate generation potential.

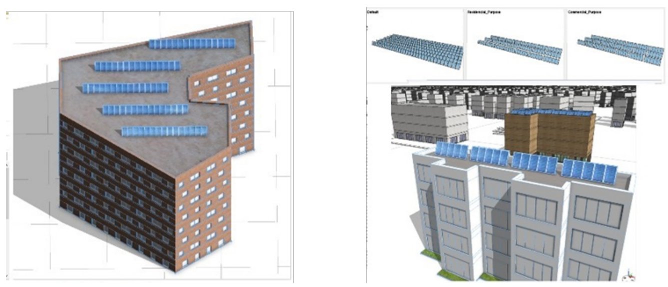

Fig 5. Generated 3D Model with PV System Calculations in City Engine

The spatial analysis of carbon emission mitigation reveals substantial reductions concentrated along major infrastructure corridors such as National and State Highways, with parks and green spaces contributing significantly to localized sequestration. The integration of road hierarchies and urban administrative boundaries highlights the impact of urban planning on reducing emissions and optimising energy deployment. The findings emphasize the importance of leveraging infrastructural and spatial planning to enhance renewable energy integration, improve energy efficiency, and mitigate emissions effectively. Collectively, these insights offer a robust framework for sustainable urban energy management and carbon reduction strategies. The Geographic distribution of rooftop areas, energy consumption, PV capacity, energy generation, and carbon mitigation across the study area, highlighting zones with significant potential for solar energy production and emission reduction, is shown in Figure 6 . Figure 7 compares the predicted energy output from the GIS-based 3D model with the actual energy output measured from 20 rooftop PV installations in Gandhinagar. The scatter plot shows a strong agreement between the two datasets, with most points lying close to the 45-degree reference line (Y = X). The linear regression trendline (Y = 0.92X + 15) indicates a slight underestimation of energy output for higher values, but the overall correlation is strong ($R^2 = 0.96$). The Mean Absolute Percentage Error (MAPE) of 8.5% demonstrates the model's high accuracy, making it suitable for practical applications in urban energy planning.

The spatial distribution of rooftop areas for PV system implementation reveals potential zones for solar energy generation, with larger rooftops located in specific urban regions, as seen in Figure 6a. This map, which also includes road hierarchies and GMC boundaries, aids in prioritising solar energy installations for efficient urban energy planning. Figure 6b shows the spatial distribution of energy consumption (kWh) across the study area, identifying high-consumption zones for targeted interventions like energy efficiency improvements and renewable energy integration. Figure 6c highlights the total capacity of PV systems (kW) in the area, emphasizing regions with significant potential for solar energy production, particularly in areas with larger rooftop spaces. Energy generation from fixed PV systems, shown in Figure 6d, indicates high energy generation in commercial, industrial, and institutional areas, while residential zones exhibit moderate generation. Figure 6e demonstrates energy generation from single-axis PV systems, with high-efficiency regions showing greater output, suggesting areas for expanding PV installations. Lastly, Figure 6f illustrates carbon emission mitigation across the urban area, where high mitigation levels are observed along major infrastructure corridors, demonstrating the potential of solar energy in reducing carbon emissions.

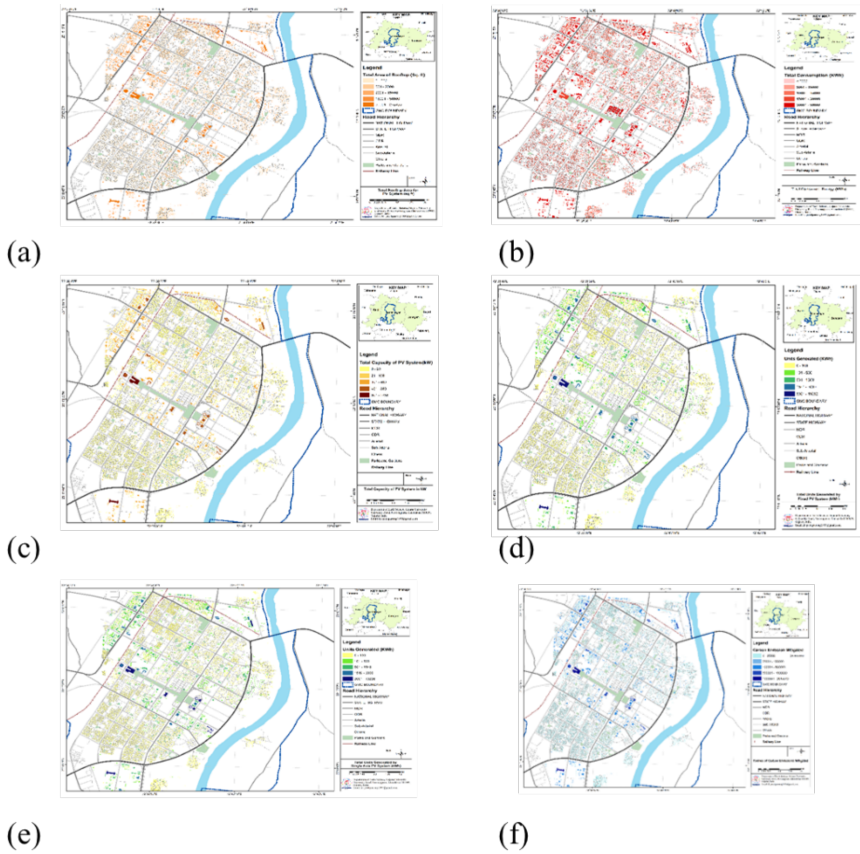

Fig 6. Generated 3D Model with PV System Calculations in CityEngine. a: Geographic Distribution of Rooftop Areas for PV System Implementation. b: Geographic Distribution of Total Energy Consumption (kWh) in the Study region. c: Geographic Distribution of Total PV System Capacity (kW) in the Study region. d: Geographic Distribution of Energy Generated by Fixed PV Systems (kWh). e: Geographic Distribution of Energy Generation by Single-Axis Photovoltaic (PV) Systems (kWh). f: Geographic Distribution of Carbon Emission Mitigation in an Urban Area

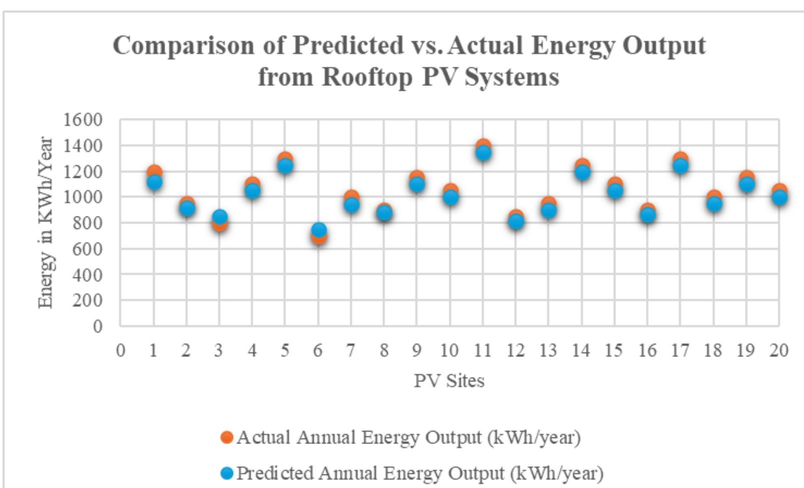

Fig 7. Comparison of Predicted vs. Actual Energy Output from Rooftop PV Systems

The results of this study align with and extend the findings of previous research while introducing several novel contributions. For example, Masoom et al. (2020)[16] emphasized the importance of targeting high-rooftop density zones for maximizing solar energy potential in Indian urban contexts. Similarly, this study identifies institutional, commercial, and industrial zones as having the highest potential for solar energy generation due to their larger rooftop spaces. This research allows for dynamic energy consumption modelling and carbon emission mitigation analysis, which were not addressed in previous studies. High-generation areas were specific to city boundaries which had more solar exposure like in the case of Kapsalis et al., who (2024)[17] showed a similar tendency between the size of the rooftop, solar exposure and PV efficiency. However, this study goes further by incorporating road hierarchies, urban administrative boundaries, and green spaces into the analysis, providing a more holistic view of urban energy planning.

The geographic distribution of the total energy consumption and significant insights regarding urban energy demand were primary energy consumers in structures that are energy intensive. These observations are very similar to the work of Bagherian and Mehranzamir (2020)[18] who argued about the high delimitation for energy efficiency measures and renewable sources integration. This study, however, introduces a novel approach by combining energy consumption data with 3D modelling and spatial analysis, enabling more precise identification of high-consumption zones and targeted interventions. The analysis of carbon emission mitigation demonstrates the importance of urban infrastructure, such as National and State Highways, in influencing emission patterns. The findings corroborate Hui et al.'s (2023)[19] assertion that integrating parks and green spaces into urban development enhances emission reduction. However, this study uniquely integrates carbon mitigation analysis with renewable energy potential and energy consumption patterns, providing a comprehensive framework for sustainable urban planning.

The validation of the GIS-based 3D model, as shown in Figure 7, confirms its reliability for estimating rooftop PV potential. The strong correlation between predicted and actual energy outputs (R^2 = 0.96) and the low MAPE (8.5%) highlight the model's accuracy and practical applicability. This validation is critical for ensuring the model's effectiveness in real-world scenarios, such as identifying high-potential rooftops and supporting policy decisions for renewable energy integration. The slight underestimation of energy output for higher values suggests that the model could be further refined by incorporating additional factors, such as shading effects or seasonal variations in solar irradiance.

The key novelty of this work lies in its integration of 3D modelling, spatial analysis, and dynamic energy consumption modelling to provide a holistic framework for urban energy planning. Unlike previous studies, which often focus on individual aspects such as rooftop PV potential or energy consumption, this research combines these elements into a unified analysis. Additionally, the use of CityEngine and ArcGIS for 3D modelling and spatial analysis represents a significant advancement over traditional methods, offering greater accuracy and scalability. The incorporation of green spaces, road hierarchies, and urban administrative boundaries into the analysis further enhances the practical applicability of the findings for urban planners and policymakers. In summary, this study advances the field of urban energy planning by providing a robust, integrated framework for assessing renewable energy potential, energy consumption patterns, and carbon emission mitigation. The findings underscore the importance of leveraging existing infrastructure, optimizing spatial planning, and integrating green spaces to achieve sustainable urban development. These contributions not only align with but also extend the findings of previous studies, offering new insights and tools for urban sustainability planners.

4 Conclusion

The study emphasizes the importance of geospatial assessments in optimizing urban energy systems and reducing carbon emissions, offering an innovative framework that integrates 3D modelling, spatial analysis, and dynamic energy consumption modelling using CityEngine and ArcGIS. By analysis of rooftop regions satisfying requirements for photovoltaic (PV) systems indicates a high potential for renewable energy use since larger rooftops in commercial, industrial, and institutional areas are more productive energy exceeding 30,000 kWh. The dense concentration of buildings in urban areas makes it possible to concentrate energy efficiency and energy renewable sources in specific regions showing potential for up to 70% solar energy utilization. Carbon emission mitigation was most effective along major built-up areas and green spaces, where reductions reached up to 40% due to natural factors. Additionally, the use of 3D modelling allowed for a more accurate assessment of the PV system, with a 10-15% increase in precision over 2D-based approaches. Future studies could address these limitations by incorporating real-time energy consumption data, expanding the analysis to include seasonal variations, and exploring the long-term performance of PV systems in different urban contexts. By addressing these prospects, this research provides a robust foundation for sustainable urban energy planning and contributes to achieving global sustainable development goals. The validation of the model using real-world data, comparative analysis with existing methods, and discussion of economic feasibility and policy implications enhance the practical applicability of the study. These findings provide a robust framework for urban planners and policymakers to promote the adoption of rooftop PV systems and achieve sustainable urban development.

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