

Article

Large-Scale Modeling of Urban Rooftop Solar Energy Potential Using UAS-Based Digital Photogrammetry and GIS Spatial Analysis: A Case Study of Sofia City, Bulgaria

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Abstract

Urban rooftop photovoltaic systems represent a substantial yet still underutilized renewable energy resource, particularly in high-density residential environments. Accurate large-scale assessment of rooftop solar potential, however, remains challenging due to the complex geometry of urban morphology and the limited availability of high-resolution geospatial data. This study presents a large-scale methodological framework for estimating the theoretical photovoltaic potential of urban rooftop spaces using Unmanned Aerial System (UAS)-based digital photogrammetry and GIS-based spatial analysis. The approach integrates centimeter-resolution Digital Surface Models (DSMs) and orthophotos derived from fixed-wing UAS surveys with detailed rooftop vectorization and solar radiation modeling implemented in a GIS environment. The methodology accounts for rooftop geometry, surface orientation, slope, shading effects, and rooftop-mounted obstacles. The methodology consists of data collection of high-resolution RGB imagery suitable for detailed three-dimensional reconstruction. The images are captured with a UAS equipped with a S.O.D.A. 3D photogrammetric camera, creating a dense, georeferenced three-dimensional point cloud based on UAS imagery. Based on the point cloud, a high-resolution Digital Surface Model (DSM) was produced. Rooftop boundaries and rooftop-mounted structures were digitized on the basis of an orthophoto created from UAS imagery. The analysis workflow consists of solar modeling using ArcGIS Pro, including calculating the solar radiation. The next methodological step is to filter low radiation rooftops, steep slopes, and northern-oriented rooftops. Finally, we calculate the potential electricity production. The framework was applied to high-density residential districts in Sofia, Bulgaria, dominated by prefabricated panel buildings with predominantly flat rooftops. Drone applications in such studies are typically restricted to modeling individual roofs, which severely limits their scalability for district-wide evaluations. To overcome this, the study employs a specialized fixed-wing UAS uniquely certified for legal operations over densely populated urban environments. This platform rapidly maps large territories, ensuring consistent lighting and shading conditions that significantly enhance the accuracy of subsequent rooftop digitization. Furthermore, the resulting centimeter-level precision enables the exact vectorization of micro-rooftop obstacles. Capturing these intricate details is a critical innovation that effectively prevents the overestimation of solar energy potential commonly observed in conventional large-scale models. Solar radiation was modeled at the pixel level for a full annual cycle and filtered using photovoltaic suitability criteria, including minimum annual radiation thresholds, slope, and aspect constraints. Theoretical electricity production



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was subsequently estimated using zonal statistics and system performance parameters representative of contemporary photovoltaic installations. The results indicate a total theoretical annual electricity potential of approximately 76.7 GWh for the analyzed rooftop spaces, with an average production of about 34 MWh per rooftop and pronounced spatial variability driven by rooftop geometry and exposure conditions. The findings demonstrate the significant renewable energy potential embedded in existing urban rooftop infrastructure and highlight the applicability of UAS-based photogrammetry for high-resolution, large-area solar potential assessments. The proposed framework provides actionable information for urban energy planning, municipal solar cadaster development, and the strategic integration of photovoltaic systems into dense urban environments, particularly in regions lacking open-access high-resolution geospatial datasets.

Keywords: rooftop solar potential; digital surface model; geographic information system; large-scale; UAS; digital photogrammetry

1. Introduction

Rapid urbanization, coupled with accelerating climate change and increasing energy demand, has placed urban energy systems under growing pressure to transition toward more sustainable and resilient models. Cities concentrate population, infrastructure, and energy consumption while simultaneously intensifying environmental challenges such as urban heat islands, air pollution, and resource scarcity. In this context, the urban energy balance has emerged as a critical research domain, linking urban morphology, surface properties, and climatic processes with energy production and consumption patterns [1–5].

Among renewable energy sources, solar energy holds a particularly prominent role in urban environments due to its widespread availability and compatibility with the built fabric. Rooftop photovoltaic (PV) systems, in particular, represent a significant yet still underutilized resource for decentralized electricity generation [6,7]. Urban rooftops offer extensive surfaces that can be exploited with relatively low land-use conflict, limited technical constraints, and steadily decreasing installation costs. Consequently, the assessment of rooftop solar potential has become an essential component of sustainable urban energy planning and climate adaptation strategies [8–10]. This resource is abundant, has relatively few technical limitations in its use, and allows for easy installation of equipment at a relatively low cost of PV panels [11].

Accurate estimation of rooftop solar potential remains a complex task that requires a detailed representation of urban morphology, including building height, roof geometry, orientation, slope, and the spatial configuration of surrounding structures influencing shading and solar exposure [12,13]. These parameters are highly heterogeneous in dense urban environments and cannot be reliably captured using coarse-resolution datasets [11].

Existing approaches for rooftop solar potential assessment can be broadly categorized into several methodological groups. Large-scale studies often rely on satellite imagery and generalized building datasets, which enable regional or national assessments but typically involve simplified representations of roof geometry and shading conditions, leading to potential overestimation of solar potential [9,14].

More detailed analyses are commonly based on LiDAR data, which provide high-resolution three-dimensional information and enable more accurate modeling of urban morphology and shading effects [15,16]. However, the application of LiDAR is frequently constrained by high acquisition costs, limited data availability, and operational challenges, particularly in large or heterogeneous urban areas.

In recent years, UAV-based photogrammetry has emerged as a promising alternative, offering very high spatial resolution and detailed reconstruction of rooftop geometry [17–19]. These approaches allow for accurate identification of roof features and improved solar radiation modeling. Nevertheless, most UAV-based studies are limited to relatively small spatial extents due to operational constraints related to flight time, coverage efficiency, and data processing requirements.

As a result, a fundamental trade-off persists in the literature between spatial resolution and spatial coverage: high-resolution methods (e.g., LiDAR and UAV) are typically applied at local scales, while large-scale assessments rely on generalized data with reduced geometric accuracy.

In this context, the present study aims to bridge this gap by integrating fixed-wing UAS photogrammetry, which enables centimeter-level spatial resolution over extensive urban areas. By combining high-resolution data acquisition with efficient spatial coverage, the proposed approach extends detailed rooftop solar potential assessment from building- or neighborhood-scale analyses to the district level while maintaining a high level of geometric accuracy and operational feasibility.

Geographic Information Systems (GISs) have become the dominant analytical framework for rooftop solar potential studies, enabling the integration of spatial datasets with solar radiation models [11,14]. When combined with high-quality elevation data, GIS-based approaches can account for shading effects, surface orientation, and temporal variations in solar irradiance [15]. Airborne LiDAR data have been widely used for this purpose due to their high vertical accuracy; however, their application is often constrained by limited availability, high acquisition costs, logistical complexity, and operational restrictions in densely populated areas [16]. These limitations reduce the feasibility of LiDAR-based approaches for rapid, large-scale assessments in many urban contexts, particularly in regions lacking open-access high-resolution datasets [17].

In recent years, Unmanned Aerial Systems (UASs) combined with digital photogrammetry have emerged as a viable alternative for high-resolution urban data acquisition [18,19].

Advances in UAS technology, sensor quality, and photogrammetric processing now allow the generation of detailed Digital Surface Models (DSMs) and orthophotos with centimeter-level spatial resolution [17]. Fixed-wing UAS platforms, in particular, enable efficient coverage of large urban areas while maintaining high geometric accuracy [16]. These capabilities make UAS-based photogrammetry especially suitable for large-scale rooftop solar potential assessments that require both spatial detail and operational flexibility [15].

Despite the growing body of research on rooftop photovoltaic potential, several gaps remain. Many studies focus either on small-scale analyses at the level of individual buildings or on city-wide assessments based on generalized or medium-resolution datasets [12,20,21]. There is a lack of methodological frameworks that effectively combine very high spatial resolution, large spatial extent, and practical applicability for urban planning and energy management [16]. This gap is particularly evident in Eastern European cities, where urban morphology is strongly shaped by large-scale residential developments constructed during the second half of the twentieth century and where detailed, open-access geospatial datasets are often unavailable [9,22,23].

Against this background, the present study aims to adapt and test a large-scale methodology for assessing the theoretical photovoltaic potential of urban rooftop spaces using UAS-based digital photogrammetry and GIS spatial analysis. The approach is applied to the high-density residential district of Lyulin in Sofia, Bulgaria, characterized by extensive flat-roof panel buildings and complex urban morphology. By integrating centimeter-resolution DSMs, detailed rooftop vectorization, and GIS-based solar radiation modeling, the study

seeks to provide a realistic and spatially explicit estimation of rooftop solar energy potential suitable for large urban areas.

The main contributions of this research are threefold. First, the study demonstrates the operational applicability of fixed-wing UAS photogrammetry for generating centimeter-resolution DSMs over extensive urban areas. By combining very high spatial resolution with efficient area coverage, this approach improves the scalability of UAV-based methods and helps overcome the well-known trade-off between spatial resolution and spatial extent.

Second, it introduces a high-resolution rooftop characterization framework that explicitly accounts for rooftop obstacles and geometric constraints. This significantly improves the accuracy of photovoltaic potential estimation by enabling a more realistic assessment of usable rooftop area and reducing overestimation biases commonly associated with generalized datasets and simplified roof representations.

Third, it proposes an integrated, large-scale solar potential assessment workflow that combines high-resolution data acquisition, detailed 3D modeling, and GIS-based solar radiation analysis. This enhances the applicability of the method for urban solar cadaster development by delivering spatially explicit, operationally relevant outputs that can directly support municipal planning, energy policy development, and the integration of renewable energy into urban energy systems.

Compared to satellite-based methods, the proposed approach achieves significantly higher spatial resolution and data fidelity while remaining operationally flexible [24]; in contrast to LiDAR-based solutions, it represents a more cost-efficient and practically deployable alternative, particularly in urban environments where high acquisition costs and operational constraints may limit the use of such data [25,26].

2. Materials and Methods

The methodological framework of this study is based on the premise that accurate and detailed characterization of urban morphostructural parameters constitutes the primary informational basis for assessing the theoretical solar energy potential under specific geographic conditions. Accordingly, particular emphasis is placed on the precise definition and generation of the Digital Surface Model (DSM). In the context of solar energy assessment, a high-quality DSM provides critical information on elevation differences and surface topography of urban objects, which strongly influence solar irradiance distribution across the studied area. By integrating DSM data into the analytical workflow, shading effects caused by surrounding buildings, vegetation, and other terrain features can be explicitly accounted for, resulting in a more realistic estimation of potential electricity generation from rooftop photovoltaic systems. Below in Figure 1 is the principal methodological scheme of the conducted research.

As the methodological basis for solar potential assessment, the study adopts an approach developed by the ESRI training and research team. The approach has been further adapted and extended by the authors to meet the specific objectives and spatial characteristics of the investigated area. The original workflow provides a standardized GIS-based framework for estimating theoretical solar radiation using high-resolution surface models. The approach modifications introduced in this study are aimed at improving its applicability to large-scale urban environments and complex rooftop geometries. The officially documented version of the base methodology is publicly available through ESRI's learning platform [27].

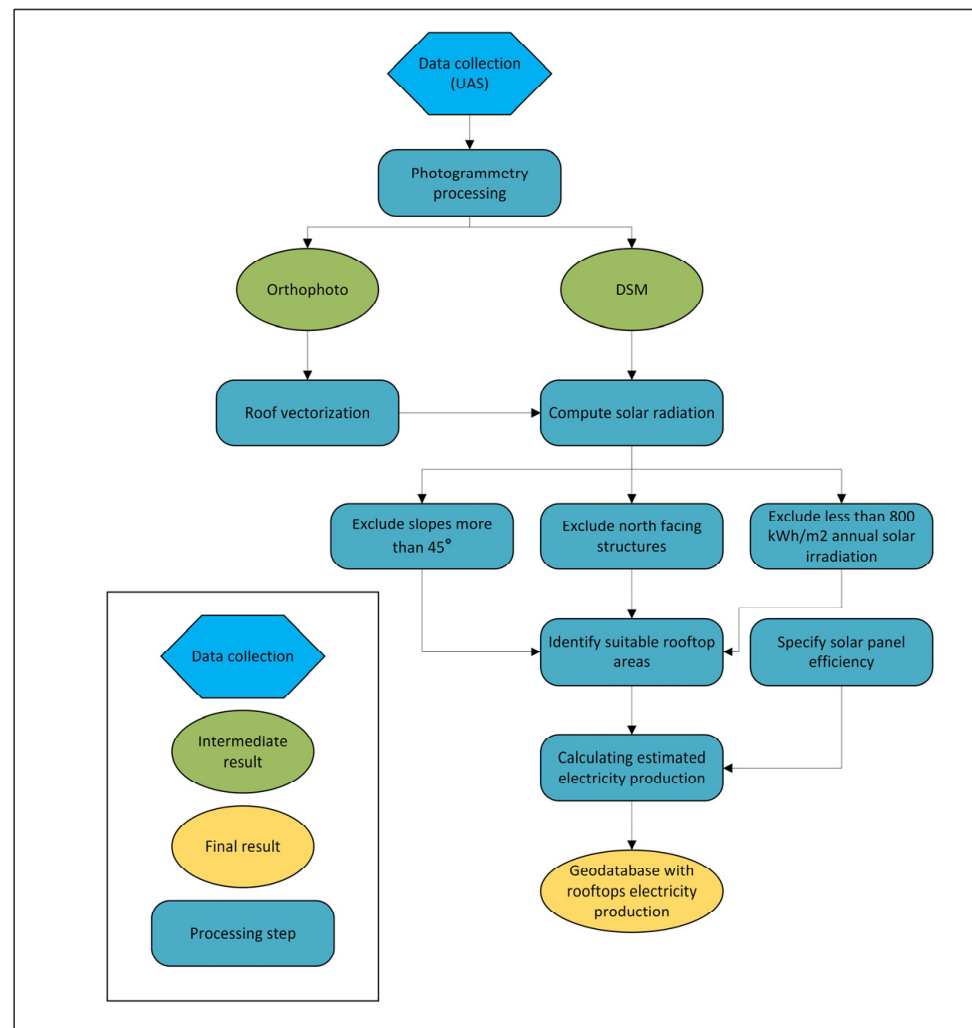


Figure 1. Methodological scheme of the research. The flowchart details the step-by-step spatial filtering and calculation process used to estimate theoretical rooftop electricity production.

2.1. Study Area

The study area comprises the most western residential district of Sofia (Bulgarian capital), Lyulin (Figure 2). This is the largest residential area in Bulgaria, with 101 thousand inhabitants in 2024 (according to the National Statistical Institute). It was designed in the 1960s (and built by the mid-1980s) as a relatively self-contained structure with ten micro-districts on an area of 5.7 km². It is executed in the style of large-panel construction (about 70%), typical for Eastern European cities with a predominance of high-rise residential buildings. New constructions are concentrated mainly in the micro-districts through which the Sofia Metro passes and around the center of the complex. In the northeastern parts of Lyulin, there are single-family houses with yards.

According to the cadastral map, there are 3863 buildings in the study area, 80% of which are privately owned. In terms of functional type, the largest percentage is multi-family residential buildings—42% containing over 46,000 apartments. According to the number of floors, the largest number of buildings have 1 to 6 floors (58%), buildings with 6 to 10 floors account for 38%, and high-rise buildings with more than 11 floors account for 4%.

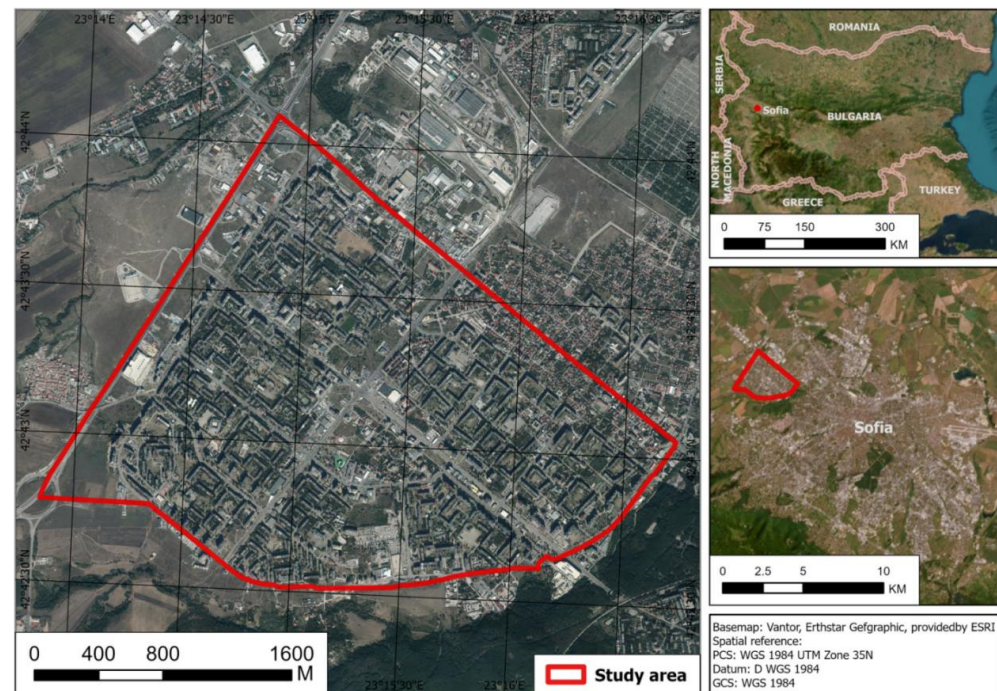


Figure 2. Location and administrative boundaries of the Lyulin district in Sofia, representing the study area.

The selection of the study area was motivated by three main considerations related to geographic location, urban scale, and building typology.

- First is the geographic location of the Lyulin district. The district is located in the northwestern part of Sofia's urbanized territory, at a greater distance from the Vitosha Mountain. The greater distance from the mountain results in comparatively higher annual solar radiation levels than those observed in the southwestern and southern districts located closer to the mountain foothills. This spatial setting provides favorable conditions for assessing rooftop solar energy potential under relatively unobstructed solar exposure.
- Second, Lyulin represents the largest residential district in the capital, with approximately 101 thousand inhabitants in 2024. The large number of inhabitants makes it a representative and statistically significant case for evaluating the applicability of the proposed large-scale assessment methodology. The district's size and population density allow the testing of the method under conditions typical of high-density urban environments.
- Third, the study area is characterized by a high proportion of prefabricated panel residential buildings. These structures were predominantly designed in the 1960s and constructed in the late twentieth century, including the mid-1990s, following the large-panel housing typology widely implemented across Eastern Europe. Approximately 70% of the residential buildings are high-rise structures exceeding six floors, with some reaching up to sixteen floors. The feasibility of installing solar PV panels on high-rise buildings is often low due to safety, maintenance, and property rights issues. However, they are included in the model because of the geometric configuration and physical characteristics of their predominantly flat rooftop surfaces, with a lack of shading from surrounding buildings or high trees, which makes them a substantial theoretical potential for photovoltaic electricity generation.
- Sofia is located in a temperate continental climate zone, with a mean annual air temperature of 10.3 °C and average annual precipitation of approximately 612 mm. July is

the warmest month, with a mean temperature of 21.2 °C, while extreme summer conditions are not uncommon, with recorded absolute maximum temperatures reaching 37.4 °C (National Institute of Meteorology and Hydrology). These climatic conditions, combined with the city's urban morphology, contribute to pronounced urban heat island effects and the accumulation of air pollutants in the near-surface atmosphere, posing persistent challenges for municipal environmental management [28].

2.2. Data Collection

Aerial photogrammetric data acquisition was carried out in July 2023 and constitutes a key step in the generation of a high-resolution digital model for the assessment of rooftop photovoltaic potential. The survey was conducted using a fixed-wing Unmanned Aerial System (UAS), specifically the eBeeX platform (AgEagle Aerial Systems Wichita, KS, USA), operated in accordance with the applicable regulatory framework. For the purposes of this study, the UAS was equipped with a S.O.D.A. 3D photogrammetric camera (AgEagle Aerial Systems, Wichita, KS, USA) designed for the acquisition of high-resolution RGB imagery suitable for detailed three-dimensional reconstruction. Flight planning was organized into two main blocks of flight lines with perpendicular orientations, ensuring optimal image overlap and multi-directional object visibility across the complex urban environment. This configuration was selected to improve the reconstruction of building geometry and rooftop features critical for subsequent morphometric and solar radiation analyses. In total, 2562 georeferenced RGB images were acquired, providing a comprehensive and up-to-date representation of the study area at the time of data collection.

The acquired imagery achieved a ground sampling distance of approximately 5 cm per pixel. The positional accuracy of the derived products was enhanced through real-time kinematic (RTK) corrections, resulting in horizontal and vertical deviations of less than 5 cm. The primary objective of the photogrammetric survey was to generate a highly detailed three-dimensional representation of the Lyulin district, serving as a digital twin of the urban environment. This dataset provides the geometric basis for precise measurement of building forms and dimensions and for the extraction of key parameters characterizing urban morphology, which are subsequently used in the assessment of rooftop solar energy potential.

The use of this specific approach and data acquisition technology constitutes a central methodological strength of the present study. While most UAV-based studies remain constrained to small spatial extents, the proposed framework demonstrates that fixed-wing platforms can achieve district-scale coverage at centimeter-level resolution. In doing so, it directly addresses a persistent limitation in the literature—namely, the lack of approaches capable of combining very high spatial resolution with operational scalability [29].

2.3. Data Pre-Processing

Image processing was performed using the photogrammetric software platform Pix4Dmapper (version 4.5.6, Pix4D SA, Lausanne, Switzerland). The acquired imagery was processed to generate a dense, georeferenced three-dimensional point cloud comprising millions of points, each attributed with X, Y, and Z coordinates. Based on this point cloud, a high-resolution Digital Surface Model (DSM) was produced, representing the elevation of the terrain and all above-ground objects, including buildings with their structural elements and vegetation. In addition, an orthophoto map was generated as a geometrically corrected, high-resolution aerial image of the study area. The quality of the derived geospatial products is a critical factor for reliable solar energy potential assessment. Accurate information on building heights, rooftop geometry, and surrounding obstacles is essential for correctly modeling shading effects and solar radiation distribution and consequently for estimating

the photovoltaic potential of rooftop surfaces. The final DSM and orthophoto products were exported in GeoTIFF (.tiff) format to ensure compatibility with subsequent analyses in GIS environments.

In addition to the raster products, precise vector delineation of rooftop areas was required. Rooftop boundaries were digitized using the orthophoto map with a spatial resolution of 5 cm per pixel in a GIS environment (ArcGIS Pro 3.1, Esri Inc., Redlands, CA, USA). The digitization focused on the internal functional boundaries of rooftop surfaces intended for photovoltaic assessment. The boundaries of the rooftop digitized during this step of the process differ substantially from cadastral building footprints and can only be accurately identified using high-resolution aerial data. The level of detail of the orthophoto allowed for reliable visual identification and vectorization of rooftop features larger than approximately 10 cm.

Furthermore, vector layers were created for rooftop-mounted structures and elements that influence solar exposure and system placement, including elevator shafts, chimneys, ventilation pipes, antennas, dormers, and air-conditioning units. Incorporating these elements into the analysis enables a more realistic estimation of the theoretical solar potential of the rooftop spaces. In addition, rooftop areas of kindergartens and schools within the study area were included following visual inspection, as these buildings typically possess large, predominantly flat rooftop surfaces that are currently underutilized.

2.4. Data Processing and Modeling

Solar Radiation Modeling: Solar radiation modeling was performed to estimate the theoretical incoming solar energy for each rooftop surface within the study area. This stage of the analysis was implemented using GIS software ArcGIS Pro (version 3.1) and the Solar Radiation toolset within the Spatial Analyst toolbox. The applied model is based on the Solar Analyst approach developed by Fu and Rich [28], which enables comprehensive estimation of solar radiation by accounting for terrain morphology, surface orientation, and shading effects. Solar radiation was calculated for a full calendar year, with an hourly temporal resolution. For each raster cell, solar exposure was evaluated using 16 directional sectors, allowing for detailed representation of horizon obstruction and anisotropic sky conditions. The modeling procedure followed a standardized sequence of computational steps:

1. Computation of hemispherical sky view from the Digital Surface Model (DSM).

For each pixel of the DSM, an upward-looking hemispherical view was generated to estimate the proportion of visible sky and the fraction obstructed by surrounding elements such as buildings, vegetation, and terrain features. This was achieved by calculating the maximum horizon angle in 16 evenly distributed directions around each pixel, resulting in a fisheye-type representation of sky visibility (Figure 3).

2. **Integration with a direct solar radiation map.**

The hemispherical sky view for each pixel was overlaid onto a direct sun map representing the apparent position and trajectory of the sun throughout the day and year for the geographic location of the study area. The sun map is divided into discrete sectors corresponding to specific solar positions, enabling the calculation of direct solar radiation received from unobstructed sky directions.

3. **Integration with a diffuse radiation sky map.**

Diffuse solar radiation, resulting from atmospheric scattering, was calculated using a sky model map representing a hemispherical division of the entire sky dome into multiple sectors. Diffuse radiation was computed for each sector, and the hemispherical sky view

was applied to exclude obstructed directions, yielding pixel-specific estimates of diffuse radiation (Figure 4).

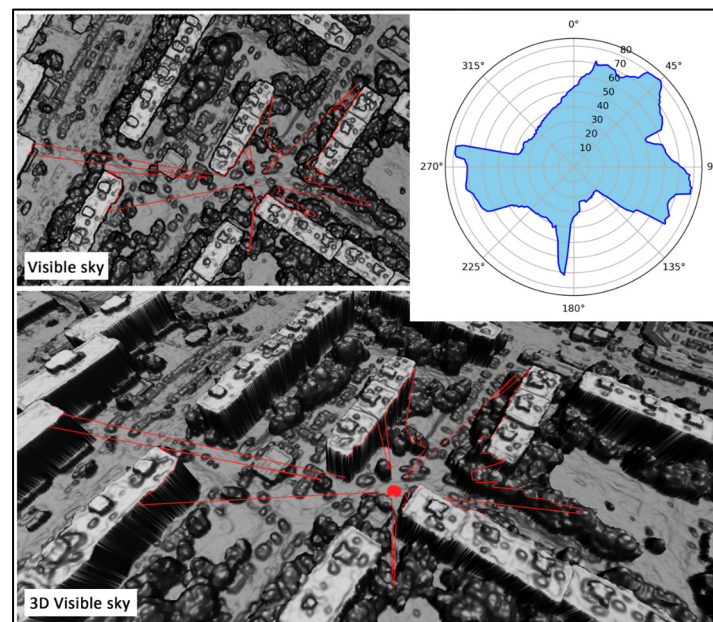


Figure 3. Visible sky and the portion obscured by surrounding objects such as buildings, trees, or terrain features.

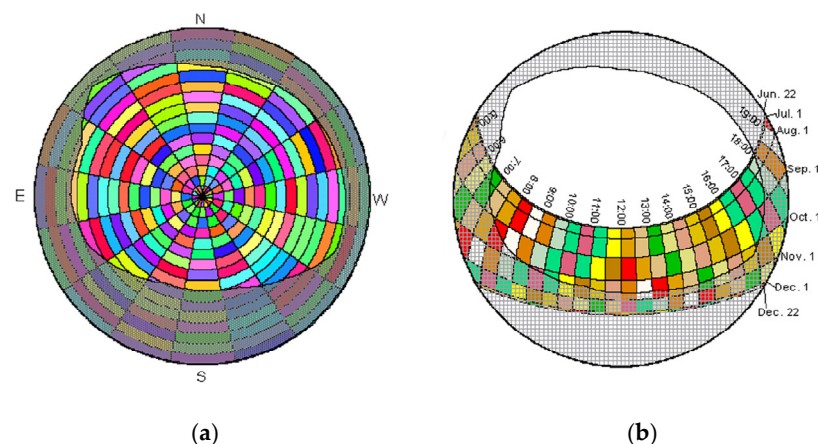


Figure 4. Overlay of a viewshed on (a) a sky map with sky sectors defined by 16 zenith divisions and 16 azimuth divisions and (b) a sunmap using one-hour intervals through the day and month intervals through the year. Shaded areas are obstructed sky directions [28].

4. Generation of total solar radiation raster.

The above steps were repeated for each pixel across the study area. Total theoretical solar radiation was calculated as the sum of direct and diffuse radiation received from unobstructed portions of the sky. The output of this process is a raster layer representing the annual theoretical solar radiation for each pixel, initially expressed in Wh/m^2 . For subsequent analyses and improved interpretability, these values were converted to kWh/m^2 .

Filtering Criteria and Energy Yield Estimation: Following consultation with experts from the Bulgarian Solar Association (BSA), a minimum threshold of 800 kWh/m^2 of annual solar radiation was defined as a prerequisite for photovoltaic suitability. Raster cells with values below this threshold were excluded from further analysis.

Two additional criteria were applied as part of a secondary filtration process aimed at identifying rooftop surfaces with higher photovoltaic potential:

1. Rooftop surfaces with slopes exceeding 45° were excluded;
2. Surfaces with a northern orientation were removed from the suitable area set.

These criteria were adopted to ensure a balance between economic viability and technical efficiency, specifically by excluding surfaces where insufficient irradiation, sub-optimal sun exposure, or excessive installation complexity would result in a poor return on investment.

South orientation of the roof sections provides the highest degree of self-sufficiency and the lowest levelized cost of electricity. Conversely, north orientations are typically excluded from such models because they yield the lowest annual solar output, significantly impacting economic feasibility. Regarding tilt, while the optimum angle for maximum yield is often around 44° in similar European latitudes, surfaces exceeding this range are frequently avoided to manage installation complexity and maintain cost-effectiveness [30].

The estimated rooftop solar potential is inherently sensitive to these predefined filtering criteria, particularly the radiation threshold and the exclusion of north-facing surfaces. For instance, by lowering the radiation threshold or including suboptimal orientation, it would naturally increase the total suitable area and the absolute theoretical energy yield of the district. However, while this would inflate the district-wide technical potential, it would simultaneously reduce the average system efficiency and economic viability of individual installations due to lower energy returns per square meter. Consequently, the chosen conservative thresholds ensure that the reported figures represent highly realistic, economically feasible deployment scenarios rather than purely theoretical maximums.

As a subsequent step, a zonal statistics approach was employed to estimate the theoretical annual electricity production within the remaining suitable rooftop spaces. For each digitized rooftop polygon, the method calculated the average annual usable solar radiation based on the raster values intersecting the vector boundaries. The area of the suitable rooftop sections was derived automatically from the spatial resolution of the raster dataset and the number of pixels falling within each polygon, with all results stored as attribute values in the output table.

Following the slope and orientation filtering, a spatial constraint was applied to exclude rooftop segments with a suitable area of less than 20 m². This 20 m² threshold was confirmed by the BSA as a realistic benchmark for the Bulgarian market, reflecting the increased power density of modern high-efficiency modules, which allow for economically viable domestic installations on smaller scales. This adjustment ensures that smaller residential roof sections are not prematurely excluded from the potential yield assessment.

The potential energy yield of photovoltaic installations was then estimated for each suitable rooftop space. Based on data from the Fraunhofer ISE photovoltaics report [31] and additional consultation with experts from the Bulgarian Solar Association, two baseline performance parameters were adopted: a photovoltaic module efficiency of 22% and an overall system efficiency coefficient of 0.86, accounting for typical system losses. The theoretical annual electricity production was calculated using the following equation:

$$E_p = G_i \times \eta_m \times PR$$

where

E_p —produced energy. The total annual electricity generated by the system.

G_i —usable solar radiation. The total solar energy falling on the specific rooftop area over the course of a year.

η_m —module efficiency. The ability of the solar panel to convert sunlight into DC electricity. A value of 0.22 (22%) reflects high-performance, modern silicon modules.

PR—performance ratio. A quality factor that accounts for losses. A value of 0.86 means that 86% of the energy effectively captured by the panels actually reaches the building's electrical system.

3. Results

Photogrammetric 3D Acquisition, DSM and Orthophoto Generation: The photogrammetric 3D acquisition of the study area, conducted in July 2023 using a fixed-wing Unmanned Aerial System (eBeeX, AgEagle Aerial Systems) equipped with a S.O.D.A. 3D photogrammetric camera, resulted in the collection of 2562 high-resolution RGB images. The acquired imagery was subsequently processed using the Pix4Dmapper software platform (version 4.5.6), following the workflow described in the Section 2.

The photogrammetric processing produced a dense, georeferenced three-dimensional point cloud representing the urban environment of the study area. The resulting point cloud comprised over 317 million points, each characterized by X, Y, and Z spatial coordinates, enabling detailed representation of building geometry, rooftop structures, and surrounding urban features (Figure 5).

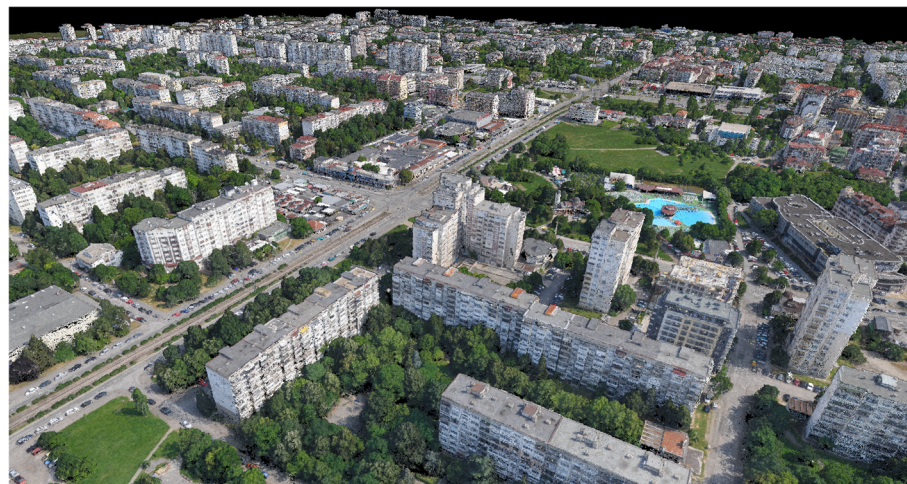


Figure 5. Detailed 3D colorized point cloud of the studied area, obtained after photogrammetric processing in a Pix4D environment.

Based on the generated point cloud, a high-resolution Digital Surface Model (DSM) was derived, capturing the elevation of the terrain and all above-ground objects, including buildings and vegetation (Figure 6). In addition, a geometrically corrected orthophoto map was produced, providing a high-resolution, spatially accurate representation of the surface characteristics of the study area. These datasets constitute the primary spatial inputs for subsequent analyses of rooftop geometry and solar energy potential.

Grouping of Objects and Vectorization of Rooftop Spaces: As a result of the rooftop digitization process, the boundaries of more than 1600 individual rooftop spaces were delineated within the study area. The total number of rooftops was identified based on the layer containing the official cadastral building footprints within the defined territorial extent (Figure 7).

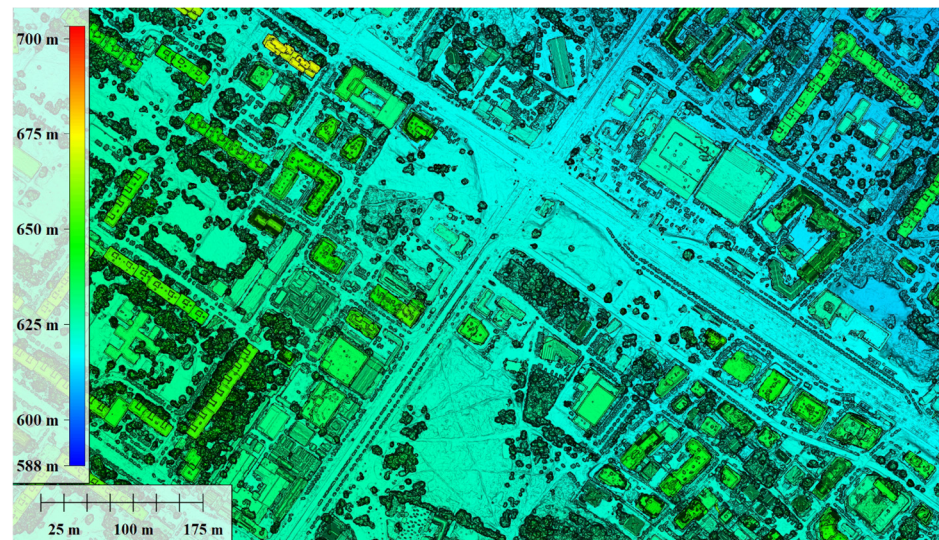


Figure 6. Digital Surface Model (DSM) with high spatial resolution (5cm/px) obtained after photogrammetric processing.



Figure 7. Map of digitized roof areas within the boundaries of the studied area.

Within these rooftop boundaries, more than 10,000 rooftop-mounted elements and structures influencing solar exposure and the potential placement of photovoltaic systems were identified and vectorized. These elements include chimneys, elevator shafts, ventilation structures, and other rooftop installations (Figure 8). Their explicit representation allows for a detailed characterization of rooftop morphology and spatial constraints relevant to photovoltaic deployment.

An integrated GIS database was compiled for all buildings within the study area. The database includes vectorized rooftop sections available in both GIS- and CAD-compatible formats. Attribute information associated with each building comprises geometric characteristics such as rooftop area and building height, as well as the inventory of rooftop elements. In addition, address information for each building was extracted and stored in tabular form, enabling spatial linkage between the rooftop database and external administrative or planning datasets.



Figure 8. Digitized boundaries of functional roof areas and explicitly vectorized rooftop obstacles, including chimneys, elevator shafts, and ventilation structures.

Assessment of Theoretical Solar Potential: The theoretical solar energy potential was quantified for each digitized rooftop space using integrated geospatial analysis within a GIS environment (ArcGIS Pro 3.1, Solar Radiation toolset). Solar radiation was initially calculated at the pixel level across the study area, and the resulting values were subsequently aggregated to obtain average annual solar radiation estimates for each individual rooftop.

Following the initial calculation, the results were subjected to a filtration process in order to identify rooftop surfaces with higher photovoltaic suitability. Raster cells that did not satisfy predefined suitability criteria were excluded from further analysis. Specifically, rooftop sections receiving less than 800 kWh/m² per year were removed, as were surfaces with a slope exceeding 45° and those with a northern orientation. The application of these criteria resulted in a refined subset of rooftop areas considered suitable for photovoltaic deployment, forming the basis for subsequent estimation of theoretical electricity production.

Zonal statistics combined with the estimation of potential energy losses were applied to quantify the theoretical annual electricity production within the suitable rooftop areas. Based on the resulting electricity production values, the vectorized rooftop spaces were subsequently classified and typified according to their theoretical photovoltaic energy yield. The Natural breaks classification method was used because it identifies inherent groupings in the data by minimizing variance within classes and maximizing the difference between them, effectively highlighting the significant spatial disparities in energy yield across the Lyulin residential district (Figures 9 and 10).

Statistical analysis indicates that the total theoretical annual electricity production from the suitable rooftop spaces of the investigated panel residential buildings amounts to 76,715.35 MWh. At the individual rooftop level, the calculated annual electricity production ranges from 3.67 MWh to 476.68 MWh, with an average value of 34.21 MWh per rooftop (Figure 11). The relatively high standard deviation of 28.49 MWh reflects substantial variability in solar potential among the analyzed rooftop spaces, highlighting pronounced differences in rooftop geometry, exposure, and shading conditions across the study area.



Figure 9. Visualization of classified rooftop areas based on theoretically produced electricity for a one-year period. The Natural breaks classification method is applied, with red indicating the highest energy potential and yellow representing the lowest yield.



Figure 10. Map of theoretical solar potential of roof areas of residential buildings within the boundaries of Lyulin District. The Natural breaks classification method is applied, with red indicating the highest energy potential and yellow representing the lowest yield.

At the neighborhood scale, the calculated average theoretical annual electricity production from suitable rooftop spaces is 6974.12 MWh. For most neighborhoods, the estimated potential is relatively evenly distributed and slightly exceeds this average (Figure 12), including Lyulin-1, Lyulin-2, Lyulin-4, Lyulin-5, Lyulin-6, Lyulin-7, and Lyulin-9. The highest theoretical electricity production is observed in Lyulin-3, reach-

ing 9204.98 MWh per year, followed closely by Lyulin–10. In contrast, Lyulin–8 and Lyulin–Center exhibit lower values than the neighborhood average, with Lyulin–Center showing the lowest potential at 2037.22 MWh per year. Further analysis reveals a positive relationship between the extent of suitable rooftop area and the magnitude of theoretical annual electricity production across neighborhoods.

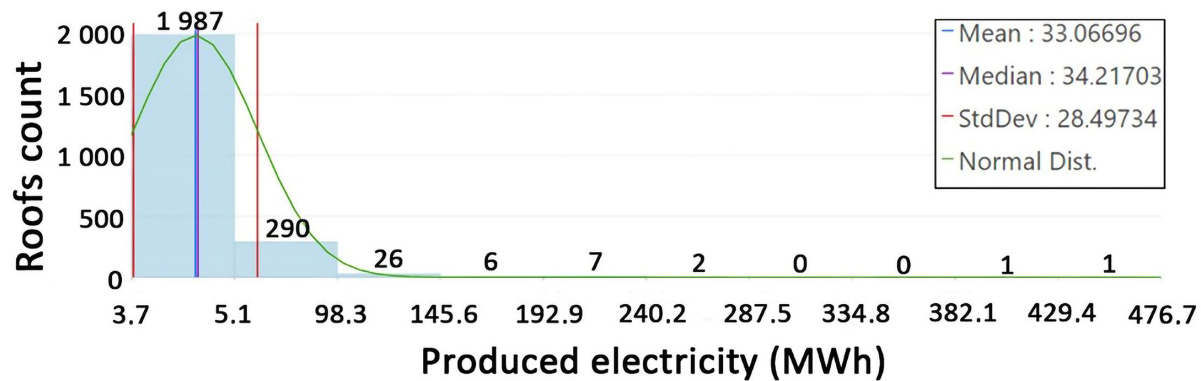


Figure 11. Statistical distribution of theoretically produced electricity within the boundaries of the analyzed roof areas. The histogram displays the frequency of rooftops within specific production ranges.

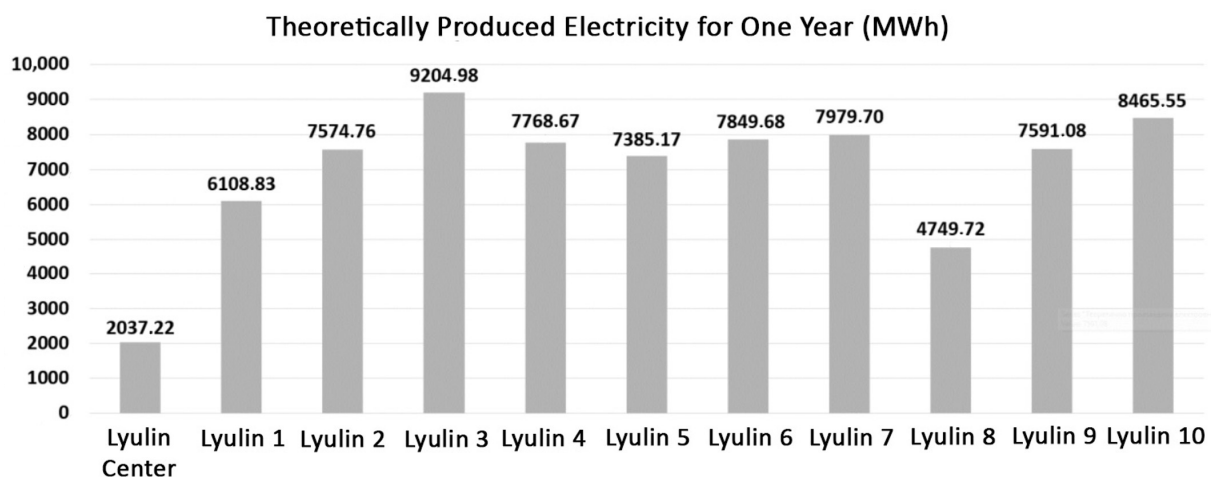


Figure 12. Theoretical annual electricity production (MWh) aggregated by neighborhood within the Lyulin district.

To ensure an objective evaluation of the findings, a detailed correlation analysis was performed across all eleven neighborhoods. The results indicate an exceptionally high linear relationship between the suitable roof area and the annual energy yield, with R^2 values ranging from 0.9938 to 0.9992. Such values demonstrate that the available area is a near-absolute predictor of solar potential in the studied urban environment. It is important to note, however, that this nearly perfect correlation is likely a characteristic feature of the specific residential building typology in the Lyulin district, which consists predominantly of large-scale residential blocks with flat roofs. The uniform geometry of flat surfaces allows consistent panel orientation and tilt, minimizing the variance typically introduced by complex roof shapes, varying pitches, or unfavorable azimuths found in other types of residential developments. Consequently, while the identified relationship is robust for this urban context, it may exhibit higher variability in areas with diverse or sloped roof architectures (Figure 13).

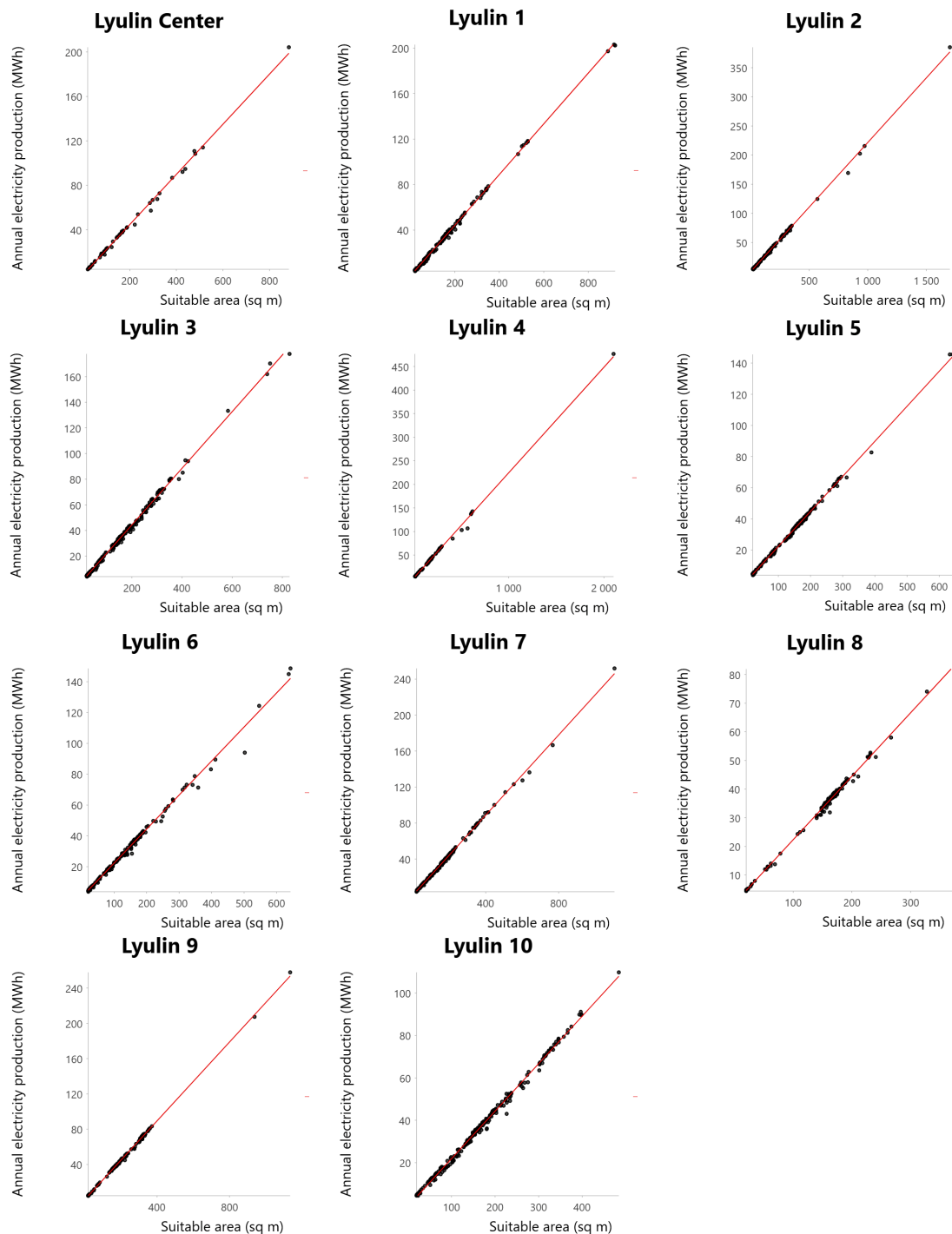


Figure 13. Correlation between suitable roof area (m^2) and estimated annual electricity production (MWh) across the district of Lyulin (Lyulin Center and Lyulin 1–10). The scatter plots represent individual building data points, while the red line indicates the linear trend for each district (made in ArcGIS Pro 3.1).

4. Discussion

The integration of renewable energy technologies has become a strategic imperative for the long-term sustainability of urban energy systems. This transition is essential for enhancing climate adaptation and mitigating the risk posed by the increasing frequency of extreme climatic events. Furthermore, such measures are vital to address escalating societal energy demands. Within this framework, the present study addresses key challenges in urban planning, specifically focusing on the decarbonization and resilience of energy

infrastructures. It further examines climate-adaptive landscape planning as a means to alleviate the economic burdens associated with energy consumption. The low theoretical values for solar energy production in the Lyulin Center (Figure 12) can be explained by the morphology of the building roofs, their distribution in space, and also their height. In this part of the neighborhood are mostly newly constructed buildings whose roofs are pitched or have a much smaller area than the roofs of buildings in other parts of the neighborhood. The pitched roofs and their correspondingly smaller area led to a smaller area for assessment and correspondingly lower values for solar energy production. In addition, the high building density in this area in combinations with irregular building heights, contributes to significant inter-building shading. This spatial arrangement frequently obstructs solar access for lower structures. Consequently, the total theoretical potential for solar energy production in this sector is markedly reduced. (Figure 14).

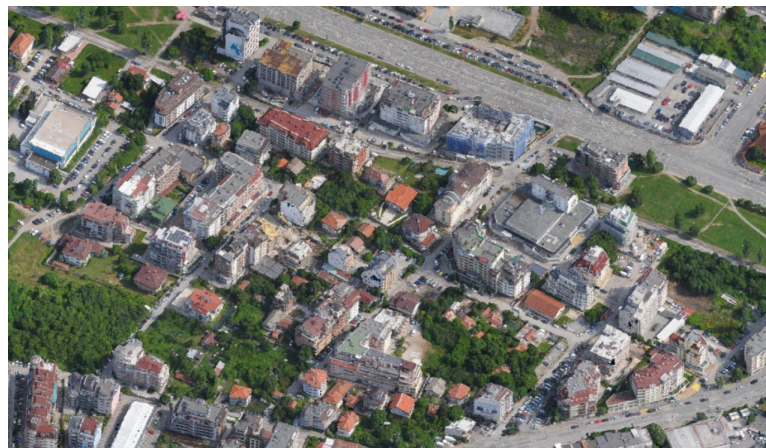


Figure 14. 3D view of building rooftops in the Lyulin center study area, characterized by pitched roofs, smaller surface areas, and uneven building heights. Visualization generated in CloudCompare using standardized parameters: 540 m altitude, 40° pitch angle, and fixed orientation.

The parts of the neighborhood with high theoretical values for solar energy production are covered with buildings of the same height and construction, flat roofs and wide inter-block spaces, which leads to an increase in suitable areas for solar energy production (Figure 15).

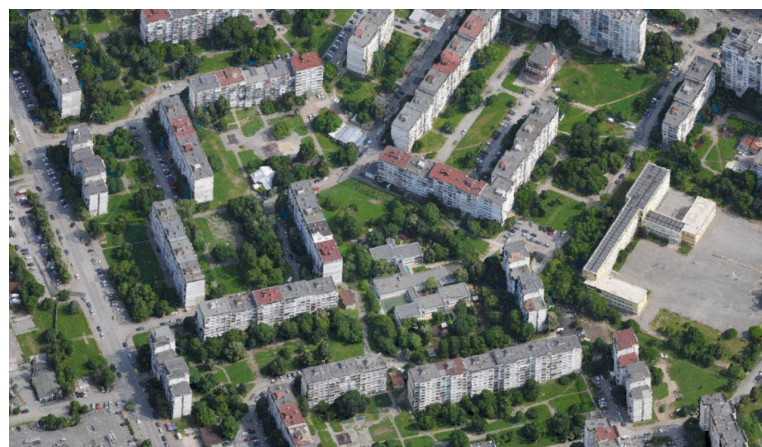


Figure 15. 3D view of building rooftops in the Lyulin 7 neighborhood, featuring flat roofs, uniform building heights, and wide inter-block spaces. Visualization generated in CloudCompare using standardized parameters: 540 m altitude, 40° pitch angle, and fixed orientation.

The building with the highest value for solar electricity production or 476.7 MWh (Figure 11) is a school, whose roof is flat with a significantly larger area than the roofs of other buildings in the neighborhood. On the other hand, the roof has very few rooftop-mounted elements, and the building is located in an open area where there is practically no shading from neighboring buildings (Figure 16).

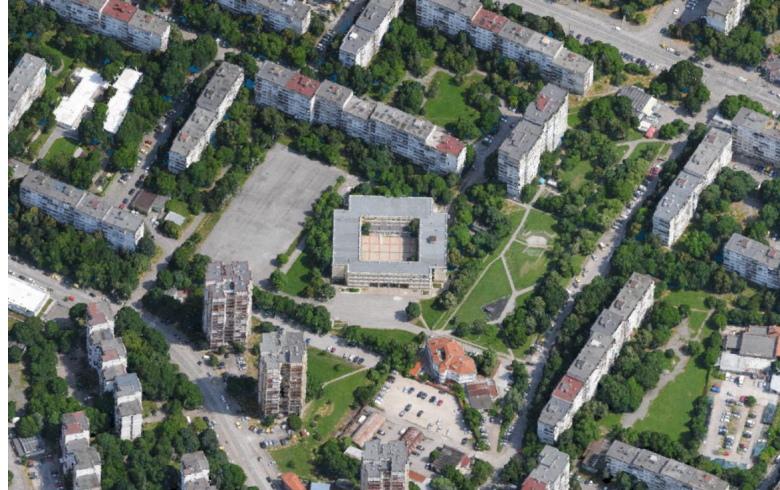


Figure 16. The school building exhibiting the highest theoretical rooftop solar potential (476.7 MWh/year) among all assessed structures. Its exceptionally high energy yield is attributed to a large flat roof area, minimal rooftop-mounted obstacles, and an open location free from surrounding shading. Visualization generated in CloudCompare using standardized parameters: 540 m altitude, 40° pitch angle, and fixed orientation.

Logically, the study raises some logical specific questions that should be discussed in depth:

- **Urban Energy Sustainability and the Role of Rooftop Solar Potential:** The integration of renewable energy technologies into urban energy systems is widely recognized as a key priority for the long-term sustainability and resilience of cities, particularly in the context of climate change and the increasing frequency of extreme climatic events. At the same time, urban energy systems must respond to continuously growing societal demands for energy. Within this framework, the present study addresses several pressing needs in urban planning and energy management, including the diversification and decarbonization of urban energy systems, climate-adaptive urban landscape planning, and the reduction in economic burdens associated with energy consumption. At its core, the study explores the interaction between two highly dynamic and interdependent factors: **urban climate** and **urban morphology**. From this perspective, the discussion of rooftop solar potential can be structured around two main dimensions:
 - (1) The accurate representation of geometric and morphostructural conditions that govern solar energy availability, which directly relates to methodological choices and the quality of primary geospatial data; and
 - (2) The influence of urban climate and microclimatic conditions on both present and future solar potential and on the operational efficiency of photovoltaic systems.
- **Limitations of the methodology used in primary data collection and urban morphology modeling:** When interpreting the results, it is important to consider several objective technological and methodological limitations, despite the robustness of the proposed approach. First, the applied GIS-based solar radiation model relies on well-established algorithms that have been widely validated in previous studies. Nev-

ertheless, discrepancies may arise when compared to ground-based meteorological measurements or reference databases such as PVGIS. These differences are primarily related to local atmospheric variability, which is not fully captured by the model. Second, although the use of centimeter-resolution UAV-derived DSMs substantially reduces geometric uncertainty compared to coarser datasets, residual errors may still occur. These are mainly associated with photogrammetric reconstruction artifacts, particularly in areas characterized by low surface texture or complex geometries. A related limitation concerns the representation of shading effects and rooftop obstacles. While the explicit identification and vectorization of such elements is one of the key strengths of this study, certain dynamic or seasonal factors—such as vegetation changes or temporary structures—may not be fully represented. This may introduce additional uncertainty in the estimation of solar radiation. Another important constraint is the lack of publicly available, high-resolution geospatial datasets in Bulgaria that accurately describe the geometry and structure of urban environments. As a result, reliable assessments of rooftop solar potential require the use of specialized geospatial technologies for primary data acquisition. In this context, the development of a comprehensive municipal solar cadaster would necessarily depend on the systematic implementation of such data collection workflows. The integration of advanced LiDAR data and more sophisticated 3D modeling techniques could further improve the accuracy of solar potential estimates, particularly through a more precise representation of complex roof geometries and obstacles. However, the limited availability, high cost, and operational constraints associated with LiDAR currently restrict its widespread application in many urban contexts. More broadly, the accurate estimation of rooftop solar potential remains challenging due to the lack of freely available datasets with sufficient spatial detail. Commonly used sources, such as OpenStreetMap (OSM) building data, are generally unsuitable for high-precision analyses. This is due to inaccuracies in building footprints and height attributes, as well as the absence of detailed information on roof morphology (e.g., slope variability, micro-relief, and surface roughness), which are critical for reliable solar potential assessment. Finally, the integration of high-resolution or real-time meteorological data represents an important direction for future research. Such data would enable the development of more dynamic and adaptive solar energy models, better reflecting actual operating conditions and further reducing uncertainty in energy yield estimates.

- **Comparison with previous studies:** The results of this study are consistent with previous research that applies GIS-based and high-resolution approaches for rooftop solar potential assessment. For example, Bergamasco and Asinari [32] present a methodology based on UAV photogrammetry and GIS analysis of building characteristics and solar radiation, demonstrating the potential of detailed urban-scale solar mapping. In a similar direction, Han et al. [33] demonstrate the applicability of UAV photogrammetry for generating high-resolution 3D models and performing solar simulations at the building scale. In this context, the present study follows and extends these methodological approaches by combining detailed rooftop characterization with high-resolution spatial modeling. However, a key advancement lies in the use of fixed-wing UAS for data acquisition, which enables significantly more extensive spatial coverage while maintaining centimeter-level resolution. While previous UAV-based studies are typically limited to small study areas, the proposed approach allows the extension of such high-precision analyses to the district scale, thereby improving the scalability and practical applicability of UAV-based solar potential assessments. Furthermore, while GIS-based approaches relying on generalized data may introduce uncertainties related to simplified roof geometry, and LiDAR-based methods—although highly

accurate—are often constrained by high costs and operational limitations, the proposed methodology provides a balanced solution that combines high geometric accuracy, operational flexibility, and cost-efficiency.

- **Scope and Representativeness of the Results:** The results presented in this study do not represent the total solar potential of the investigated districts but are limited to the selected rooftop spaces of prefabricated panel residential buildings. Within each district, numerous additional buildings possess rooftop surfaces that could potentially accommodate photovoltaic installations and likely conceal substantial, yet currently unquantified, energy potential. Furthermore, many rooftop types excluded from the present analysis—such as pitched roofs with steeper slopes or specific orientations—exhibit complex geometries that require more advanced analytical approaches. These rooftop forms may still offer viable opportunities for solar energy generation, provided that the analysis accounts for their specific structural and geometric characteristics. We also want to point out that the estimation of electricity production is based on standard assumptions regarding system efficiency, losses, and conversion factors. These parameters can vary depending on technology, installation quality, and maintenance, introducing uncertainty in the final energy yield estimates.
- **Scale limitations:** Although the proposed methodology enables high-resolution solar potential assessment over relatively large urban areas, its practical implementation is subject to operational, financial, and logistical constraints. In this context, the approach is most suitable for district- to neighborhood-scale applications, where detailed spatial information is required for planning and decision-making. While fixed-wing UAV platforms significantly improve coverage efficiency compared to multi-rotor systems, the application of such methods at the full city scale may still involve substantial effort in terms of data acquisition, processing, and resource allocation. Therefore, the proposed methodology is best considered as part of a multi-scale framework, in which large-scale screening is performed using generalized datasets, followed by targeted high-resolution analyses in selected priority areas.
- **Relative Nature of Results: Sky View Factor and DSM Accuracy:** The relative nature of the obtained results is closely linked to the processing methods applied, particularly those related to sky visibility and shading representation. The Sky View Factor (SVF)—a dimensionless parameter ranging from 0 to 1 that quantifies the proportion of visible sky from a given surface—has been established as a strong predictor of solar irradiation availability. Chatzipoulka et al. [34] demonstrated a strong linear relationship ($R^2 > 0.8$) between SVF and annual global irradiance in urban environments, suggesting that SVF can serve as a reliable proxy for rooftop solar potential. Similar findings from Lisbon indicate that SVF-based shadow modeling improves the accuracy of diffuse radiation estimation on rooftops and façades [35]. Lu et al. (2022) further showed that incorporating SVF derived from LiDAR and shadow analysis into photovoltaic models enhances energy yield estimation by capturing seasonal variability and occlusion effects [36]. The accuracy of the Digital Surface Model (DSM) plays a critical role in determining the uncertainty of solar potential estimates, as it directly affects the calculation of shading and sky visibility. As demonstrated by Polo and García (2023), inaccuracies in DSM data can significantly propagate uncertainty in rooftop solar potential assessments, underscoring the importance of high-resolution and geometrically reliable surface models [37]. The SVF dataset already calculated for the study area provides a strong basis for future methodological refinement and for improving the accuracy of solar potential forecasting across complex urban surfaces.
- **Solar Energy and Urban Climate, Interdependencies and Vulnerabilities:** The interpretation of the obtained results should be further refined through complementary

studies focusing on urban climate characteristics. In the present study, a prior assessment of the physical solar energy potential explicitly incorporating urban climate parameters—such as temperature regimes, atmospheric conditions, and urban heat island intensity—was not conducted, as recommended in the methodological framework proposed by Fakhraian et al., 2001 [12]. Successful urban energy transitions in the context of climate resilience require careful consideration of the impacts of extreme climatic events on urban energy systems in order to minimize their vulnerability [38]. Although research on solar radiation modification remains limited, existing studies highlight its importance for informed decision-making in the design and operation of renewable energy systems [39–42]. Additionally, the secondary effects of climate change on photovoltaic performance constitute an active research field [31,41] and should be examined in relation to regional climatic conditions. The authors' prior experience in analyzing urban heat island effects in the studied cities [23] provides a strong foundation for future work aimed at integrating rooftop solar potential assessments with surface thermal patterns and evolving microclimatic regimes under climate change scenarios.

- **Practical Implications and Large-Scale Solar Potential:** From a practical standpoint, the results of this study contribute to the broader discussion on **large-scale urban rooftop solar potential**, as emphasized in recent state-of-the-art reviews [12]. The adopted methodology demonstrates that high-resolution, large-area assessments based on UAS-derived data can provide actionable information for municipal planning, energy policy development, and the strategic deployment of photovoltaic systems in dense urban environments.

5. Conclusions

The analysis of rooftop solar potential conducted using geospatial data and GIS-based processing provides robust evidence of a substantial, currently underutilized renewable energy resource within the urban environment. The results indicate that rooftops within the investigated area are capable of generating, on average, approximately 30 MWh of solar electricity per year per rooftop, highlighting the significant contribution that rooftop photovoltaic systems could make to urban energy supply.

These findings are highly relevant in the context of sustainable urban development, as they demonstrate the magnitude of renewable energy potential embedded within existing urban structures. The effective utilization of this potential could contribute to a meaningful reduction in carbon emissions and support the transition toward a lower-carbon and more environmentally sustainable urban energy profile.

Beyond environmental benefits, the identified solar potential also carries important economic implications. Reduced dependence on conventional energy sources offers opportunities for long-term cost savings for both municipalities and private stakeholders. In addition, the deployment of rooftop photovoltaic infrastructure can stimulate local economic activity through job creation and support broader socio-economic development within urban areas.

Unlike conventional approaches that rely on medium- to high-resolution satellite imagery or generalized building footprints, our method is based on centimeter-level UAV-derived Digital Surface Models (DSMs). This allows for precise reconstruction of rooftop geometry, including small-scale features such as dormers, chimneys, and roof inclination variability, which are typically omitted in coarser datasets. The proposed workflow directly incorporates high-resolution 3D morphological characteristics (slope, aspect, shading effects) derived from photogrammetric processing. This enables a more accurate estimation of solar irradiance at the micro-scale compared to studies that rely on simplified or planar

roof assumptions. An additional important advantage of the applied technology is the use of a fixed-wing UAS, which provides significantly enhanced capabilities for large-scale mapping in urban environments. Compared to multi-rotor platforms, fixed-wing UAVs offer longer flight endurance, higher coverage efficiency, and improved operational stability, enabling the acquisition of high-resolution data over extensive urban areas within a limited time frame. This makes the proposed approach particularly suitable not only for detailed local analyses but also for scaling up toward city-level assessments, effectively addressing one of the key limitations of UAV-based solar potential studies related to spatial coverage and operational efficiency.

Overall, the study underscores the strategic importance of high-resolution, large-scale assessments of rooftop solar potential as a foundation for informed urban energy planning and policy-making, particularly in densely built environments with substantial unused rooftop capacity.

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