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Assessment of Solar Photovoltaic Potential of Building Rooftops Based on Multicriteria Spatial Analysis

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Abstract: This paper presents a methodology using Geographic Information Systems (GIS) to assess the photovoltaic potential of building rooftops by applying available data in North Macedonia. Applied to a case study, the method encompasses a high-resolution 3D model from LiDAR data to accurately represent rooftop surfaces and terrain. The approach includes generating a Digital Surface Model (DSM), analysing rooftop slopes and aspects, calculating solar radiation, and identifying suitable rooftops. It was concluded that out of 628 buildings, an area of 73 544 m², about 62% of the total rooftop area, is suitable for photovoltaic system installation. The potential electricity production from each building varies from 4 MWh to 1000 MWh annually and can be estimated at a total of 11 329 MWh from all suitable rooftops within the study area. The proposed method enables a large-scale valuation of suitable roof surfaces for photovoltaic system installation.

Keywords: building rooftops; GIS; LiDAR; solar potential; spatial models

1 INTRODUCTION

In recent decades, the world has undergone rapid urbanization, technological advancement, and industrial growth. While these developments have brought many benefits, they have also resulted in increased electricity consumption and increased atmospheric pollution. According to a United Nations report [1], although cities cover only 3% of the Earth's surface, their contribution is up to 80% of global energy consumption and 75% of greenhouse gas emissions. Rapid urban development and the electricity demand represent a complex challenge that requires innovative solutions, finding new ways to sustainably satisfy this demand, without negative impact on the environment or the economy. One of the potential solutions for addressing this challenge is focusing on the use of renewable sources of energy. Among them, solar energy is the most promising one.

In urban areas, where solar energy is generally one of the more accessible renewable energy sources, building rooftops is considered one of the most suitable locations for installing a photovoltaic system for electricity production. However, it is important to note that not all roof surfaces are equally suitable for installing a photovoltaic system. The identification of suitable building rooftops in terms of their solar potential and estimation of the amount of electricity that could be produced if there is a photovoltaic system installed can be performed using multicriteria spatial analysis utilizing GIS.

In recent years, innovations like advanced data analysis have made it possible to realistically evaluate the prospects of deploying rooftop solar photovoltaic systems. Gagnon et al. (2016) studied the solar capacity and photovoltaic potential over the entire USA in detail by estimating the solar resources both in terms of amount and geographical distribution. The author's findings highlighted sustainable energy production from urban Rooftops and stressed the regional differences in solar potential across the country by showing notable scope for photovoltaic deployment [2].

Palmer et al. (2018) developed a GIS-based methodology employing LiDAR and photogrammetry data to investigate the rooftop-portion of urban areas that can be devoted to photovoltaic installations. This allows for the spatial analyses of rooftops by reinforcing the scale's components such as slope, orientation, and shading and therefore supporting on estimation of the solar energy production potential [3].

Huang et al. (2022) went further by utilizing GIS methodologies when carrying out a case study in Japan, that compared solar potential on rooftops applying remote sensing and solar radiation datasets. The comparison made it clear that it is necessary to use diverse sources of information for better accuracy of solar potential resources. Huang et al have shown that in places with immense rooftop infrastructures (which are often the case in urban environments), combining imagery with solar radiation data, can improve the assessment's accuracy of how much solar energy can be collected [4].

In a recent study, Kozlovas et al. (2023) examined the feasibility, both technical and economic, of the respective rooftops with photovoltaic units in cities of Lithuania. Their study involved a self-determined search encompassing the cost of installing solar photovoltaic units, energy conservations and returns on investments, thus enhancing research on economic aspects of rooftop solar resources. Kozlovas et al. argued that besides factors related to the building, the level of economic is also important when looking for the factors that would increase the use of rooftop photovoltaic systems. This combination of the two parameters provides decision-makers a better idea about the case in hand regarding deployment of photovoltaic technologies [5].

Assessing photovoltaic potential of building rooftops is highly dependent on the available data sources, and consequently, the applied methodology needs to be adapted accordingly. Today many recent or ongoing research are focusing on this topic trying to incorporate different parameters coming out from many different data sources. In general, four potentials can be incorporated into the estimation model: physical, geographical, technical, and economic potential [6].

Depending on the level of requested assessment accuracy, different types of data could be incorporated. Spatial data used in the assessments can go from statistical data for assessing types of buildings and roof characteristics, all the way to LiDAR scanning or photogrammetry-based data for modelling the position, type, and orientation of the building rooftops.

Large-scale assessment usually is based on statistical data where roof types and roof surfaces are statistically calculated. Calculations of the needed parameters are based on other available data such as the size of the municipality, number of inhabitants, building types, etc. [7]. Further on, additional spatial data such as satellite images, airborne images, and land use data combined with other relevant statistical data is used to provide better estimation results [8]. As details are increasing the assessment accuracy is higher and better. For higher accuracy assessment, usually on smaller target areas, 3D City models are used with LoD not less than 2, or LiDAR data to provide higher detailed model of building rooftops [9, 10].

2 METHODOLOGY

The purpose of this paper is to evaluate the solar photovoltaic potential of building rooftops, by applying GIS technology and available spatial data in the Republic of North Macedonia. The main objective is to estimate the photovoltaic potential for individual rooftops on each building, as well as to determine the total photovoltaic potential across all buildings in the study area that are suitable for installing photovoltaic systems. The research was conducted as a case study in a particular urban area, in which a three-dimensional model had been developed. This included topographic features of the terrain, together with a three-dimensional surface model that represented morphological characteristics of the building's rooftop surfaces.

Assessment methods and approaches for determining rooftop photovoltaic potential vary, most of them rely upon a common foundation: the use of a digital surface model to execute the assessment. The DSM contains crucial information on elevation, not only of the buildings themselves but also of surrounding objects, which once more is an essential ingredient in arriving at a reasonably accurate estimate of solar energy.

As already mentioned in the introduction, most of the methodologies proposed to estimate the photovoltaic potential take into consideration four categories of potential: physical, geographical, technical, and economic potential [11]. Each of the above contributes to a holistic view of solar energy potential, but their usefulness varies depending on the study or area under consideration.

In the specific approach adopted in this research, emphasis is placed on physical and geographical potentials, as these two have a direct and significant impact on the initial stages of estimating photovoltaic feasibility.

Physical potential refers to the total amount of solar radiation that reaches a given area over a specific period. It considers factors such as latitude, weather conditions, and the amount of sunshine received throughout the year. This potential provides a raw estimate of how much energy can be captured in the absence of obstacles. It is crucial for determining how much solar energy can be generated under ideal conditions, setting the baseline for further analysis.

Geographical potential, on the other hand, involves a more detailed spatial assessment. It focuses on the physical characteristics of the rooftop and its surroundings. This includes the shape, orientation, and slope of the roof, as well as the height and proximity of surrounding buildings, trees, or other structures that might obstruct sunlight. These elements influence how much of the solar energy calculated in the physical potential can actually be captured by photovoltaic panels. In urban environments, this factor is particularly important due to the potential for shadowing from neighbouring structures, which can significantly reduce the efficiency of solar panels.

By focusing primarily on physical and geographical potentials in this research, a more accurate estimation of photovoltaic potential can be achieved, especially in densely populated or built-up areas. Once the physical potential provides the theoretical energy input, the geographical potential allows for adjustments based on real-world conditions, ensuring that the final estimates reflect both the available sunlight and the practical limitations of the built environment.

Technical and economic potentials, although crucial in a broader energy planning context, are considered secondary in this particular study. Technical potential typically addresses the efficiency of solar panels and the feasibility of installation, while economic potential considers cost-benefit analyses and return on investment. These factors are often applied after the physical and geographical potentials have been thoroughly assessed to fine-tune the feasibility and scalability of solar installations.

To achieve the highest possible DSM accuracy as a necessity for accurate assessment of photovoltaic potential, the three-dimensional model of the urban area could be generated using a LiDAR point cloud data. The LiDAR point cloud enabled the development of a high-resolution 3D model, which is vital for accurately capturing the characteristics of building roof surfaces, necessary to obtain the most reliable information about the solar photovoltaic potential of the building. In this context, Palmer et al. (2018) suggested a new method for identification of suitable rooftop areas based on LiDAR data by applying criteria related to slope, aspect, and minimum suitable rooftop area, but doesn't go further in estimating potential electricity production from the suitable roof surfaces [3].

In this research the methodology for assessment of the solar photovoltaic potential of the roof surfaces was established based on multicriteria spatial analysis, integrating a three-dimensional urban area model, building footprints, and solar radiation data. This approach is conceptually close to the applied Method 1 in the study by Huang et al. (2022) where high-resolution DSM is used for identification of suitable roof surfaces and estimation of potential electricity production [4]. This comprehensive approach allowed for a more accurate and detailed evaluation of each building solar energy potential by considering multiple factors that influence photovoltaic performance.

The process of assessment of solar photovoltaic potential of buildings consists of five consecutive steps:

1) Creation of Digital Surface Model (DSM) and extraction of building footprints,
2) Providing model for slope and aspect of roof surfaces,
3) Creating model of solar radiation for each roof surface,
4) Identifying appropriate roofs for installation of photovoltaic systems,
5) Assessment of solar photovoltaic potential of each building.

The **first step** of the process generates two key outcomes. The first outcome is the creation of a DSM, which is derived from the point cloud by utilizing only the first return points from the LiDAR beam. The DSM captures the highest elevation points on the surface, whether from buildings, vegetation, or terrain features. By providing a detailed representation of the surface's highest points, the DSM delivers valuable data for subsequent analyses, such as solar potential or shading effects. The second outcome is the building footprint extracted from the LiDAR point cloud data. These building footprints are basic inputs since they provide the bases for analysing rooftop photovoltaic potential. This potential is computed by means of roof geometry, but it is bounded within the areas set by the polygons representing building footprints. This ensures that only relevant portions of the Digital Surface Model (DSM) are considered in certain steps of the analysis.

The **second step** focuses on generating detailed data about the rooftop geometry, which is crucial for accurately assessing the photovoltaic potential of a building. Two key geometric factors, slope and aspect, play a significant role in determining how much solar radiation a roof can receive.

The slope of the roof defines the angle of incidence that the sunbeams have with the surface, the amount, and the period they are exposed to. A well-angled roof maximizes the capture of solar energy, therefore becoming more efficient in electricity production. On the contrary, a too-steep roof reduces the total solar gain.

The aspect of the roof includes the orientation, whether it is facing north, south, east, or west, which in turn decides upon the exposure of the roof to sunlight during the day and throughout the seasons of the year. In the northern hemisphere, south-oriented roofs have maximum sunshine, therefore, they are ideal for photovoltaic systems. East and west-facing roofs also present possibilities, though not as good as those oriented to the south, while north-facing surfaces receive considerably less solar radiation.

By accurately calculating the slope and aspect of each rooftop, this step enables a precise estimation of solar potential, ensuring that the placement of photovoltaic panels is optimized for maximum energy efficiency.

In the **third step**, the solar radiation at rooftop surfaces needs to be computed. An algorithm based on Rich et al. [12, 13, 14], Rich et al. 1994, Fu and Rich 2000, 2002 is employed for calculating the solar radiation, which integrates various factors to estimate how much solar energy a surface receives. These include the following:

1) Digital Surface Model: It provides the surface elevation and slope and aspect created in step two.
2) Sun position - The model simulates the movement of the sun during both the daily and yearly cycles and takes into account all variations in solar altitude and azimuth in a rough approximation of how much sunlight actually reaches the surface at given day and time of year.
3) Atmospheric Condition: This is a rough approximation of the amount of cloud cover, moisture, and scattering in the atmosphere. It subtracts from the calculated quantity the sun lost through the mentioned conditions.
4) Shading: Here, the model considers DSM to yield the shading from surrounding features that reduce solar exposure, such as hills or buildings.
5) Radiation Types: The model differentiates between direct, diffuse, and reflected radiation in developing an elaborate estimation of solar energy potentials.

These factors are combined to produce an estimation of solar radiation (W/m^2). The output of the step three is a solar radiation raster that registers the amount of solar radiation at each pixel.

The **fourth step** deals with selection of suitable roof surfaces for electricity production. All roof surfaces have different potentials for electricity production, depending on factors like slope, aspect, and exposure to solar radiation. The identification of suitable roof surfaces for electricity production involves elimination of roof surfaces that do not meet specific criteria. The selection process includes the following criteria groups:

- *Elimination of excessively steep surfaces:* Such roofs that are steeply angled are not fit for installation of solar panels. Shading often result from their nature and the angle is quite high to expose fully sunshine on the solar panels.
- *Exclusion of areas with insufficient solar radiation:* Roof surfaces receiving poor solar irradiance, whether because of the effect of shading by nearby objects or orientation, will not be suitable for electricity generation.
- *Removal of north-facing surfaces:* In the Northern Hemisphere cases, north-facing roofs receive hardly any sunlight and so are usually inefficient for solar energy generation.

After filtering out all unsuitable roof surfaces, the remaining suitable surfaces are identified, and a raster model is generated, consisting solely of pixels that meet the predefined criteria. This raster represents the areas with optimal conditions for solar energy production.

The **fifth step** as a final one is providing the assessment of solar potential for each building in the model. The solar potential per building is determined by first grouping all pixels identified as suitable within a specific building and calculating both the total area they occupy and the mean solar radiation value (in kWh/m^2) from each cell in the raster model within that particular building footprint. The size of the suitable roof area is one of the main factors in consideration for the assessment of the building's suitability for installing photovoltaic panels.

Roofs with suitable area less than the defined minimum in square meters are considered too small for installation of photovoltaic panels from economical aspect and have been excluded from further analysis. For the rest of the buildings, with suitable roof areas above the minimum defined area, total solar radiation is calculated for every single building.

The total solar radiation per building is expressed in megawatt-hours per square meter (MWh/m²) and is calculated using the following formula:

$$\text{Solar radiation per building} = (\text{Suitable area} \times \text{Mean solar radiation})/1000$$

To estimate the potential electricity production, the total solar radiation is converted using the following formula:

$$\text{Electricity production potential} = \text{Total solar radiation per building} \times 0.16 \times 0.86$$

In this calculation, the energy production depends not only on solar radiation but also on the efficiency of the solar panels and the system's performance ratio. According to the US Environmental Protection Agency (EPA), a conservative estimate for solar panel efficiency is 16%, meaning that 16% of the incoming solar energy is converted into electricity. Additionally, the performance ratio of 86% reflects the system's ability to retain and store 86% of the electricity generated as it passes through the installation [15].

These values are used to provide an accurate estimation of the building's potential for solar electricity production, factoring in both the available roof area and the efficiency of the technology in place.

3 CASE STUDY

To test the proposed methodology, a research area was selected, focusing on a section of the central part of the town of Strumica. The town is situated in the southeastern Republic of North Macedonia, in the western part of the Strumica Valley, at 41° 26' N latitude and 22° 38' E longitude, at an average elevation of 230 meters above sea level.

Strumica is well-known for its long periods of sunshine and high light intensity, factors that enhance its solar energy potential. On average, the region experiences approximately 230 sunny days per year, or around of 2,377 hours of sunshine annually, making it an ideal candidate for solar energy studies.

The selected research area, covering 38 hectares in the city centre, was chosen with the aim of assessing the solar photovoltaic potential of building rooftops. This area includes buildings with various heights, sizes, and types such as: individual and collective residential buildings, public and commercial buildings, a shopping centre, schools, a kindergarten, a hospital, and many more. These buildings are characterized by various geometries and roof types, with different slopes and orientations of the roofs, which is considered one of the important factors when studying the solar potential of roofs.

The research area also includes vegetation of different types and heights, providing an opportunity to assess the impact of greenery and tall trees on the solar photovoltaic potential of nearby rooftops.

LiDAR point cloud data served as the primary source for building extraction, the creation of a Digital Surface Model (DSM), and subsequent analyses. This LiDAR data was acquired through aerial scanning during the 2019–2020 period and was provided by the Agency for Real Estate Cadastre of North Macedonia. The parameters of used point cloud are given in Tab. 1.

Table 1 Characteristics of LiDAR point cloud

Parameter	Value
LiDAR sensor	RIEGL VQ-1560i S.N. S2223066
Height of flight	1400 m
Scanning angle	± 20°
Distance between points	0,3 m
Minimal point density	5 points/m^2
Average point density	10 points/m^2
Hight accuracy	0,1 m

The first step in the analysis is the creation of a Digital Surface Model (DSM). A raster surface model with a spatial resolution of 0.5 meters was generated. Although raster models with higher resolutions can define surface features with greater precision, they are more computationally intensive to process.

In this study, a spatial resolution of 0.5 meters was selected as the optimal balance between accuracy and efficiency. This resolution was chosen because LiDAR point cloud data has a point spacing of approximately 0.3 meters. Even though a higher resolution would provide more surface details, the chosen resolution was considered as satisfactory since it preserves enough details while minimizing processing time.

The second step involved detecting building footprints. To create a building footprint model, a classified LiDAR point cloud with a class "Building" was required, and an automatic classification approach was applied. During the automatic classification, points corresponding to flat roof characteristics were identified with a moderate tolerance for irregularities. The classification conditions were set as follows:

- Minimum roof height: The lowest height from which points on the roof would be detected (set to a minimum of 2 meters).
- Minimum roof area: Only roofs with a surface area of at least 10 m² were included.

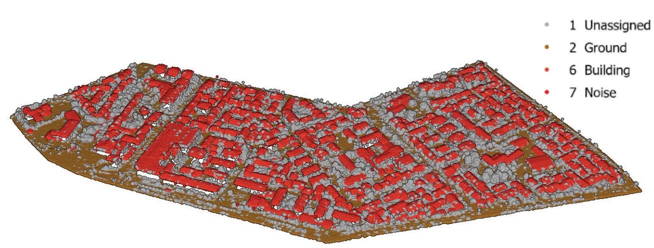

Figure 1 Classified LiDAR point cloud of the study area

After the automatic classification of the class "Building", a raster model of the buildings was created. This raster model, with a resolution of 0.5 meters, was then converted to vector format to create polygons representing the building footprints.

Figure 2 Buildings as raster data combined with orthophoto image

The position and shape of the automatically created polygons were visually cross compared with high-resolution orthophoto images. This showed that it corresponds well with the real position and actual geometry of the buildings. As this has been an automatic processing of data, some irregularities existed, like empty spaces within the polygons or uneven edges of polygons. To fix this, a regularization process that straightens the sides of polygons and creates right angles, where appropriate, was applied. For small empty spaces in the polygons below threshold, these were removed, though some empty space was retained if it represented an actual building feature.

After this additional automatic processing, a manual correction phase followed. This involved comparing the generated polygons with the digital surface model, satellite imagery, and Google Street View photos. Manual adjustments were made, particularly for attached buildings, ensuring that separate polygons were created for each building.

Figure 3 Regularized building footprint

At the end of this step, a 3D model of the urban area was produced, clearly showing the buildings within the research area, providing a solid foundation for further analysis.

Figure 4 3D model of buildings within study area

Based on the digital surface model, digital models of roof slope and orientation were generated for the buildings. These spatial models were created with an optimal resolution of 0.5 meters.

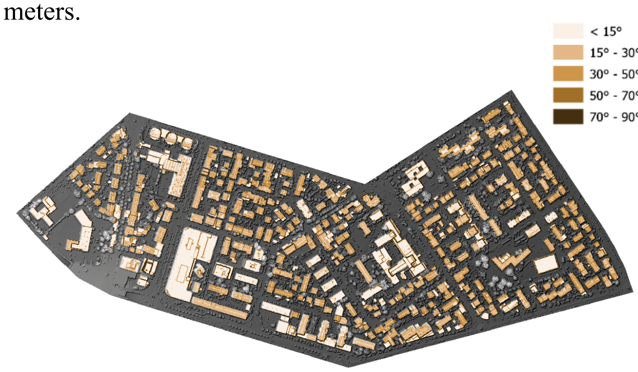

Figure 5 Building rooftop slope

The digital slope model assigns a value to each pixel representing the roof's inclination, ranging from 0° (completely flat) to 90° (vertical). Lighter colours indicate flatter surfaces, while darker colours correspond to steeper slopes. The digital orientation model, on the other hand, assigns a value to each pixel that indicates the direction the roof surface faces, with 0° representing true north and 180° representing true south.

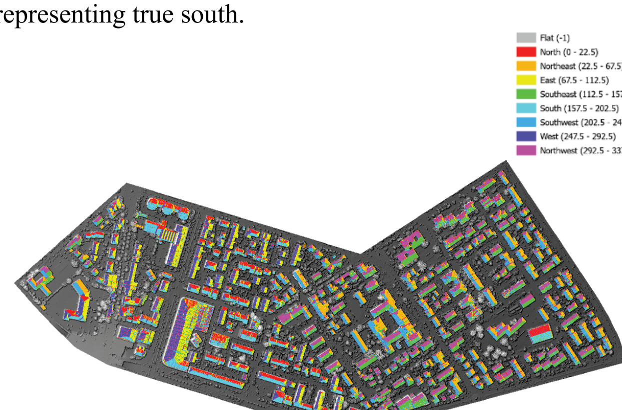

Figure 6 Building rooftop aspect

To estimate the solar photovoltaic potential, a digital solar radiation model was created for each building's roof. This model is based on the digital surface model and incorporates data on obstacles, roof slope, and orientation. The solar radiation calculation uses an advanced algorithm that accounts for the sun's position throughout the year and different times of day, as well as obstacles like nearby trees or buildings that can block sunlight. The model also considers the slope and orientation of the surface. Additional parameters include the time interval for the calculation and the number of directions to the sky to detect shadows and visible areas. Each pixel in the resulting raster model contains a value representing the amount of solar radiation, measured in watt-hours per square meter (Wh/m²) or kilowatt-hours per square meter (kWh/m²).

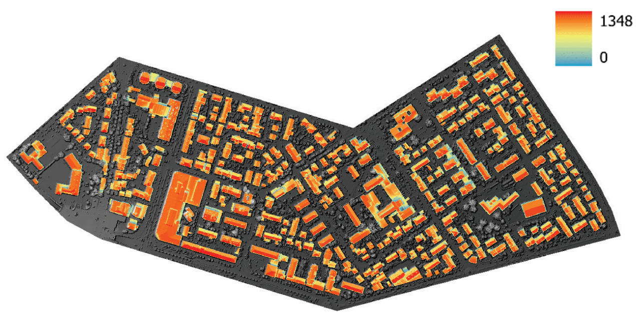

Figure 7 Building rooftop solar radiation

After generating all necessary spatial data, the following criteria have been used to identify roof surfaces that are suitable for the installation of solar photovoltaic systems:

- Slope: The slope of the roof surface should be less than 45°.
- Solar Radiation: The annual incident solar radiation received should be more than 800 kWh/m².
- Aspect: The roof surfaces shouldn't be oriented to the north except flat roofs whose inclination is less than 10°.

To qualify as suitable for solar photovoltaic installation, a building must have at least 30 m² of roof area that meets these conditions. For buildings that meet the criteria, the average annual solar radiation is calculated. The total annual available solar radiation for every building is calculated by multiplying the suitable roof area with the average solar radiation.

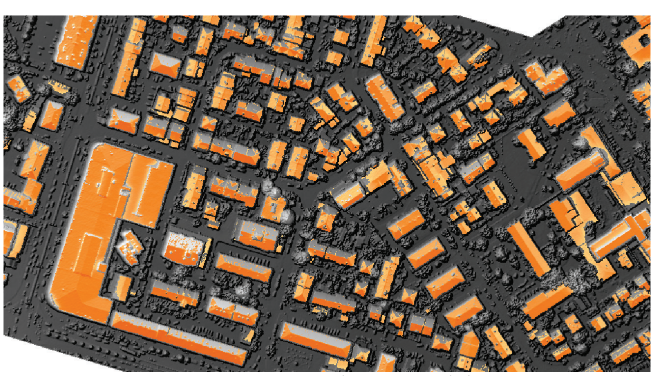

Figure 8 Photovoltaic potential on rooftops that are fulfilling given criteria

Finally, to estimate the solar photovoltaic potential for each building, the following three values are taken into consideration: the roof area that is considered suitable, the conversion efficiency of solar energy to electricity, and any losses incurred by the photovoltaic system equipment. The photovoltaic potential is calculated for each building as well as collectively for all buildings within the study area.

4 RESULTS

Based on the analysis of the urban area selected as a case study, building footprints were extracted for 628 buildings, covering a total area of 119 079 m². The smallest building has an area of 17 m², while the largest building is 6932 m².

Out of these 628 buildings, 529 were identified as suitable for the installation of photovoltaic systems, after applying the conditions for roof suitability. The total roof area suitable for solar photovoltaic installation is 73 544 m², representing 62% of the total rooftop area analysed.

Although the number of suitable buildings is reduced compared to the total number analysed, most of the excluded buildings were small auxiliary structures with minimal roof space. These buildings are typically low in height and situated close to other buildings, resulting in significant shading of their rooftops.

Figure 9 Photovoltaic potential (MWh) per year

Figure 10 3D model of the case study area coloured by estimated photovoltaic potential

On the other hand, most of the individual, collective housing, and public buildings, like schools, the shopping centre, and the city hospital, were highlighted to have large parts of their rooftop area suitable for installing a photovoltaic system. These buildings have a high potential in terms of electricity production.

The potential electricity production per building ranges from 4 MWh to 1000 MWh annually, with larger and taller buildings generally producing more electricity. If photovoltaic systems were installed on all suitable rooftops in the study area, the total potential electricity generation would amount to 11 329 MWh per year.

The largest building in the study area is a shopping centre with a flat roof. It has a suitable roof area of 6198 m² and an estimated electricity production potential of nearly 1000 MWh per year. The entire rooftop was determined suitable for photovoltaic installation, because of its flat design, height, and low shadow coverage, making it an ideal candidate for maximizing solar energy production.

5 CONCLUSION

The integration of LiDAR data, spatial modelling, and Geographic Information Systems (GIS) allows for a highly sophisticated and efficient analysis of optimal locations for solar photovoltaic system installations.

This approach takes into consideration all critical spatial factors affecting the solar energy potential of rooftops, such as roof slope and orientation, shading from nearby objects, and solar exposure throughout the year. In this case study, out of 628 analysed buildings, 529 buildings were selected to be suitable for the installation of photovoltaic systems, covering 73 544 m², or 62% of the total rooftop area, with an impressive electricity production potential. Notably, larger structures such as individual buildings, residential buildings, schools, shopping centres, hospitals were found to have rooftop areas capable of producing between 4 MWh and 1000 MWh annually, with a cumulative potential of 11 329 MWh across all suitable rooftops.

LiDAR data provides the precise input necessary for creating spatial models that assess the solar photovoltaic potential of building rooftops. These models, developed through the established methodology, are used to determine the feasibility and effectiveness of installing solar photovoltaic systems for electricity generation. Since LiDAR data of the entire territory of the Republic of North Macedonia is available, this methodology is implementable on every part of the country.

Such high-resolution spatial data availability allows the estimation of photovoltaic potential not only of large urban areas but also of single residential or commercial buildings. This flexibility can ensure that the methodology will be used to maximize energy production by solar photovoltaic installations across various building types and regions.

This approach raises the level of awareness of all stakeholders in regard to property owners, investors, and authorities at the local government level by assessing the potentials of each individual building for solar photovoltaic system installation. The detailed, data-driven assessment can further encourage more participation in the adoption of solar energy to achieve national and local renewable energy goals. These can also serve as a basis for policy development in motivating or incentivizing sustainable energy investments or providing information for urban planning strategies toward clean energy access.

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