Roof’s Potential and Suitability for PV Systems Based on LiDAR: A Case Study of Komárno, Slovakia

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Abstract: The case study focuses on evaluating the suitability of roof surfaces in terms of their solar potential based on their geometric parameters. The selected processing methodology detects segments of roof surfaces from the LiDAR base, supplemented with spatial information (orthophoto map, real estate cadastre (REC)—footprint, basic database for the geographic information system (ZBGIS)—classification of buildings—current use). The approach based on spatial analyses takes into account the limit conditions for determining the impact of solar radiation resulting from the roof area, slope, aspect, and hillshade. Considering to the available subsidy scheme for family houses in the conditions of the Slovak Republic, a narrower sample of 35 family houses was selected from the total number of typologically represented buildings (194). A 3D model of the building created by combining REC and LiDAR substrates shows the roof surface without overlap, while another 3D model made of LiDAR substrates alone represents the actual dimension of the roof surface. The results presented for each selected building show good agreement with each other, and their visualizations were obtained using two GIS environment approaches. In the area of family houses, up to 94% of the roof areas of buildings registered in the REC meet the conditions for the installation of a PV system with an output of 2.6/3.3 kW.

Keywords: LiDAR; roof; high vegetation; spatial analyse; 3D modeling; solar potential; PV system

1. Introduction

Renewable energy sources (RES) are considered as an alternative to fossil fuels (mainly gas, oil, and coal). Directive (EU) 2018/2001 of the European Parliament and Council [1] on the promotion of the use of energy from renewable energy sources has set a new binding EU target for 2020–2030 to achieve at least 32% of final energy consumption from renewable energy sources. Slovakia has set a target value of 19.2% for 2030.

In order to fulfill the obligation arising from this Directive, Slovakia is actively approaching the creation of conditions for solutions that will fully support sustainability in the issue of production and supply of electricity from renewable energy sources in the future. Adopted legislative changes in this area, in particular Law no. 309/2009 Coll. on support for renewable energy sources and highly efficient cogeneration (www.slov-lex.sk/pravne-predpisy/SK/ZZ/2009/309/), forms part of the state support mechanisms.
As cities in the EU consume around 80% of energy [2], they are expected to move towards reducing consumption using energy planning [3,4]. To increase the use of RES at the level of regional and local self-government is the fundamental objective of the Concept of Municipal Development in the field of thermal energy according to Law no. 657/2004 Coll. on thermal energy (https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2004/657/20200721). Within the scope of that Law, at the municipality level, there is an obligation to develop an energy plan for each municipality with more than 2500 inhabitants, even with the possibility of switching to the use of RES.

The assessment of energy systems in terms of their sustainability is described in a study by Dincer and Acar [5], which takes into account several factors in each evaluation. In another work [6], Abu-Rayash and Dincer developed a model for assessing the sustainability of energy systems.

The production of electricity using current technologies operating on the principle of photovoltaic systems (PV) installed mainly on buildings has significant potential in the conditions of the Slovak Republic [7].

Assessing the potential of solar energy is an important area of research and needs to be addressed, as it is considered a crucial source of energy for the future [8]. From this point of view, it is necessary to use all available tools, methods, and approaches to find a comprehensive solution to this issue. The active use of solar energy requires relatively detailed data on solar radiation falling on the earth’s surface. The study by Mousavi Maleki et al. [9] deals with estimating the intensity of solar radiation incidents on inclined surfaces, and Mecibah et al. [10] carried out a similar study focusing on horizontal surfaces in Algeria. Regarding the territory of Saudi Arabia, there is the study by El-Sebaii et al. [11], and the study by Ma et al. [12] for the territory of China. Korachagaon and Bapat [13] proposed universally applicable global models and confirmed the strong influence of meteorological, climatic, and geographical parameters on the resulting values of global radiation.

Spatial information files are used to determine the potential solar radiation (solar potential) incident upon the roofs of buildings [14]. These data are used as a basis for different types of computational models based on the use of 3D models of existing places, without the need to create models [15], models created based on building typology [16], models created using procedural modeling [17], or models created from the building library [18]. Similarly, the potential usability of buildings for the installation of PV systems, or specific PV capacity, can be analyzed using GIS tools based on the evaluation of energy consumption in urban areas [19] and large-scale photovoltaic systems [20].

The Aboushal study [21] proposes a solution for optimizing the selection of PV panels, taking into account the specifics of the locality, while the work [22] also emphasizes social and socio-economic factors [23]. The study by Li et al. [24] focuses on solving the problem of hillshade analysis, as the density of buildings (e.g., high-rise buildings) can be a limiting factor for the use of PV systems in urban environments.

Assessment of the usability of solar potential in the urban structure is influenced by the diversity of individual urban forms [25], and therefore the placement of PV panels is mainly considered on roofs [26]. The suitability of the roof surface and the usability of solar potential can be determined by applying a group of spatial analyses from the GIS environment [27,28], algorithms from the MATLAB environment [29], and advanced 3D modeling tools [30]. The overall assessment of solar potential for a selected part of the urban structure according to Verso et al. [31] requires a multi-criteria approach to the area addressed.

Most of the research at present is based on 3D models. Methods for creating a 3D model are based on aerial laser scanning with Light Detection and Ranging (LiDAR) [32,33] or ground or aerial photogrammetry [34] in combination with terrestrial laser scanning [35]. Creating 3D models of larger cities is financially demanding, as it requires detailed data collection and subsequent maintenance of the database in terms of its timeliness and accuracy.

Roof surfaces are used to determine PV potential [36], but it should be borne in mind that not every roof surface is fully accessible for installation. The study by Singh et al. [37] also simplifies roofs, where by the roof area is extracted from the building footprint. Roofs contain elements such as
chimneys or dormer windows, which can form shielding barriers. The solution lies in the creation of 3D models of places with different levels of detail (LOD) [38,39] and their further use for spatial analysis. This approach is suitable not only for experts, but also for the general public. People are increasingly trying to live in the spirit of nature with regard to zero waste, low-energy housing, and green households.

In our study, we analyze the extent of the possibility of installing and using PV systems on roofs in the conditions of Slovakia. The selected area of the town of Komárno is promising for the direct use of solar energy due to its suitable climatological conditions (the town lies in a warm climate zone with longer periods of sunshine). We focus in more detail on the analysis of family houses in terms of the availability of financial support for small PV systems (generating up to 10 kW).

2. Materials and Methods

This study is based on a combination of software environments using Geographic Information Systems (GIS) with Computer-Aided Design (CAD) software to create detailed 3D models of buildings. The methodology of the study consists of three parts (Figure 1): (i) preparation and pre-processing of source data, (ii) creation of 3D models and spatial analysis, and (iii) evaluation of the potential use of PV systems on roofs. This case study follows the methodology proposed by [40], and the three parts of our methodology are described in more detail in Sections 2.2 and 2.4 below.

2.1. Study Area

This study was carried out in a selected part of the town of Komárno (47°46′ N, 18°07′ E), which lies at the confluence of the Danube and Váh rivers, near the south-eastern edge of the Danube Plain (Figure 2). The city lies at an altitude of 110 m above sea level and is located in a warm climate, in a warm and arid district with a mild winter. Near the town there is the Hurbanovo climatological station. The average annual air temperature at the Hurbanovo station is 10.4 °C. The average annual amount of global radiation is 4300 MJ/m² [41].
2.2. Data Collection and Processing

Data from aerial laser scanning (LiDAR) format (*.las) in a combination of orthophotos and data from the real estate cadastre (REC), which is part of the Geodesy, Cartography, and Cadastre Information System, were used as input data in this study. The use of LiDAR data to determine solar radiation potential is also reported by Le et al. [42] and used in combination with orthophotos in the study by Nelson and Grubesic [43]. Data from the REC were used to display the building footprints registered in it. All source data were provided by the Geodesy, Cartography, and Cadastre Authority of the Slovak Republic (GCCA SR). The data were then processed using GIS (a combination of ArcMap 10.7.1 and ArcGIS Pro 2.4.3) and the Bentley Descartes V8i SS10 environment.

There are various types of buildings in the selected locality: family houses, production halls, and multi-storey buildings (administrative buildings and apartment blocks). The total number of buildings in the case study was 194. Of that number, industrial buildings make up 46.9%, ancillary 5.7%, commerce and services 13.9%, individual residences 23.7%, office premises 4.6%, public services 1%, residential blocks 3.6%, and retail trade 0.5% (Figure 3a).

Figure 3. Input data based on orthophoto: (a) type of use of buildings; (b) display of LiDAR point cloud of buildings in the case study.
The parameters of the LiDAR point cloud (Figure 3b) for the Komárno locality (area 1767 km²) are its altitude accuracy of 0.03 m in ETRS89-h, positional accuracy of 0.07 m in ETRS89-TM34, average point density 33 points per m², and average distance between points 0.17 m. The data are processed in the geodetic reference coordinate system defined by the Datum of Unified Trigonometric Cadastral Network (D-UTCN) in implementation of UTCN03/Krovak East North (EPSG: 8353) and the Baltic Vertical Datum—After Adjustment (BVD-AA).

The vector cadastral map (VCM) in this area consists of a numerical cadastral map, the content of which is formed from numerical results obtained from terrestrial geodetic surveys. The accuracy characteristic for determining the x, y coordinates of detailed points mxy is in the range 0.08 to 0.14 m. Numerical results of the measurements transferred into the vector cadastral map are expressed in the coordinates of the geodetic system D-UTCN implementation of UTCN. Building data from the REC were supplemented from the ZBGIS database with the current use and height above the land surface. Heights were measured from the base of the building to its highest point. If the height difference was more than 6 meters for individual parts of the building, its geometry was divided. With different types of use of the buildings, each one was interpreted separately from its actual height.

Aerial photogrammetry was carried out in 2017. The results were digital orthophotos or orthophotomosaics, which were also used in our study in the D-UTCN coordinate system in the implementation of UTCN (EPSG: 5514) with a resolution of 25 cm per pixel. Accuracy was characterized by Root Mean Square Error RMSEXY = 0.30 m; Circular Error (CE) with probability 90% (coefficient value 1.5) was RMSEXYCE90 = 0.45 m and CE with probability 95% (coefficient value 1.73) was RMSEXYCE95 = 0.52 m.

2.3. Solar Model in GIS Environment

For the active use of solar energy, it is necessary to take into account detailed data on incident solar radiation, in terms of both quality and quantity. Climatic conditions, air purity, climatological indicators (air temperature, degree of cloud cover), and compass orientation also have a significant impact. Slovakia, with its geographical location between 48–50°N, can be included among the areas suitable for the practical use of solar energy [44].

The decisive climatic factors also include the mean monthly sum of sunshine duration. At a distance of 16 km from the city of Komárno is the Hurbanovo climatological station of international importance (Figure 4) (indicative 11 858, position 47º52′21″ N and 18º11′35″ E, height 115 m above sea level). The meteorological/climatological data collected by this station include the duration of sunlight measured by calculating the heliogram.

![Figure 4. International climatological station Hurbanovo: (a) spatial localization, (b) southern view.](image-url)
Data from the Hurbanovo climatological station (Figure 5a) include monthly totals of sunshine duration forming a visualization of available data recorded and processed over 11 years (2009–2019). Figure 5b shows the number of sunny, partly cloudy, cloudy, and rainy days in each month for the locality of Komárn. Sunny days are days with less than 20% clouds, partly cloudy means 20–80% clouds, and cloudy means more than 80% clouds. The data are based on hourly simulations of weather models over the last 30 years (meteoblue.com).

![Figure 5](source: shmu.sk); (b) meteorological chart (Source meteoblue.com).

The solar radiation model is based on the ArcGIS Pro Solar Radiation computational algorithm (pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/an-overview-of-the-solar-radiation-tools.htm). The Area Solar Radiation tool with an integrated calculation model was used for the analysis of solar radiation, which allows the calculation to be performed on the input topographic surface. Solar Radiation tools in ArcGIS Pro were created based on methods from the hemispherical vision sequence algorithm (pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-solar-radiation-is-calculated.htm). We specifically applied the work of Chow et al. [45], which was based on the modeling of solar radiation using the Solar Radiation tool from the ArcGIS environment.

### 2.4. Assessment of Suitability of Location of PV Equipment on Roof Surfaces

The basis for the use of photovoltaic equipment is to determine the area and shape of the roof. The overall usability of the roof is limited by roof details, which are based on the typology of roofs. A more detailed description of roof details is given in Table 1 below [46].

<table>
<thead>
<tr>
<th>Roof Area</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brim/border</td>
<td>eaves, gable edge/shield edge, roof ridge</td>
</tr>
<tr>
<td>Edge</td>
<td>ridge, saddle ridge, corner, groove, notch, degree</td>
</tr>
<tr>
<td>Penetration</td>
<td>chimney, window, dormer</td>
</tr>
<tr>
<td>Connections</td>
<td>wall</td>
</tr>
</tbody>
</table>

The suitability of the roof surface for PV systems, moreover, is also defined by the surface on which the panels can be installed. The methodology reported in the study by Palmer et al. [47] recommends the installation of 1 kW equipment on a roof with a minimum area of 8 m².
According to the manufacturers of PV panels, the value of the relationship between the electrical power of PV panels and their area in the assessed locality is set at 5 m²/kWp (nominal power) of the produced PV electricity. Taking into account the electrical input of the system as well as power losses, this value is comparable to the parameters of the study by Palmer [47]. Thus, the maximum area, taking into account the legislative restrictions for on-grid PV systems generating up to 10 kW, corresponds to approximately 80 m² of sloping roof area. Since the articulation of the roof surfaces also determines the compass orientation of the PV panels, these panels should be installed on roofs so as to minimize losses related to the current position of the sun. In practice, however, the relationship between the nominal power and the resultant power of the installed device is at the level of 1:1.6, which corresponds to the above-mentioned area.

According to the Energy Manual [48], photovoltaic panels are structural systems that must be stable as a whole, but also with regard to their elements. The mounting system must be dimensioned in such a way that the panels cannot be lifted or overturned by the wind, nor slip under the effect of the load, i.e., their position must not change under their weight. The constant action of the load in terms of the panels’ weight and occasional loads in the form of the effects of wind and snow are complementary forces that add up, and the calculation of the forces must be based on the most unfavorable case in the form of the greatest potential loading forces. The actual load results from the weight of the components, and the magnitude of that load must be determined with sufficient accuracy. The self-load is related to the size of the modules, and their force vector acts vertically downwards. Due to the large area of the modules and their relatively low dead weight, wind acting in the form of dynamic load and snow in the form of static load are important factors.

2.4.1. Spatial Analyses

The spatial diversity of the urban environment is a crucial factor for the installation of PV systems. In addition to the main tasks of roofs (forming the crown of the building, bearing the strain from wind, rain, and snow, protecting the building interior, providing thermal protection, soundproofing, and fire protection), the roof structure currently takes over an extended auxiliary function and receives or integrates elements of energy conversion. The Energy Manual [48] states that, according to the slope of the roof, structures can be divided into flat roofs (slope less than 5°), slightly sloping roofs (slope 5–22°), normally sloping roofs (slope between 22–45°), and extremely sloping roofs (slope greater than 45°).

Spatial analyses can be used to reveal various problematic aspects, limitations, and ultimately the benefits of installing PV systems on roof surfaces. These analyses are used, among other things, to process, visualize, and interpret the diverse representation of real-world objects. Slope, aspect, and hillshade are used to determine the typological and geometric properties of roof surfaces.

The slope of roofs in built-up areas is still influenced by the adopted regulations of the zoning plans of the respective towns and villages in the conditions of the Slovak Republic. Determining the roof pitch is important for the selection of suitable areas, as the optimal roof pitch for the installation of PV systems varies with latitude [49]. The azimuth of the roofs is adapted to the spatial arrangement of roads in built-up areas. The presence of roof elements has a local effect on the total usable area suitable for the installation of PV systems [47]. Hillshade is a technique used to visualize shaded relief and thus to detect unshaded roof surfaces. Hillshade is influenced by the daily (changes in azimuth angle) and seasonal (changes in elevation angle) dynamics of the apparent movement of the sun across the sky.

In addition to the roof area and its articulation, slope, and orientation, as well as secondary shading, in the case of PV systems installation the determining factor is also the load-bearing capacity of the roof structure (especially when installing a larger number of panels on roof structures with larger areas). In general, all roof areas are suitable for the exploitation of solar energy if their area is sufficient for economically meaningful installations of PV systems (generally solar panel systems). In the case of curved surfaces, different angles of inclination lead to different exposure ratios around the compass points, which must be taken into account when connecting the PV panels.
2.4.2. 3D Modeling of Buildings

Data in 3D space is needed to support decisions on the possibilities of using and modeling solar energy in a GIS environment [45]. Estimating incident solar radiation on the surfaces of inclined and flat roofs in the urban environment requires the processing of complex geometry in the form of 2D polygons representing buildings [50] and the subsequent generation of 3D models of these buildings [51]. Our study partially applied the methodology described in [40] to ensure the segmentation of flat and sloping roofs from the LiDAR substrate. This methodology recommends using an approach based on modeling the roof ridge using the flow direction method to achieve segmentation of sloping roof surfaces. For flat roofs, it is rather recommended to use Simplify Building and Regularize Building. Modeling the incidence of solar radiation in built-up areas presupposes a diversity of representation of objects located in the defined area. The extent of the area and the representation of objects in our study were chosen with regard to solar radiation’s potential usability. For more detailed specification, this would involve the potential of the roof surfaces only. In this context, further account should be taken of level of detail (LOD). From the point of view of complex processing of 3D model of buildings with up to five LODs [52], it is necessary to consider the first four levels of LOD (LOD0, LOD1, LOD2, and LOD3) within the process of the study. The following figure presents this in more detail (Figure 6). It is necessary to obtain more detailed information about roofs at the LOD3 level from a homogeneous point of view. This approach is also recommended in study [53].

![Figure 6. Levels of detail of 3D objects for estimating the impact of solar radiation.](image)

LOD0 is a representation of building footprints and roof-edge polygons. LOD1 is a coarse prismatic model usually obtained by extruding a LOD0 model marking the transition from 2D to 3D GIS. According to [54], the height of the building model H on LOD1 can be varied starting at the level of the lower edge of the roof; the edge of the building; 1/3, 1/2, and 2/3 roof height and roof ridge up to the highest roof object (H0–H6). LOD2 is a model with a simplified roof shape and building walls. LOD3 is an architecturally detailed model with building elements (windows, doors, roof windows, dormers, and chimneys) [38]. For this case study, the important windows and doors were not located on the buildings’ facades, but all elements were located on the roofs (dormers and roof windows). For this reason, building facade points, including outlier points, have been reclassified from class 5—Buildings—to a separate classification class of 67.

2.5. State Support Mechanisms for PV

The Ministry for the Environment of the Slovak Republic (www.minzp.sk/) has announced calls for the support of production and distribution of energy from renewable sources within the operational program entitled Quality of the Environment (www.op-kzp.sk/en/energetics/). The calls are aimed at increasing the use of RES in households, in businesses premises as well as in public buildings.

Support for the installation of small facilities for the use of renewable energy sources within the national project name “Green for households” (zelenadomacnostiam.sk) is intended for private residences. The support is also intended for the installation of small photovoltaic systems with electrical power rating of up to 10 kW and solar collectors for water heating. Financial support is up to 50% of eligible expenditure. The maximum contribution is €1500 (€500/kW of installed capacity).
The researchers noted that the study [55] confirms the need for financial support through subsidies to expand the use of PV systems.

For manufacturing companies, support is provided to increase energy efficiency through the use of RES and reduce the energy intensity of production. Another measure is aimed at public infrastructures and public buildings. One of the goals is to develop the tendency to build low-energy buildings or buildings with almost zero energy consumption. One of the solutions is the installation of equipment for the use of RES, which is designed primarily to cover the energy needs of the building.

3. Results and Discussion

This section of our study is divided into the following subsections, which present approaches based on the application of GIS tools in the field of spatial analysis, modeling the impact of the amount of solar radiation and modeling of 3D objects. An overview of these tools can be used as a support mechanism for determining roof areas suitable for the installation of PV systems.

3.1. Data Processing for the Purpose of Roof Surface Area Delimitation

In the application of the chosen methodology workflow (Figure 2), processing of the spatial data set from LiDAR technology played an important role. This file presented a classified point cloud, which was processed into vector and raster formats for the purposes of this study. Due to the intention of the study, the subject of processing consisted of two classification classes: 6—buildings and 5—high vegetation (Figure 7a).

![Figure 7](image-url)

**Figure 7.** Data selection: (a) View of the classification class 5—High Vegetable and 6—Building. “Source of product ALS: GCCA SR”; (b) Roofs typology presentation.

The starting point for the processing was spatial data on buildings according to the Building Law’s applicable provisions (Law no. 50/1976 Coll., §43a, paragraph (2)), which are also the subject of registration in the REC of the SR. Taking this fact into account is linked directly to the conditions for applying for the subsidy, where the applicant is obliged to submit binding data on real estate kept under the owner’s name in the cadastral documentation of REC. The buildings in the area in question have different shapes, and typologically there was a range of flat and sloping roofs. The graphical presentation of the typological variety is presented in Figure 7b below, processed on a vector graphic of REC, supplemented with an attribute of the roof type from the orthophoto. In percentage terms, flat roofs accounted for 55.2% (107 buildings in total) and sloping roofs for 44.8% (total of 87 buildings).

In the first step, it was necessary to focus on identifying all the roof areas. There are mostly roof objects on most of the roof surfaces, the representation of which can significantly limit the usability of the roof surface. LiDAR was fully used for this purpose, which allowed us to create a 3D model of the roofs. Segmentation was used to identify individual roof planes, according to the methodology [40]. This methodology was modified by applying spatial slope analysis [56], which allowed the joint segmentation of flat and sloping roofs together. Spatial analysis slope was performed on the graphic of...
a generated raster file DSM (from class 6—Buildings) with a resolution 30 cm per pixel. This processing step was necessary to obtain a vector layer of the outline of the roof planes \[37\] and the details of the objects placed on them. This approach had to be applied to obtain the roof surface area with the possibility of excluding those parts taken up with roof elements (e.g., chimney, skylight, dormer, air conditioning units). The choice of this processing procedure also confirmed a specific set of limitations. It was found that segmentation could capture those groups of objects whose height dimension above the roof surface area was more pronounced. Roof windows, installed PV systems, ventilators, and chimney pipes could not be identified using this procedure, in contrast, for example, to dormer windows, brick chimneys, or air conditioning units (Figure 8).

![Figure 8. Segmentation of roof planes of a selected object: (a) aerial image of roof, (b) results of segmentation shown on an orthophoto map.](image)

A segmented group of roof planes and their objects with available area data was used to determine the actual area required for the installation of PV systems. If we did not consider these limitations, the resulting roof area would be overestimated and probably all the performed analyzes would indicate only the theoretical (technical potential) of these areas. We encountered similar conclusions in study \[57\]. We assumed that the PV system could be installed in an area with a minimum size of 8 m\(^2\) \[47\] (Figure 9a). That area corresponds to a system with an output of 1 kW. In our study, we used the ArcGIS aspect tool to determine roof orientations. A sampling of the orientation of roof planes was reclassified into four classes (1—north: 315°–0°, 0°–45°; 2—east: 45°–135°; 3—west: 135°–225°; 4—south: 225°–315°) for selection of more accessible roofs (Figure 9b). The slope of the roof plane was determined based on the slope analysis, the result of which is shown in Figure 9c. The obtained data on slope ratios were reclassified into three classes. The first class consists of slopes between 0–10°: flat roofs, the second class 10–60° consists of pitched roofs, and the third class 60–90° consists of very steep roofs (Figure 9c). The prerequisite for obtaining a suitable area for the installation of PV systems was a calculation according to the following given condition: \(\text{("Slope" < 3) \& \("Aspect" > 1)}\), which resulted in a map of the suitability of roof areas (Figure 9d). These factors indicate the geographical potential for the area. In the last phase of this processing part, the obtained output was reclassified into two classes (1—suitable segments of roof; 2—unsuitable segments of roof). Numerical evaluation of the results obtained in this part of the study is shown in Table 2.
Figure 8. Segmentation of roof planes of a selected object: (a) aerial image of roof, (b) results of segmentation shown on an orthophoto map.

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Figure 9. Selection of roof surface segments according to the results: (a) areas over 8 m², (b) aspect analyses, (c) slope analyses, (d) according to the suitability of the areas.

Table 2. A numerical evaluation of roof surfaces for selected area.

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<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofs</td>
<td>194</td>
</tr>
<tr>
<td>Roof area</td>
<td>639</td>
</tr>
<tr>
<td>Orientation</td>
<td>N–181 E–143 S–172 W–146</td>
</tr>
</tbody>
</table>

The distribution of solar radiation was calculated for suitable roof areas (Figure 9d—green parts). The spatio-temporal sum of global solar radiation was generated for four seasons (spring season—21 March 2020–21 June 2020; summer season—21 June 2020–23 September 2020; autumn season—23 September 2020–21 December 2020; and winter season—21 December 2020–21 March 2021). We applied the ArcGIS Pro Solar Radiation Toolset to calculate the theoretical irradiance in the selected area (Figure 10).

The calculated theoretical amount of incident solar radiation’s annual values is given in the left side of Table 3 below, where the units Wh/m² are converted to MJ/m². These values represent the maximum amount of incident sunlight under ideal conditions.
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</tbody>
</table>

The distribution of solar radiation was calculated for suitable roof areas (Figure 9d—green parts). The spatio-temporal sum of global solar radiation was generated for four seasons (spring season—21 March 2020–21 June 2020; summer season—21 June 2020–23 September 2020; autumn season—23 September 2020–21 December 2020; and winter season—21 December 2020–21 March 2021). We applied the ArcGIS Pro Solar Radiation Toolset to calculate the theoretical irradiance in the selected area (Figure 10).

The resulting solar radiation maps are a standard method for visualizing various geographical variations and intensities of solar radiation on roofs for a selected period. Finally, when it comes to modeling solar radiation on roofs, such results are also presented in study [58], which similarly uses specific days. Processed visualizations of solar maps were scaled for values from 30–5840 Wh/m². The choice of scaling was adapted to visualize better the differences in total solar impact between specific days in a given year. In terms of the length of day and night, there are four specific days during the year, i.e., the summer solstice (the longest day), the winter solstice (the longest night), and the vernal and autumn equinoxes (the day is as long as the night). During the longest day of the year, i.e., on 21 June 2020, the duration of sunshine was 16 hours and 6 minutes (sunrise 4:46 a.m.—sunset 8:52 p.m.), and the theoretical total of sunlight was at the level of 5831.11 Wh/m² (Figure 11b). During the shortest day of the year, i.e., on 21 December 2020, the duration of sunshine will be 8 hours and 30 minutes (sunrise will be 7:30 a.m.—sunset will be 4 p.m.), and the theoretical total of sunlight will
be at the level of 674.16 Wh/m² (Figure 11d). During the two special days of the equinox, the durations of sunshine were 12 hours and 18 minutes, with theoretical totals of sunlight ranging from 3255.35 to 3413.86 Wh/m² (Figure 11a,c), see Table 3, right side.

![Solar radiation maps for different seasons](image)

**Figure 11.** The theoretical daily sum of solar radiation for (a) vernal equinox; (b) summer solstice; (c) autumnal equinox; and (d) winter solstice.

### 3.2. 3D Objects

3D modeling of buildings consists of a sequence of several steps. To define individual geometric aspects of LOD levels of the modeled group of buildings, the specification [38,39] (Figure 6) was applied, according to which we used a combination of sequences for LOD0.1, LOD1.1, LOD2.1, and LOD3.0. Modeling LOD0.1 was based on managed data in a current VCM, which is part of the file of geodetic information in the cadastral documentation of the REC in the cadastral unit of Komárno town. Data for the creation of LOD0 represent coordinates on breakpoints at the property boundaries of land in the places of projection of the outer perimeter of the building down to the earth’s surface. The geometry specification for creating the LOD1.1 level is based on extrusion of the LOD0 model to the level of the roof ridge. In essence, it is a presentation of a simple block model, which has great potential in various areas. By adding a simple roof model with standard roof structures within LOD1.1, LOD2.1 can be created. To create LOD3.0, it is necessary to add standard and simplified roof structures in 3D visualization. LiDAR data combined with elevation data from ZBGIS and building footprints from REC were used to create 3D building models at LOD0.1, LOD1.1, LOD2.1, and LOD3.0 levels. When creating our 3D models, we used two aspects, presented in Figure 12, for a selected building, processed with ArcGIS Pro tools. The building in question was selected for its further use in shadow analysis concerning the effects of the local environment (high vegetation). The first perspective is based on the footprint of the binding layer of the REC (Figure 12a), from which we developed the model as multipatch, set up to the LiDAR point cloud (Figure 12b). We combined the two levels, LOD1.1 and LOD2.1, using the multipatch format in the process. The result is a 3D model of a building...
divided into two discontinuous parts (Figure 12c), because the footprint consisted of two (separate) plots registered in the REC of SR. This 3D model of the building was displayed with LiDAR point clouds to compare the similarity (Figure 12d). The second aspect compared was based only on LiDAR data (Figure 12e). The boundary of the roof surface (Figure 12f) was obtained by segmentation into the footprint plane. Subsequently, the footprint boundary was obtained and used to create a 3D model (LOD1.1 and LOD2.1) as a multipatch type (Figure 12g). The result is a 3D model of a continuous building (formed from one part). This 3D model of the building (Figure 12h) is shown with LiDAR point clouds to compare their similarity.

Figure 12. Guide for creating a 3D model of building: (a) REC, (b) REC + LiDAR, (c) REC multipatch, (d) REC multipatch + LiDAR, (e) LiDAR, (f) Boundary + LiDAR, (g) LiDAR multipatch, (h) and LiDAR multipatch + LiDAR.

The 3D model created above the REC represents the building’s real footprint, but the roof surface is without an overhang (Figure 12d). With the second approach, we created a 3D model from the LiDAR, representing the real form of the roof surface only. In contrast, the building under the roof surface is extended to the roof’s edge compared to reality (Figure 12h). The use of data from the REC has a disadvantage due to removing protruding parts of the roof from the facade of the building. However, the grant scheme requires the submission of binding data from the REC. LiDAR data for the creation of 3D models is more advantageous due to the real capture of the roof shape. The use of these models for solar energy potential also requires the real capture of roof surfaces’ shape and dimensions, including roof elements.

The next part of the study presents the created 3D models’ results up to LOD3.0 level. For this part, we chose a group of buildings representing typological variety, such as an administrative building, apartment building, production hall, and family house displayed on the orthophoto map (Figure 13, 1st line). Visualizations of height ratios are presented through cross-sections of individual buildings created in the ArcGIS Pro environment (Figure 13, 2nd line). The resulting 3D models at LOD3.0 level are examples of processing in the Bentley Descartes V8i SS10 environment (Figure 13, 3rd line). These models are displayed with all roof elements to show all the limitations of the roof area in relation to the installation of the PV system. 3D building models created using geoprocessing tools in both ArcGIS Pro and Bentley Descartes also have a wide range of interchangeable file formats available. This option provides space for export/import of selected interchangeable formats of these models into the environment of various information systems. It is possible to use them, for example, for the needs.
of creating the platform of Smart Cities, the development of which is currently rapidly intensifying in the conditions of the SR.

The previous results of the roof area analyses presented in Section 3.1 and the availability of the created 3D models then contributed to the fact that the shadow analysis results (i.e., the effects of the local environment and high vegetation) must also be taken into account for further processing [24]. This is also confirmed by the study [59], which ranks shading among the four key factors for solar potential mapping. The selected area’s shadow distribution was analyzed on two specific days (21 June 2020, and 21 December 2020) at three different time points (9 a.m., 12 noon, and 3 p.m.). Shadow analysis was performed on the selected building and its surrounding environment using ArcGIS Pro tools based on LiDAR data. A Digital Surface Model (DSM) with raster resolution of 0.30 m was derived from the LiDAR data, and based on this, the graphical outputs of shadow analysis were generated. The setting of input parameters for shadow analysis is given in Table 4, specifically oriented for summer and winter solstices.

**Table 4.** Solar parameters to determine the distribution of shadows.

<table>
<thead>
<tr>
<th>Solstice of the Year</th>
<th>Changes for Selected Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elevation Angles [°]</td>
</tr>
<tr>
<td>Time</td>
<td>9 a.m.</td>
</tr>
<tr>
<td>Summer—21 June 2020</td>
<td>48.63</td>
</tr>
<tr>
<td>Winter—21 December 2020</td>
<td>09.76</td>
</tr>
</tbody>
</table>

![Figure 13. Selected buildings: (a) administrative building, (b) eight story apartment building (reduced to 66.7%), (c) production hall, (d) family house.](image-url)
The obtained data on the distribution of shadows within the built-up area is presented in Figure 14. Black sites show the generated shadows (without the impact of sunlight), and gray sites are the areas affected by sunlight. In summer, the sun’s position is quite high above the horizon (the elevation angle is the greatest). The representation of roof surface shadows is generated here in lighter shades of gray (Figure 14a). In winter, the sun’s position is relatively low above the horizon (the elevation angle is the smallest). The representation of roof surface shadows is generated now in dark shades of gray (Figure 14b). The presence of high vegetation did not significantly affect the shading of the monitored building on the first specific day, i.e., the summer solstice (Figure 14a). The building is without the presence of areas of shade from high vegetation. On the second specific day, i.e., the winter solstice (Figure 14b), shady areas from high vegetation are visible on the roof objects. The obtained results of shadow analysis have a significant effect (especially in winter) on roof areas’ solar potential. Failure to take shadow analysis into account will result in incorrect results in the final calculation of the roof areas’ potential.

![Figure 14. Hill shading applied to a selected building for (a) summer solstice and (b) winter solstice.](image)

The ArcGIS CityEngine 2019.1 software environment was used to validate the results presented above. 3D objects (buildings and trees) were created using selected Computer-Generated Architecture (CGA) rules. The specification of spatial conditions and typology of roof areas for buildings and spatial conditions for high vegetation were defined using descriptive attributes represented in *.shp files. The data processing procedure for the shadow analysis was different compared to ArcGIS Pro. The advantage of this processing approach lies in the immediate visualization of shadow analysis results in 3D space (Figure 15b,c). Shadow analysis was performed for the specific day of the winter solstice at two time points: 9 a.m. (Figure 15b) and 12 noon (Figure 15c). The time of 3 p.m. did not show any shading of the roof area due to high vegetation. The shadow analysis results in the ArcGIS CityEngine environment confirm the results from ArcGIS Pro, i.e., high vegetation repeatedly affected the roof area shading. The shadow analysis results from ArcGIS Pro (Figure 14) show good agreement with the results of the shadow analysis from the ArcGIS CityEngine environment (Figure 15). The shadows of individual objects are variable for each nearby roof during the day, which affects the amount of incident sunlight on these areas. In our study we applied the shadow analysis results to the results presenting the suitability of the roof surfaces (Figure 9d) for the installation of PV systems. This approach allowed us to detect those roof planes that are not affected by shadows and therefore need not be excluded from the potentially suitable areas for PV installation. To identify these areas, we chose a selected calculation rule.
3.3. State Support Mechanisms for PV

When submitting an application for subsidy, it is necessary to specify the place of installation of the device, which is a building (family house or apartment block). An extract of the title deed from the REC must also be included. The application must specify the property owners and, in the case of several owners, the consent of an absolute majority of the owners. Our study’s processing of input data was primarily based on building data registered in the REC. Although the LiDAR system identified some buildings which would theoretically meet the criteria for installing PV equipment due to their location and size, we did not consider them in our study. These buildings were excluded due to problems with owner identification.

In our study we considered two alternatives of installed power for a family house of 2.6 kW and 3.3 kW with respect to the effective use of the subsidy (methodology 2.5) (Table 5). The amount of subsidy for the installation of PV systems is about 43% (2.6 kW) or 36% (3.3 kW) of the guide price for those systems. Only PV panels and a voltage converter are included in the monitored prices. The choice of technical accessories of the PV system is based on the intended purpose: use for electric water heating, power supply of electrical appliances, supply to the electricity network, or charging of an electric car. However, the overall technical accessories considerably increase the purchase price of the complete PV system. Given the amount of direct subsidy support for family houses (max. €1500), the selected location of houses was assessed according to the established classification criterion, which was the minimum usable area for the installation of the selected PV system from Table 5, Alt1 (1st line) with an area (value) of 28 m².

![Figure 15. Shadow analysis of the selected building with its surroundings: (a) Orthophotos; (b) December at 9 a.m.; (c) December at 12 noon.](image)

**Table 5.** Parameters of selected photovoltaic panels for efficient drawing of a subsidy of €1500, including the maximum installed capacity for family houses.

<table>
<thead>
<tr>
<th>Alt</th>
<th>Nominal Power [kWp]</th>
<th>Count</th>
<th>Dimension [m]</th>
<th>Panel Area [m²]</th>
<th>Minimum Continuous Roof Area [m²]</th>
<th>Suitable Roofs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.64</td>
<td>8</td>
<td></td>
<td>14</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>3.3</td>
<td>10</td>
<td>1.7 × 1.0</td>
<td>17</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>30</td>
<td></td>
<td>51</td>
<td>102</td>
<td>123</td>
</tr>
</tbody>
</table>

There are a total of 33 family houses in the area in question, of which, according to the given rule, 31 roofs meet the conditions for the installation of PV (Figure 16). This figure also graphically shows a building that only partially meets the conditions for the installation of a PV system, due to the...
presence of shielding obstacles (high vegetation—Figure 7a). From a statistical point of view, 94% of the buildings are suitable for an installed capacity of 2.64 kW.

![Figure 16. Visualization of shadow analysis of suitable and unsuitable roof surfaces for installing PV.](image)

Further increase in the power capacity of the PV system above the level of 3 kW reduces the recalculated amount of subsidy for resultant power output of 1 kW. Increasing the installed capacity increases the requirement for usable area (e.g., 42 m² is required for 4 kW). The dependence between the installed capacity and the required area is an increasing function (Figure 17a). Simultaneously with increasing output, the number of suitable roofs of buildings progressively decreases, and at a power output value above 8 kW, a significant decrease in that number is recorded. The dependence between the required area and the number of suitable roof areas represents a decreasing function (Figure 17b).

![Figure 17. Graphical evaluation on a selected area: (a) dependences of the requirements of the installed PV system on the roof area; (b) number of roofs according to their suitable areas.](image)

4. Conclusions

This study shows how the integration of data from different sources (LiDAR, REC, ZBGIS) can be used for assessing a roof’s potential and suitability for PV system installation in a GIS environment. In modeling the impact of solar radiation in our built-up area, we took into account the diversity of buildings located in the defined area. The area of the case study was selected with regard to the representation of the largest number of sunny days throughout the year, as well as the highest total of incident solar radiation per m² of area. The extent of the area and the representation of buildings
in our study were chosen with regard to the use of the potential of solar radiation incident on the roof surfaces.

We used the selected processing methodology to detect segments of roof surfaces from the LiDAR substrate. In our study, we established that the theoretical amount of incident sunlight is approximately the same during spring compared to summer, and autumn compared to winter (Table 3).

In terms of daily total, the highest sum was on the longest day, the day of the summer solstice, and the lowest total on the shortest day, the day of the winter solstice. The 3D model created above the REC base represented the proper shape of each building, including the roof area, but reduced to the size of the floor plan. The second approach created a 3D model from the LiDAR data, presenting the proper shape of the roof surface only. In comparison, in this case, the building is extended to the edge of the roof. Shadow analysis was a significant part of determining the optimal location of the PV system on each roof surface. As it is difficult to perform shadow analysis for each day and each hour of the year, specific hours were chosen on selected days. This approach made it possible to combine the results of this analysis with those of previous spatial analyses in the selected area. The result was the filtration of roof segments affected by significant shading due to the local environment and high vegetation.

This study assesses and graphically presents the dependence between the installed capacity and the usable area of the roof. In the analyzed territory, 31 roof areas of buildings meet the conditions for the installation of a PV system with an output of 2.6 or 3.3 kW. There is an Energy Plan prepared for the town of Komárno (komarno.sk/sk/energetick-koncepcia-rozvoja-mesta-komrno_4198.html). This document takes into account other perspectives on the development of the use of solar energy potential to reduce dependence on fossil fuels for power generation. It brings energy self-sufficiency and financial savings to households.

In future studies, it should be possible to extend the problem by analyzing LiDAR data in combination with detailed orthophotos for accurate identification of roof structures and subsequent creation of a 3D model at the level of LOD4 (without indoor detail). In the case of lower density of LiDAR points (pt/m²), it is not possible to capture roof details with small dimensions or larger flat objects (e.g. PV panels, roof windows). So far we have focused our research on roof areas, but building walls also provides potential space for solar-powered equipment.


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