Paradigm

# ESTIMATION OF SOLAR POTENTIAL ON FACADES AND ROOFS OF BUILDINGS

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ABSTRACT

In response to the growing demand for renewable energy sources, increasing attention is being directed toward the utilization of solar energy. The possibility of harvesting solar power through photovoltaic micro-installations on building surfaces has the potential to become a significant factor influencing the market value of real estate. This article presents a methodology for the efficient assessment of solar potential on the roofs and façades of buildings, based on publicly available data sources and validated computational algorithms. The approach involves the analysis of a Digital Surface Model (DSM) and three-dimensional building models, combined with solar radiation simulations and the identification of surfaces with optimal geometric parameters and high solar potential, to evaluate their suitability for solar energy production. Using a case study of a historic city center, the potential for meeting buildings' energy demand through photovoltaic infrastructure was assessed. Additionally, the study proposes the inclusion of solar exposure characteristics as a supplementary parameter influencing real estate valuation, while considering potential constraints from local zoning regulations.

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## 1. Introduction

The availability of free space is becoming increasingly limited, which is why energy producers are focusing their attention on urban areas, where the surfaces of existing or newly designed buildings can be used to install solar cells.

International experience provides valuable insights into the practical implementation of solar technologies in urban areas. In Germany, building-integrated photovoltaics (BIPV) have been widely tested, particularly on façades of office and residential buildings (Hagemann, 2004; Ballif et al., 2018). In France, urban energy policies increasingly require PV integration in new buildings, creating a strong regulatory driver for utilizing solar potential (DLA Piper, 2023). Southern European countries, such as Spain and Italy, benefit from higher solar irradiation, enabling more efficient electricity generation, although challenges remain regarding overheating and architectural integration (Sun et al., 2017).

Support for the development of renewable energy sources is also visible in the strategic and legal initiatives of the European Union. The REPowerEU Plan and the broader Fit for 55 package accelerate renewable energy deployment, emphasizing photovoltaics (European Commission, 2022). The EU Solar Energy Strategy, including the European Solar Rooftops Initiative, sets ambitious PV integration targets, while the Revised Energy Performance of Buildings Directive (EPBD) introduces obligations for installing solar systems on new public and residential buildings (European Commission, 2023a; 2023b). Public support mechanisms under the Climate, Energy and Environmental Aid Guidelines (CEEAG) further facilitate BIPV deployment (European Commission, 2023c).

These examples confirm the growing need for accurate and rapid assessments of solar potential in densely built environments. Evaluating the effectiveness of PV installations requires detailed analyses of solar radiation, with particular consideration of obstacles and shading caused by surrounding buildings, tall vegetation, and other structures.

Photovoltaic installations can meet partial or total demand for primary energy in buildings, while contributing to the development of passive and zero-energy construction. Photovoltaic panels are most often installed on roofs, but they can also cover the external walls of a building or constitute their architectural details (balustrades, facade glass, solar windows). Available technical solutions provide not only new possibilities for obtaining solar energy, but can also be attractive alternatives to traditional facade coatings.

In this aspect, it is therefore important to determine the extent to which roofs and facades of buildings are exposed to solar radiation. This is particularly important in dense urban development.

Existing or planned development in urban areas has a significant impact on shading values. This may cause obvious discomfort for residents resulting from limited access to direct radiation, sanctioned by lighting regulations (Albu et al., 2023), but may also significantly limit the possibility of obtaining energy from photovoltaic cells. Insolation and shading of buildings can therefore be an additional source of information for investors or users, influencing the attractiveness of the building or the entire property.

When assessing the feasibility of photovoltaic system installations, it is also essential to consider restrictions arising from local spatial development plans and applicable regulations. These may include requirements regarding roof form (slope, covering, color), prohibitions on reflective materials, or the need for heritage conservation approval in the case of historic buildings.

Additional provisions may address structural and safety factors, such as permissible building height or roof load capacity. The feasibility of installing PV systems is also determined by energy regulations, building codes, and the rules established by housing communities or cooperatives.

Among the many price-determining factors affecting real estate value, the characteristics of solar exposure and shading caused by neighboring developments (existing or planned) may, in the future, constitute an additional factor taken into account in the process of real estate valuations (Źróbek et al., 2024). The potential for generating energy through photovoltaic micro-installations on roofs and façades can likewise be an important factor influencing market value.

At present, the degree of solar exposure and the duration of direct sunlight are emerging as significant indicators of property attractiveness. The growing importance of this issue in real estate management is reflected in the increasing availability of tools and reference materials providing data on solar radiation and the performance of photovoltaic systems at specific locations (Fig. 1). In addition, geoportals are being developed to present solar potential maps (Fig. 2) for selected urban areas. However, the information published in these resources is typically calculated on the basis of surface solar radiation values for building roofs. This data is most often presented either as two-dimensional raster maps of insolation (Fig. 2b) or as three-dimensional building models, with color coding used to indicate the average surface radiation values for each roof (Fig. 2a).

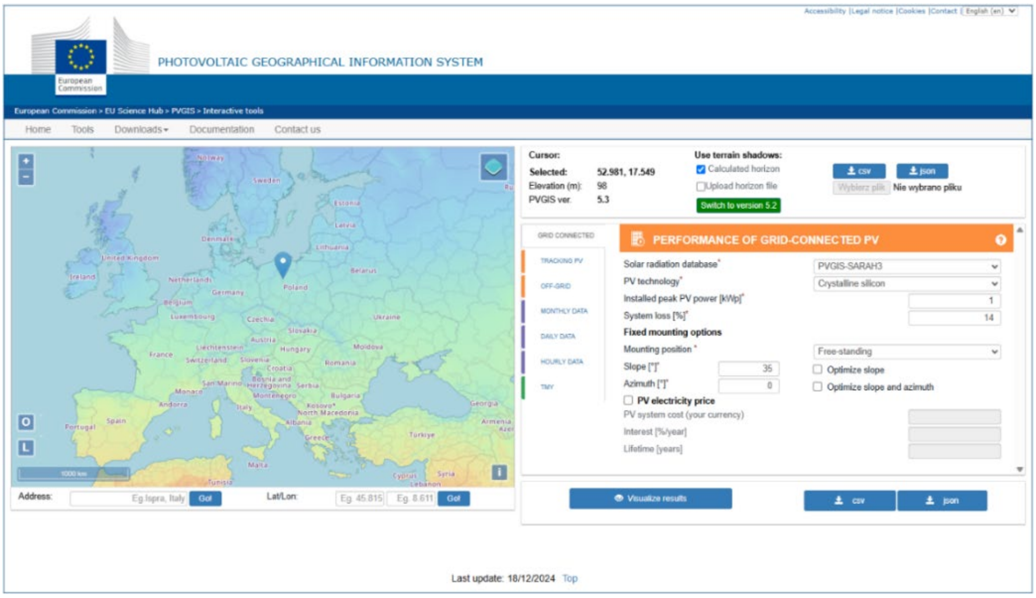


**Fig. 1.** PVGIS online tool to provide information on solar radiation and photovoltaic system performance for any location in the world.
*Source:* Joint Research Centre (2025).

(a) (b)



**Fig. 2.** Examples of geoportals with solar potential maps: (a) Spatial Information System of the City of Poznań. *Source:* Geodesy and Municipal Cadastre Board GEOPOZ (2025), (b) The Municipal Spatial Information System in Krakow. *Source:* Municipal Spatial Information System – MSIP Kraków (2025).

To obtain detailed information about a property, it is essential to perform a comprehensive and accurate assessment of the solar potential of all external building surfaces, including both roofs and façades. This information should be considered an additional attribute characterizing the buildings.

Most existing studies (Stoll et al., 2013; Forinash, 2017; Lucchi et al., 2014; De Boeck et al., 2016; Šúri et al., 2005; Caamaño-Martín et al., 2012, Perpiña Castillo et al., 2016) focus primarily on evaluating the potential for utilizing solar radiation incident on roof surfaces, often neglecting façades. Applications involving vertical building elements for photovoltaic panel installation remain limited. However, recent technological advancements have introduced a range of new possibilities for electricity generation on vertical surfaces, such as photovoltaic glazing (Gorgolis & Karamanis, 2016) and organic photovoltaic cells (Machín & Márquez, 2024) integrated into façade cladding. Consequently, with such technologies available, it becomes increasingly important to determine the levels of electromagnetic radiation accessible on the vertical external surfaces of buildings.

The scientific literature offers numerous examples of methods-varying in accuracy-for estimating the solar potential of building surfaces (Redweik et al., 2013). For flat or inclined surfaces, the methodology for calculating the amount of incoming solar radiation is well established. However, challenges arise when determining these values for vertical structures. These difficulties are primarily associated with the selection of the computational model and the representation of surrounding terrain obstacles, typically derived from a Digital Surface Model (DSM).

Several methodological approaches can be distinguished in this context: simplified approaches - treating façades as nearly vertical surfaces; discrete approaches - calculating solar radiation at selected points on vertical surfaces; and detailed approaches - estimating radiation values for precise models used in Building Information Modeling (BIM), segmented into discrete elements represented by their centroids (Lu et al., 2021).

The objective of this article is to develop a methodology for the effective estimation of solar potential on building roofs and façades using publicly available spatial data sources and validated computational algorithms.

The presented analyses focus on evaluating the applicability of existing numerical methods and open-access geospatial datasets for the rapid and scalable assessment of solar potential on both roofs and façades. The proposed approach enables efficient identification of surfaces with high energy potential without the need for detailed 3D modeling of buildings or the use of extensive computational resources. This makes the methodology particularly suitable for large-scale analyses in urbanized areas.

## 2. Area and scope of the study

The search for alternative, renewable energy sources is driven by the need to reduce reliance on fossil fuels. In Poland, as of 2023, fossil fuels still accounted for approximately 76% of electricity generation (Fig. 3). Therefore, it is crucial to propose new solutions that can improve the structure of the country's energy mix. Currently, the main directions for replacing fossil fuels in Poland are wind and solar energy.

Given its geographical location, Poland is considered to have favorable solar conditions. The vast majority of the country receives annual solar irradiation levels exceeding 1000 kWh/m$^2$ (Yearly sum, 2024). These conditions support the development of photovoltaic energy, which has seen dynamic growth over the past eight years (Fig. 4). At present, including small- and micro-scale photovoltaic power plants, solar energy accounts for over 59% of the installed capacity of renewable energy sources in Poland (Fig. 5). This share is expected to continue increasing in the coming years.

Harnessing solar radiation for energy generation requires access to sufficiently sunlit, undeveloped surfaces that do not interfere with existing building structures. This is particularly important in the case of micro-installations located on or near buildings.

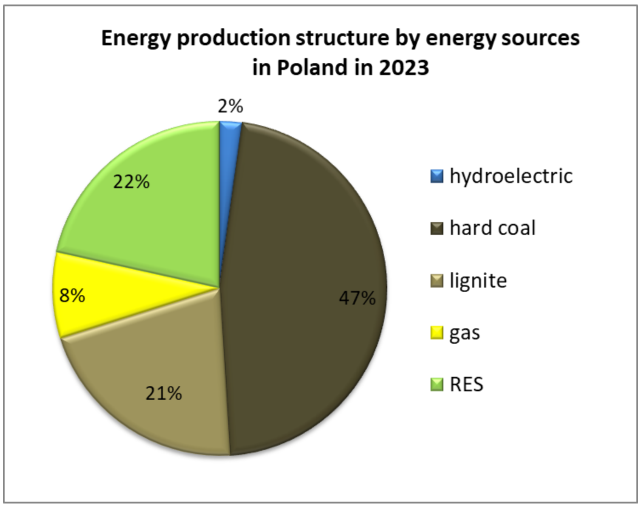


**Fig. 3.** Structure of electricity production in Poland in 2023 by fuel type. *Source:* own elaboration based on Energy Regulatory Office in Poland (2024).

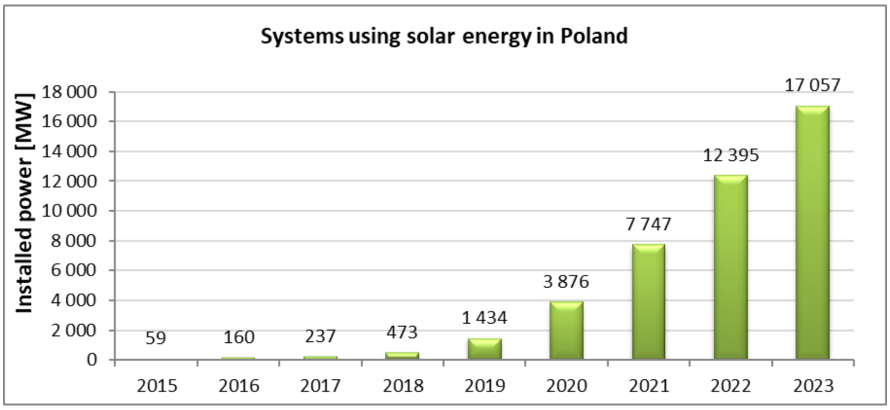


**Fig.4**. Power of systems using solar energy in Poland in 2015-2023. *Source:* own elaboration based on the Photovoltaic market in Poland (2024).

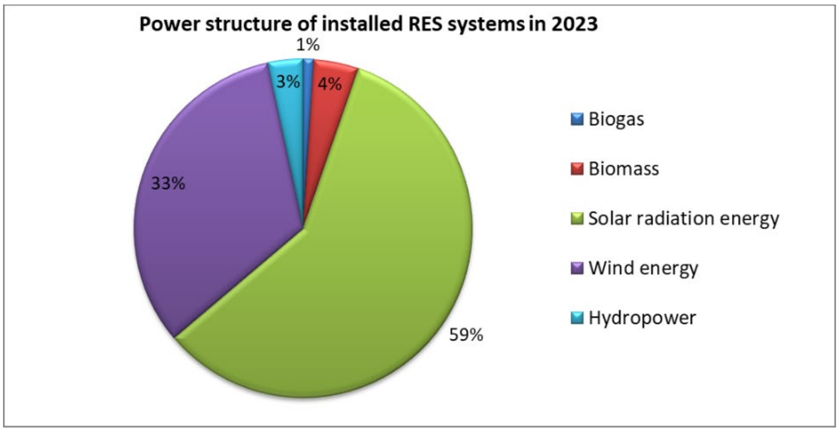


**Fig. 5.** The structure of installed capacity of renewable energy sources (RES) in Poland in 2023 (the list includes small and micro photovoltaic installations). *Source:* own elaboration based on Energy Regulatory Office in Poland (2024).


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In urban areas, due to limited availability of open, undeveloped land, rooftops and building façades are most commonly used for the installation of photovoltaic panels (Redweik et al., 2013). However, cities exhibit significant variability in building density and structural design, with rooftops differing greatly in shape and construction. Additionally, depending on the period of construction and the building's location within the city, the urban environment presents diverse characteristics that influence shading and the scattering of solar radiation.

Analyses conducted by the author (Bujarkiewicz et al., 2018; 2018a) revealed substantial differences in solar energy potential across different parts of the city, depending on building type and density. Areas with high building density (e.g., city centers) tend to have large total rooftop surface areas, where total solar radiation can be 2 to 3 times higher than in other parts of the city. However, their average solar potential is approximately 20% lower compared to areas with lower building density. The shape of rooftops and the presence of obstacles play a critical role in solar energy acquisition.

Furthermore, in historic city center districts, roof shapes limit the feasibility of photovoltaic panel installation to only about 25% of buildings. As a result, a study was conducted to determine the extent to which solar energy can be harvested from photovoltaic panels installed on building façades. The selected study area was a section of downtown Bydgoszcz, characterized by dense development with a significant presence of tenement houses built predominantly in the second half of the 19th and early 20th centuries.

## 3. Methods and data sources

The analysis focused on a central area of Bydgoszcz characterized by a consistent building type and age, with a high Floor Area Ratio (FAR). The data necessary for the calculations were obtained from the public Polish National Spatial Information Infrastructure Node (Polish, 2025), maintained by the Head Office of Geodesy and Cartography (GUGiK).

As source materials for the analysis, a LiDAR dataset covering an area of approximately 30 hectares was used (Fig. 6). The average point cloud density for the selected area was 12 points/m², with an average vertical accuracy of 0.1 meters. Additionally, building models developed in the CityGML 2.0 standard at Level of Detail 2 (LoD2) were employed (Fig. 7).

Calculations of solar potential were carried out using standard GIS tools, based on a methodology described in numerous publications (Bergamasco & Asinari, 2011; Agugiaro et al., 2012; Caamaño-Martín et al., 2012; Redweik et al., 2013; Mrówczyńska & Wawer, 2015). The calculations procedure and the spatial analysis tools applied are presented in Fig. 8.

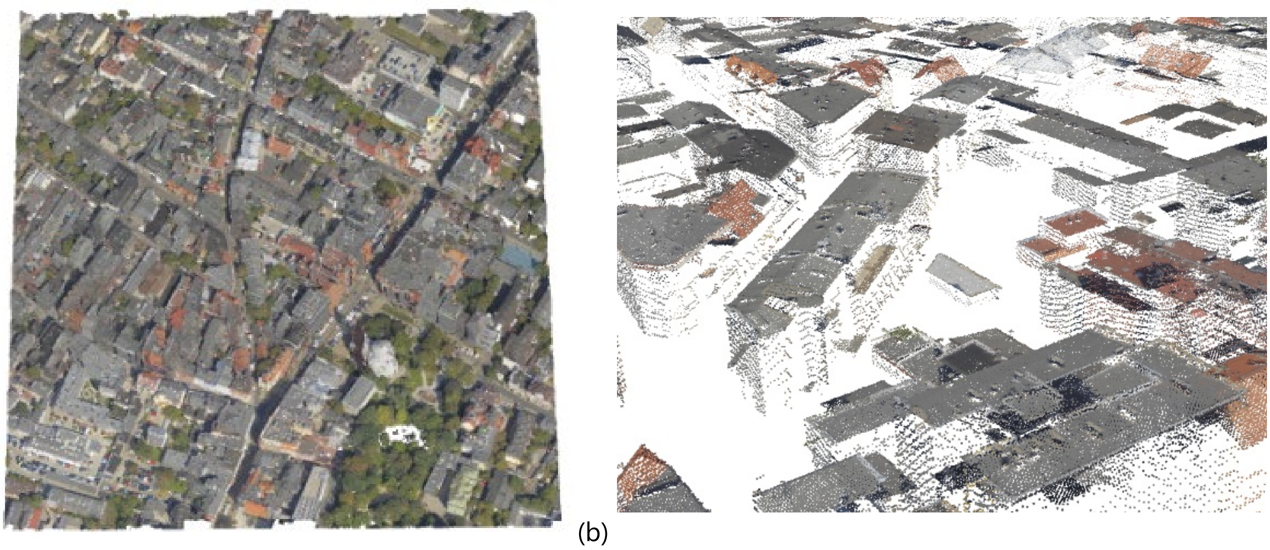
(a) (b)

**Fig. 6.** LiDAR data presented as RGB-colored point clouds for a section of downtown Bydgoszcz: (a) area analyzed, (b) zoomed-in data sample.
*Source:* own elaboration.

Based on the LiDAR measurement data, a Digital Surface Model (DSM) was generated to represent the current land use, stored in GRID format. To estimate the solar radiation values for the study area, tools employing methods based on the hemispherical view-shed algorithm developed by Rich et al. (1994), and later refined by Fu and Rich (2000), were used.

The calculation of solar exposure accounted for the geographic latitude of the study area. Additionally, diffuse radiation from all sky directions was considered, using an average atmospheric diffusion coefficient of 0.3 and a transmission coefficient of 0.5. The computations were performed for the entire year at monthly intervals.

**Fig. 7.** Building models in CityGML 2.0 standard (LoD2) used in the analysis. *Source:* own elaboration.

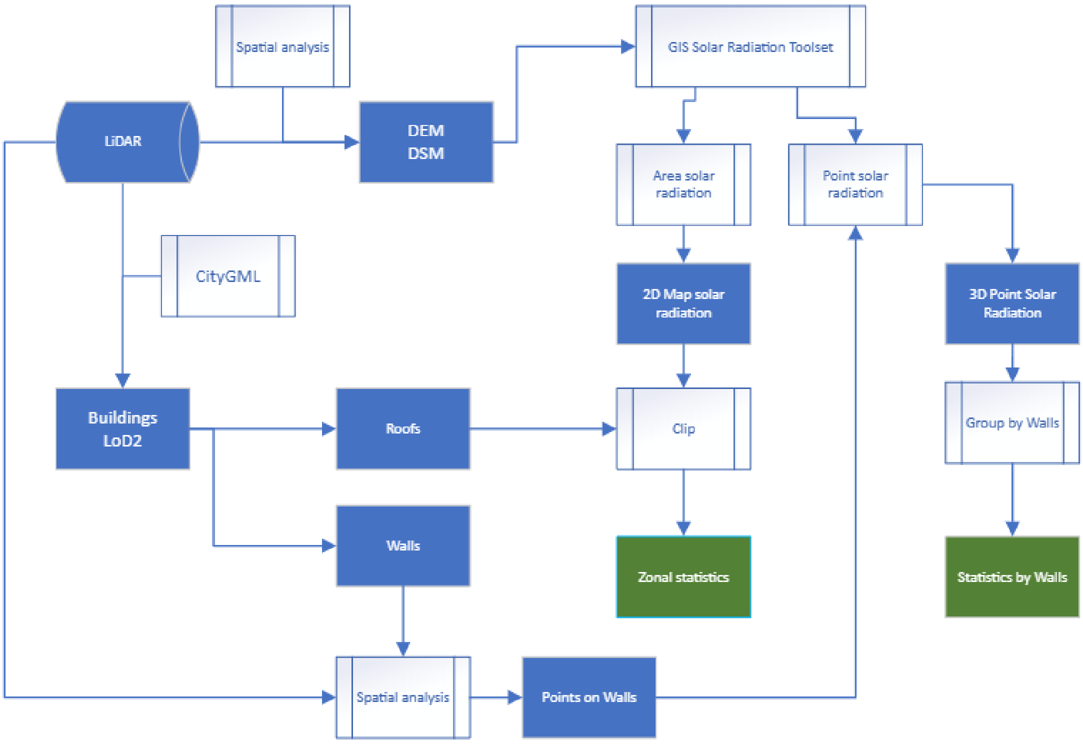


**Fig. 8.** Workflow diagram of the solar potential calculation process for building roofs and façades. *Source:* own elaboration.


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To determine solar potential and global radiation, the sum of direct and diffuse radiation was considered. This resulted in a raster representing global radiation in Wh/m² across the entire study area. To isolate the portion of radiation incident on roof surfaces, roof models extracted from CityGML data were used. Zonal statistics were also calculated to assign average radiation values to each delineated roof surface segment. A graphical representation of the analysis results is presented in Fig. 9.

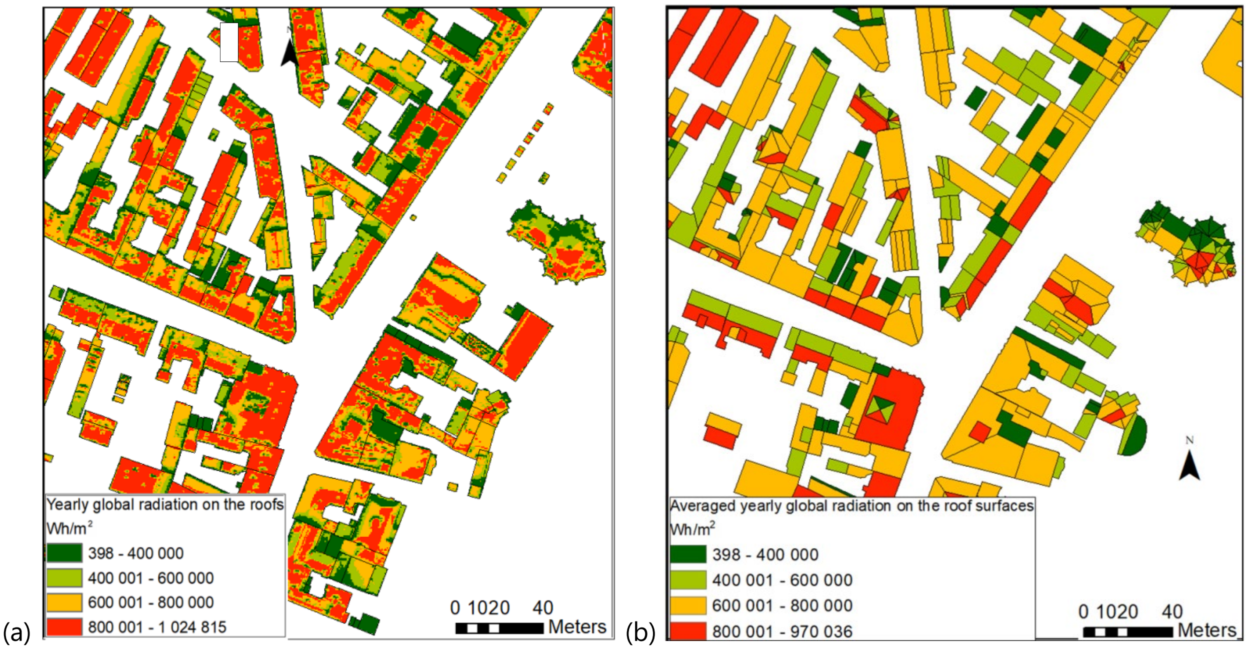


**Fig. 9.** Yearly global solar radiation on building roofs (a) and average annual global radiation values on roof surfaces (b) in Wh/m². *Source:* own elaboration.

To increase the efficiency of solar energy harvesting in urban environments, photovoltaic panels are often installed on building façades. In calculating solar potential, similarly to rooftops, it is necessary to identify façade areas that receive adequate solar radiation.

The calculation algorithm uses the same parameters as for roofs. However, an accurate 3D model of the objects is required to account for all obstacles on façades and window openings. Following the approach of Lu Xiu et al. (2021), BIM modeling and IFC model descriptions can be used to precisely define each surface of the studied object and then calculate the radiation value at its centroid. This approach demands processing large datasets and significant effort to generate models, which is especially challenging for older, existing buildings.

In the studies conducted by the author, a simplified method based on available data sources was employed. These methods are less precise than BIM models, but they still provide fast calculations for large research areas. LiDAR data were used to calculate the solar potential on building façades. For the designated area, the point cloud was spatially filtered using CityGML building models to retain only points located on building façades. After converting these to object form, solar radiation values were calculated for each point using radiation computation models (Rich et. al., 1994; Fu & Rich, 2000). Averaging radiation values across these façade points, excluding window openings and other architectural obstacles, allowed the creation of solar radiation maps on façades.

Finally, the total annual radiation values incident on both roof and façade surfaces were calculated for the study area. The results of these calculations are presented in Table 1, while a graphical representation on 3D building models is shown in Figure 10.

**Table 1**

Calculation results for the analyzed area

| Feature | Value |
|---|---|
| Building Coverage Ratio (BCR) | 38% |
| Average Floor Area Ratio (FAR) | 0.99 |
| Total roof area [m²] | 116 127 |

| | |
|---|---|
| Average roof area per building [m²] | 126 |
| Average annual radiation on roofs [kWh/m²] | 563 |
| Average annual radiation on façades [kWh/m²] | 320 |

*Source*: own study.

## 4. Results and discussion

In detailed calculations, it is important to consider that the roofs of historic tenement houses often contain various architectural elements (such as dormers, bay windows, or chimneys) that limit the available surface area for solar installations. Therefore, subsequent calculations were conducted taking into account only those roof sections where the average annual solar potential exceeds 800 kWh/m² and whose area is sufficient to accommodate photovoltaic modules of standard dimensions. The surfaces selected in this way were then compared to the total roof area.

As a result, a Roof Utilization Ratio (RUR) was obtained, expressed as a number between 0 and 1. Table 2 presents the calculation results for the analyzed city center area.

(a) (b)

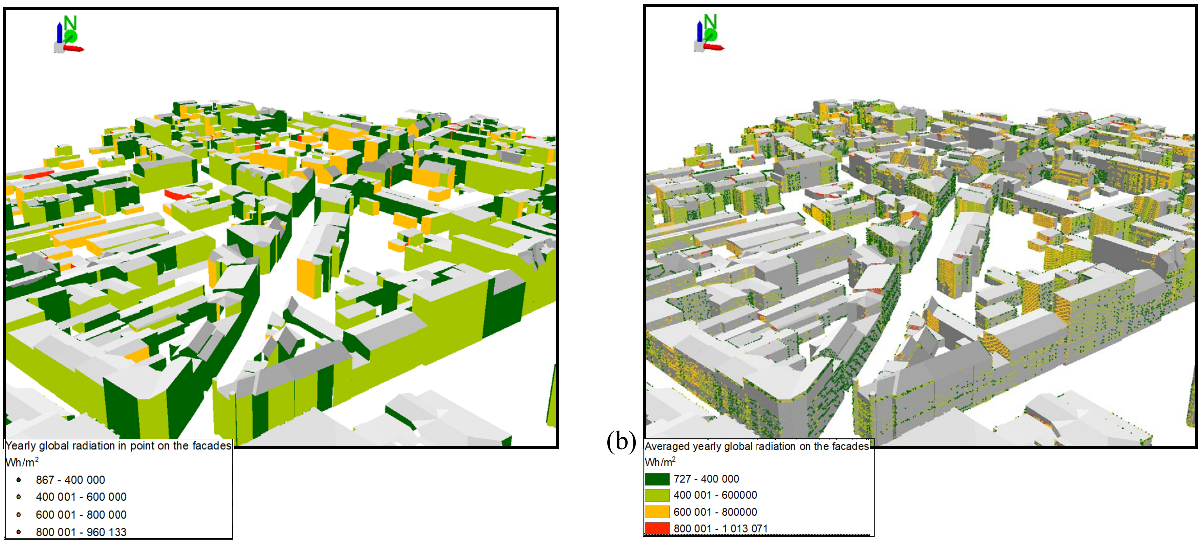


**Fig. 10.** Global solar radiation on building façades in Wh/m²: (a) at calculation points, (b) averaged for individual façades. *Source:* own elaboration.

**Table 2**

Solar potential for roof segments with potential above 800 kWh/m² and suitable size and shape

| Feature | Value |
|---|---|
| Percentage of roofs with areas suitable for PV installations | 47% |
| Average area of usable roof segments [m²] | 95.64 |
| Roof Utilization Ratio (RUR) for all roof segments with potential ≥ 800 kWh/m² | 0.42 |
| Percentage of roofs with RUR above 0.5 among all roofs in the study area | 17% |
| Total radiation on roof segments with potential ≥ 800 kWh/m² and suitable size and shape [GWh] | 36.2 |

*Source*: own study.

The data presented in Table 2 indicate that approximately half of the buildings have roofs with areas suitable for the installation of photovoltaic modules, with the average area of these segments being 95.64 m².

For roofs meeting the above criteria for photovoltaic module installation, the average coverage ratio for panels with a potential above 800 kWh/m² is 0.42, resulting in a total radiation sum of up to 36 GWh annually for all analyzed areas. The results in Table 2 also show that among all buildings in the studied areas, only 17% have roofs where more than 50% of the surface is suitable for photovoltaic module installation.

The presented approach enables rapid estimation of solar potential on building roofs and façades using available LiDAR data and 3D building models. After completing the calculations, each building element modeled in the CityGML standard can be enriched with additional information in the form of average annual solar radiation values. An example of the visualization of solar potential calculation results on 3D building models at LoD2 level is shown in Fig. 11.

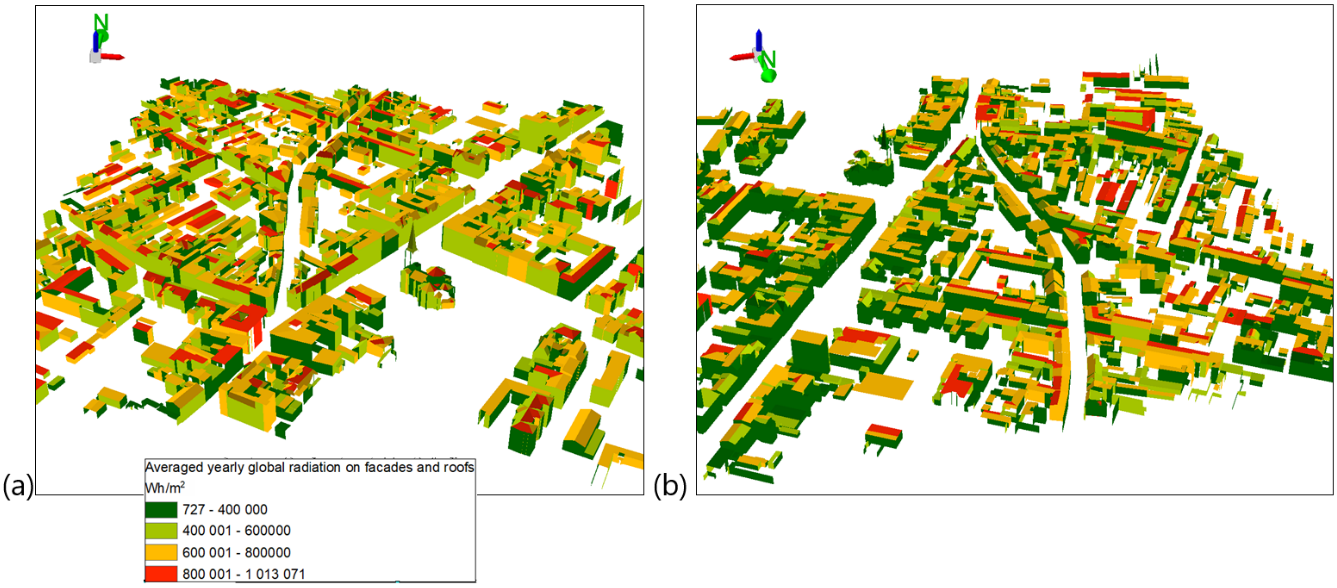


**Fig. 11.** Global radiation on roofs and façades of buildings in Wh/m$^2$: (a) view from the south, (b) view from the north. *Source:* own elaboration.

Detailed data on the solar potential of building roofs and façades can represent a significant additional factor influencing the market value of a property. The findings of this study also open new opportunities for the use of building solar potential maps in property valuation processes. Solar exposure could be treated as an additional attribute in hedonic pricing models or comparative analyses, similar to established factors such as location or building condition. For instance, higher rooftop or façade solar potential may translate into lower energy costs for occupants, thereby increasing the market attractiveness of a property. Although this parameter is not yet widely applied in real estate valuation, its inclusion could provide a more comprehensive reflection of sustainable building characteristics and contribute to more accurate market assessments.

Nevertheless, the deployment of photovoltaic systems remains subject to various legal and technical constraints. These include provisions of local spatial development plans regulating spatial order, architectural aesthetics, and the preservation of heritage-protected areas and structures. Further barriers arise from structural limitations, fire safety requirements, and energy sector regulations that define the permissible capacity range for photovoltaic micro-installations connected to the power grid.

## 5. Conclusions

The conducted calculations revealed that the average annual solar radiation on building façades in the analyzed area is approximately 320 kWh/m$^2$, which is about 45% lower than that received by rooftops. Nevertheless, façades can serve as a complementary source of solar energy, especially in cases where roof surface availability is limited.

However, the analysis also identified significant spatial constraints for installing solar panels on building façades. The main limitations include:

- limited surface area free from windows and architectural details,
- restrictions related to the conservation of historic buildings in city centers,
- lower energy yield compared to rooftop installations.

The proposed methodology, based on publicly available spatial data and validated computational algorithms, enables fast and reliable estimation of the solar potential of both roofs and façades. Its implementation does not require significant computational resources or detailed geometric modeling, which makes it a useful tool for analyses covering large urban areas.

The developed approach can serve as a practical instrument to support renewable energy investment


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planning at the municipal level. It also provides a foundation for further research on the relationship between solar potential and property value, as well as strategies for sustainable urban energy development. Importantly, information on the potential for energy generation from photovoltaic micro-installations on roofs and façades may be incorporated into property valuation practice. Solar exposure could be treated as an additional attribute in hedonic pricing models or comparative analyses, similar to established factors such as location or building condition. Although not yet widely applied, its inclusion may offer a more comprehensive reflection of sustainable building characteristics and contribute to more accurate market assessments.

Beyond real estate valuation, the developed methodology can also support urban planning and energy policy. Solar potential maps can help municipalities design local energy strategies, identify priority zones for renewable energy investments, and introduce planning regulations that encourage PV deployment. For investors and property managers, such information can guide modernization and redevelopment decisions, ensuring better alignment with the objectives of sustainable urban development.

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