GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 16 • Number 4 • 2022

https://doi.org/10.7494/geom.2022.16.4.31

Lidiia Davybida[1], Ireneusz Wyczałek[2], Artur Plichta[3]

Using GIS and SDSS Tools in the Design of a Photovoltaic System for a Built-up Roof

Abstract: The design and installation of solar panels on the roofs of urban buildings often require consideration of the specific spatial conditions that affect their efficiency. The primary purpose of this work is to develop a procedure for designing and optimizing photovoltaic installations using geomatics methods and specific tools of GIS and CAD systems. The roof of the historic building A2, which is a part of the Poznań University of Technology campus, was selected as the tested object. Solar radiation modelling and determination of suitability zones were performed using SEBE (Solar Energy on Building Envelopes) in QGIS. Possible options for the placement of photovoltaic modules on the roof were simulated with CAD technique in the web-based HelioScope software. The results of the simulation show that the current roof area can generate electrical power of 99.9 MWh/year. The proposed methodology is universal for photovoltaic installations on built-up roofs and can be applied to other buildings and, consequently, the results obtained can be used to improve the content of the solar data urban geoportal.

Keywords: solar irradiance, historic building, shadow effect, obstructions, geospatial assessment, roof-top photovoltaic system

Received: 13 February 2022; accepted: 5 July 2022

[1] Ivano-Frankivsk National Technical University of Oil and Gas, Department of Geotechnical Safety and Geoinformatics, Ukraine, email: lidiia.davybida@nung.edu.ua, https://orcid.org/0000-0002-9796-7124

[2] Poznan University of Technology, Institute of Civil Engineering, Poland, email: ireneusz.wyczalek@put.poznan.pl, http://orcid.org/0000-0003-3963-8186

[3] Poznan University of Technology, Institute of Civil Engineering, Poland, email: artur.plichta@put.poznan.pl, https://orcid.org/0000-0001-6134-290X

1. Introduction

1.1. Solar Photovoltaic (PV) Technology

By the start of the 21st century, 160 years after A.E. Becquerel first demonstrated the phenomenon of photoelectricity and 60 years after the first commercial solar cells were produced [1, 2], photovoltaics (PV) had found its rightful place as a source of electricity, ranging from small electronic equipment and night lighting [3] to powering satellites, space stations and spacecraft. Along with their technological development, photovoltaic cells have become an increasingly important alternative source of power for homes and household installations [4], even generating electricity surpluses which have now been taken over by institutions that manage energy distribution. In the era of climate protection, solar energy has become an important component of the energy mix for individual countries. Currently, there are three groups of distributed electricity producers using PV technology: individual producers for their own needs (island-type power systems), individual prosumers (producers discharging surplus energy to the open electrical grid) and photovoltaic farms (power plants – PVP) [4].

a) b) c)

Fig. 1. Photovoltaic panels in an anthropogenic landscape: a) on public utility building; b) on the roof of residential house; c) on a frame on the ground

Source: author ownership (photos from 26.11.2021)

The conversion of solar radiation into electricity takes place in solar cells as a result of the photovoltaic effect, i.e. the flow of electrons between the elements of the cell type "n" and "p" due to the excitation of valence electrons with quanta of solar radiation [5]. The current method of PV installation (Fig. 1) is mainly based on monocrystalline (or, less frequently, polycrystalline) quartz cells combined into modules with dimensions of approx. 1.0 × 1.6–1.7 m, which are assembled into panels [2, 6]. Most often, one module consists of several dozen (e.g. 60, 72, ...) cells collectively (thanks to the series connection) collecting solar energy and transmitting the received electricity through an inverter to the electrical installation or the batteries. Modules can be divided into 2–3 sectors operating independently [6], however one-piece solutions predominate. Batteries of PV panels are installed in new public buildings (Fig. 1a), on residential houses (Fig. 1b) or in their close vicinity (Fig. 1c).

The efficiency of typical PV installations based on silicon solar cells ranges from about 14% to over 22% (at 25°C) [3, 7] and depends on static factors affecting the panels (latitude, shape and orientation roof, topography and its coverage) and dynamic (duration and intensity of sunlight, air temperature, humidity, cloud cover, etc.) [8–12].

1.2. Factors Taken into Account for the Location of the Panels

The authors of various publications focused [8–10, 13–19] on the design of photovoltaic installations take into consideration different analyses and configurations of the components of these analyses.

Romero Rodríguez et al. [10] listed most of them in the form of a flowchart, divided into two groups of factors:

1) solar suitability:
   – orientation,
   – roof slope,
   – separation of photovoltaic panels;
2) architectural suitability:
   – construction restrictions,
   – protected buildings,
   – shadows effects,
   – service area.

The calculation of the amount of solar energy reaching the roof is the basis of the design of a photovoltaic installation. This value depends on the angle of incidence of sunlight (geographic coefficient) and the temporal weather conditions (atmospheric coefficient). Other factors that were omitted here, such as those resulting from local law, environment protection plan or the possibility of mounting panels on the ground, should also be taken into account in the process of designing photovoltaic installations [20].

1.3. Using IT Resources in the Design of Photovoltaic Installations

The tools enabling spatial analysis of the relevant factors are SDSS (Spatial Decision Support Systems) procedures implemented in GIS or CAD systems. They are mainly used in strategic or conceptual analyses when determining the locations of the optimal PV installation on groups of buildings, housing estates or other territorial units to determine the energy potential of these areas or groups of facilities [8, 9, 13, 14, 19–24]. Meanwhile, to locate panels on specific roofs, specialized CAD software is usually used to perform analyzes on vector models of a given roof [7, 25–27]. In recent years, specialized programs have emerged and are still being developed (GIS or CAD-type) to assess the insolation of areas and objects, as well as to design solar panels of various scales. Specialized applications are implemented in commercial environments (Area Solar Radiation in ArcGIS, PVCAD in AutoCAD) and freely distributed (UMEP (Urban Multiscale Environmental Predictor) in QGIS, Module Potential Incoming Solar Radiation in SAGA) but also separate programs (PVGIS, PVSyst, Aurora, Homer, HelioScope etc.).

Nowadays particular attention should be paid to the development of web technologies and cloud geodatabases which enable the use of interactive tools implemented in specialized geoportals to assess the insolation of the area, determine the optimal panel characteristics (angle, azimuth), model and forecast energy production and assess the payback period of installations.

An analysis of publications focused on the design and optimization of PV systems allows the identification of two main approaches that are determined by the scale of research – ground-mounted installations or solar farms within a country or region are considered on the macro-scale level, whereas solar panel installations on building roofs within a city, district or individual object are considered on the micro-scale level. Appropriate PV installation site macro-scale analysis is usually carried out by multicriterial GIS analysis associated with a variety of relevant factors (climate, land surface slope, aspects, distances from building areas, roads etc.) [8, 9, 11, 19–22]. The micro-scale analyses are primarily based on the spatial variation of incoming solar radiation on a building rooftop surface. This type of analysis needs full 2.5–3D geometrical representations of buildings (LOD 2 and LOD 3 building models) and CAD tools for optimal location determination [10, 16, 26–31].

The final step of the majority of such projects is to show results on the WebGIS platforms or specialized geoportals, where everyone can access the information about solar energy potential and supplement data with interactive maps and models [20, 29, 31]. As examples, we can cite solar data portals and cadasters of different cities [32–39], including the Portal of the Spatial Information System of Poznań, where PV potential and suitability of roofs are visualized [33].

A specific issue for many urban areas is the integration of PV installations on historic buildings. As to [40, 41], it is noted, that the design and installation of a PV system need to be carefully considered so that its efficiency can be maximized whilst avoiding damage to the significance of the building, its fabric and its setting. Supplementing the solar cadastre information block with data on restrictions for the PV installations for historic buildings is appropriate for urban spatial planning and energy management.

1.4. Problem Definition

A real problem related to the installation of photovoltaic panels on historic buildings is planning their placement to ensure an appropriate (maximum) level of power, simultaneously limiting the visibility of the panels for an observer located in public spaces. Objects that require this kind of approach include public utility buildings that were built in the 1960s and 1970s – nowadays old enough to be classified as protected buildings due to their historic character. It is generally accepted that photovoltaics should not be installed on such kind of facilities. However, many of them are covered with flat roofs, so they are suitable for mounting various installations invisible from the level of the road and sidewalk. Usually, different installations are already mounted on the roofs (i.e. chimneys, fans, external air conditioning units...), which means that the effective placement of a sufficiently large number of photovoltaic panels requires additional spatial analysis.

The purpose of the research is to develop a procedure for designing and optimizing photovoltaic installations using geomatics methods and specific tools of GIS and CAD systems that allow the character of insolation for different parts of a roof to be taken into account, as well as certain spatial constraints on the specific roof of the historic building A2, which is a part of the Poznań University of Technology (PUT) campus.

2. Methods and Materials

2.1. Tested Object

Within the practical experiment, a project was made of the positions of PV panels on the roof of the abovementioned A2 building of PUT, erected in 1953–1955 and now part of the Warta campus (Fig. 2). Poznań is located in the flat, central part of western Poland, which is characterized by a relatively low level of solar potential (1060–1090 kWh/m^2/year, according to information obtained from the Solargis Global Solar Atlas 2.0 platform [42]) (Fig. 2a). This, in turn, affects the level of insolation of the roofs of individual buildings.

According to the SIP Poznań municipal geoportal [33], the insolation of the buildings' roofs in Poznań varies from 3 kWh/m^2/year to 1050 kWh/m^2/year (Fig. 2b). These data also show that the tested object is one of the most promising for the installation of solar panels (Fig. 2c) because the insolation of the considered roof ranges from 800 kWh/m^2/year to 1000 kWh/m^2/year (except for the shaded parts) with the limitation of the sunlight amount by cloudiness, fog and air pollution with dust and aerosols.

The south wall of the study building is oriented at an angle (azimuth) of 211.6°, which should be taken into account in the analysis of the impact of lighting on the efficiency of PV installations.

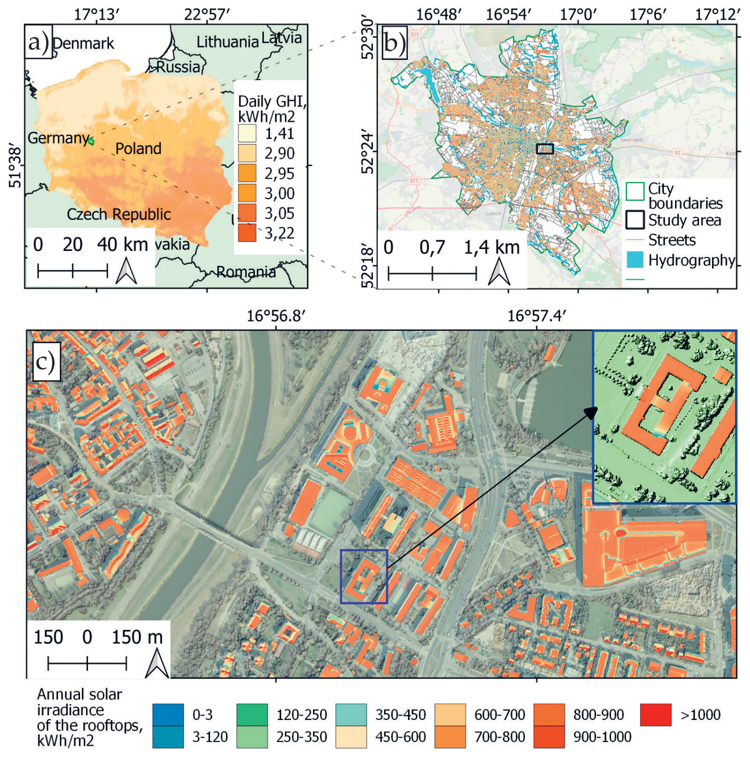

Fig. 2. Location of the research object and general conditions of solar radiation: a) zoning of the territory of Poland according to the GHI insolation index; b) location of the tested object in the city of Poznań and classification of roofs of city houses according to the level of solar potential; c) the subject of research, i.e. building of the Faculty of Civil Engineering and Transport (FCE building) against the background of the orthophotomap of Poznań, taking into account the insolation of the roofs

Source: own study based on available data [33, 42, 43]

2.2. Proposed Methodological Framework

Since designing and optimizing photovoltaic installations is a complex problem and different criteria apply, a combination of GIS and SDSS methods was used to perform the analysis. The steps are discussed below according to the proposed framework as shown in Figure 3. The methodology is as follows:

1. Data collection and pre-processing, which include the spatial and temporal data collection and data standardization processes.
2. Image processing and spatial analysis, which include geoinformation analysis involving several methods and tools, e.g., solar irradiance analysis, distance analysis, raster zonal statistics, geometric and overlay operations, visualization.
3. Installation design, which is conducted to create different options for the photovoltaic installations and their performance analysis.

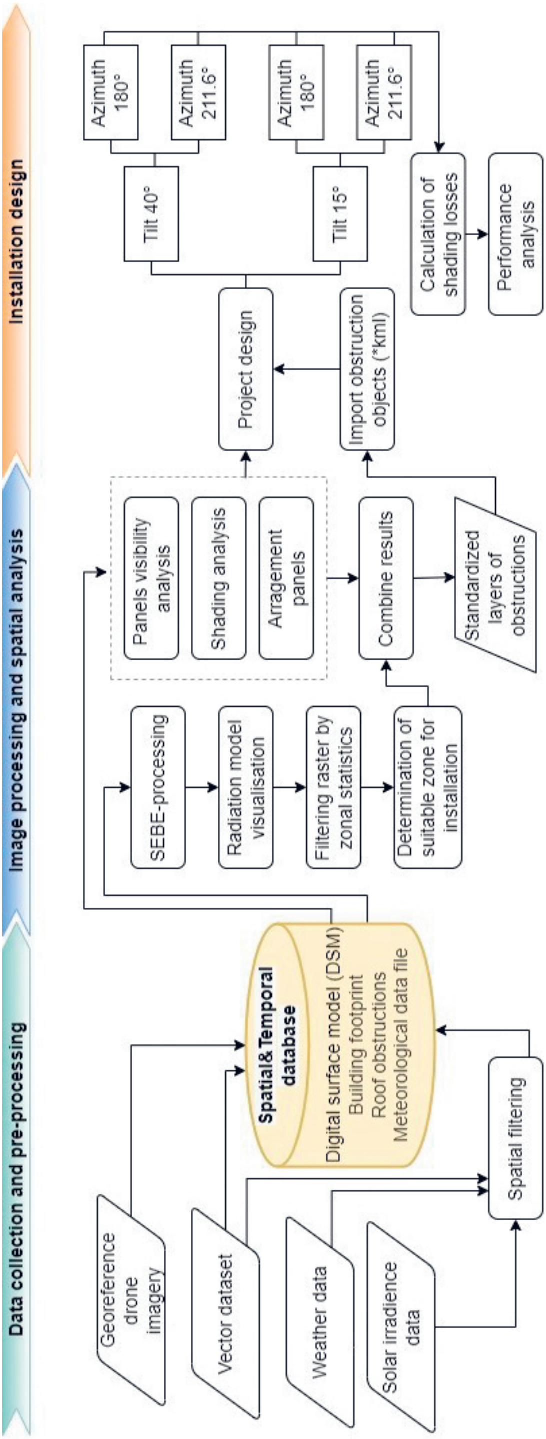

Fig. 3. Flowchart of the research methodology

Data collection and pre-processing

Spatial and temporal data, the main characteristics of which are shown in Table 1, were used to perform the steps of the framework and create a graphical visualization of the research results.

Detailed (with 15 cm resolution) orthographic imagery, obtained from a drone, and generated digital surface model (DSM) were used as the base dataset consisting of ground and building heights and deciding the latitude and longitude used for the calculation of the position of the Sun. Raster and vector datasets of topographic and administration data were downloaded and transformed to the single projection into QGIS.

The variability of the dominative dynamic factors for the studied area of the city of Poznań, obtained for the period 2013–2021 with the use of Copernicus ERA5 ECMWF global monitoring data, USGS Landsat 8, is shown in Figure 4 prepared with Google Earth Engine API tools [44] (Fig. 5).

The analysis results, compiled in the form of autocorrelation function graphs, confirmed that the amount of solar radiation and air temperature are characterized by distinct seasonality while cloud cover and precipitation are broadly less regular (Fig. 6).

Meteorological data at hourly temporal resolution were transformed into the special format used in SEBE (Solar Energy on Building Envelopes), incorporated in UMEP (Urban Multi-scale Environmental Predictor), a plugin for QGIS [45].

Image processing and spatial analysis

Solar radiation model SEBE allows estimates of solar irradiance on building roofs and walls using an algorithm with a DSMs (and derivative rasters, such as wall height and wall aspect) and the solar position to generate pixel-level information of shadow or sunlit areas [45, 46]. The result added to map canvas is the horizontal radiation, i.e. irradiance (kWh/m^2) on the roof and ground around the tested object. The suitability of the tested object's rooftop has been already confirmed, and theoretical solar power potential has been calculated [33]. Therefore, the main task for this step is to identify suitable and unsuitable zones for PV installations within the rooftop using raster zonal statistic tools and taking into account the fact that rooftop surfaces should receive at least 800 kWh/m^2 in solar radiation if solar panels are to be installed. Areas with low solar radiation have to be removed. Modelling the building rooftop with obstructions is also performed using QGIS.

A special unit of calculations, which allows taking into account the individual geometric features of the tested object, provides an assessment of the location and mutual shading of the panels, determining the visibility of panels from pedestrian areas. The obtained results are used both in the GIS environment to create additional vector layers of the unsuitable zones for solar panel installation, and in the CAD environment to set the parameters of the installation. As a result, the layers, where it is not possible or not appropriate to place the panels for various reasons, are combined into the final layers of obstructions, which will automate the design based on the CAD technique.

Table 1. Spatial and temporal datasets

Dataset	Temporal aggregation	Spatial resolution/Scale	Source	Format
Global Horizontal Irradiation in Poland [kWh/m^2]	annual average	~250.0 m	The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: SolarGIS, 2019 https://globalsolaratlas.info/download/poland [42]	raster
Solar potential [kWh/m^2]	annual cumulative	1.0 m	Portal of the Spatial Information System of Poznan, 2020 http://wms2.geopoz.poznan.pl/geoserver/solarne/wms [33]	raster
Sun exposure of roofs [kWh/m^2]	annual cumulative	0.5 m	Portal of the Spatial Information System of Poznan, 2020 http://wms2.geopoz.poznan.pl/geoserver/solarne/wms [33]	raster
Digital Surface Model [m]	–	0.5 m 0.15 m	Geoportal Poland, 2021 https://mapy.geoportal.gov.pl/imap/ [43] Author ownership	raster
Buildings	–	1:1000	Geoportal Poland, 2021 https://integracja.gugik.gov.pl/cgi-bin/ KrajowaIntegracjaEwidencjiGruntow [43]	vector (multipolygon), .shp
Meteorological data: – solar radiation [kWh/m^2] – air temperature [^{o}C] – precipitation [mm] – cloudiness [%]	monthly cumulative monthly average monthly cumulative monthly average	30 m	Copernicus ERA5 ECMWF, 2021 https://developers.google.com/earth-engine/datasets/catalog/ ECMWF_ERA5_MONTHLY USGS Landsat 8 Collection, 2021 https://developers.google.com/earth-engine/datasets/catalog/ LANDSAT_LO08_C01_T1_RT Post-processed by Google Earth Engine [44]	.csv

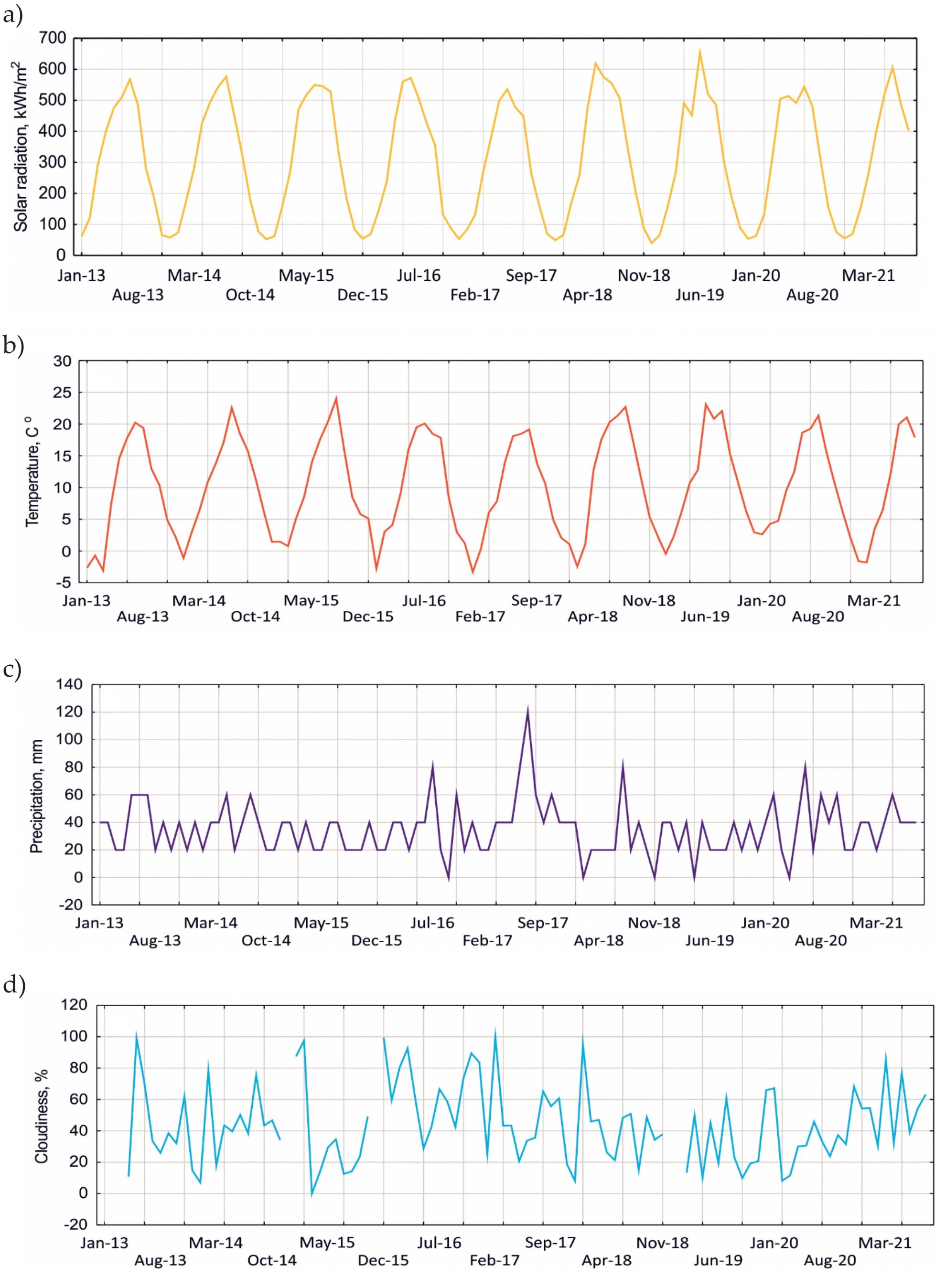

Fig. 4. Graphs of dynamic factors influencing the power of solar electricity in Poznań: a) amount of solar radiation; b) air temperature; c) precipitation; d) cloud cover

Source: own study based on available data [44]

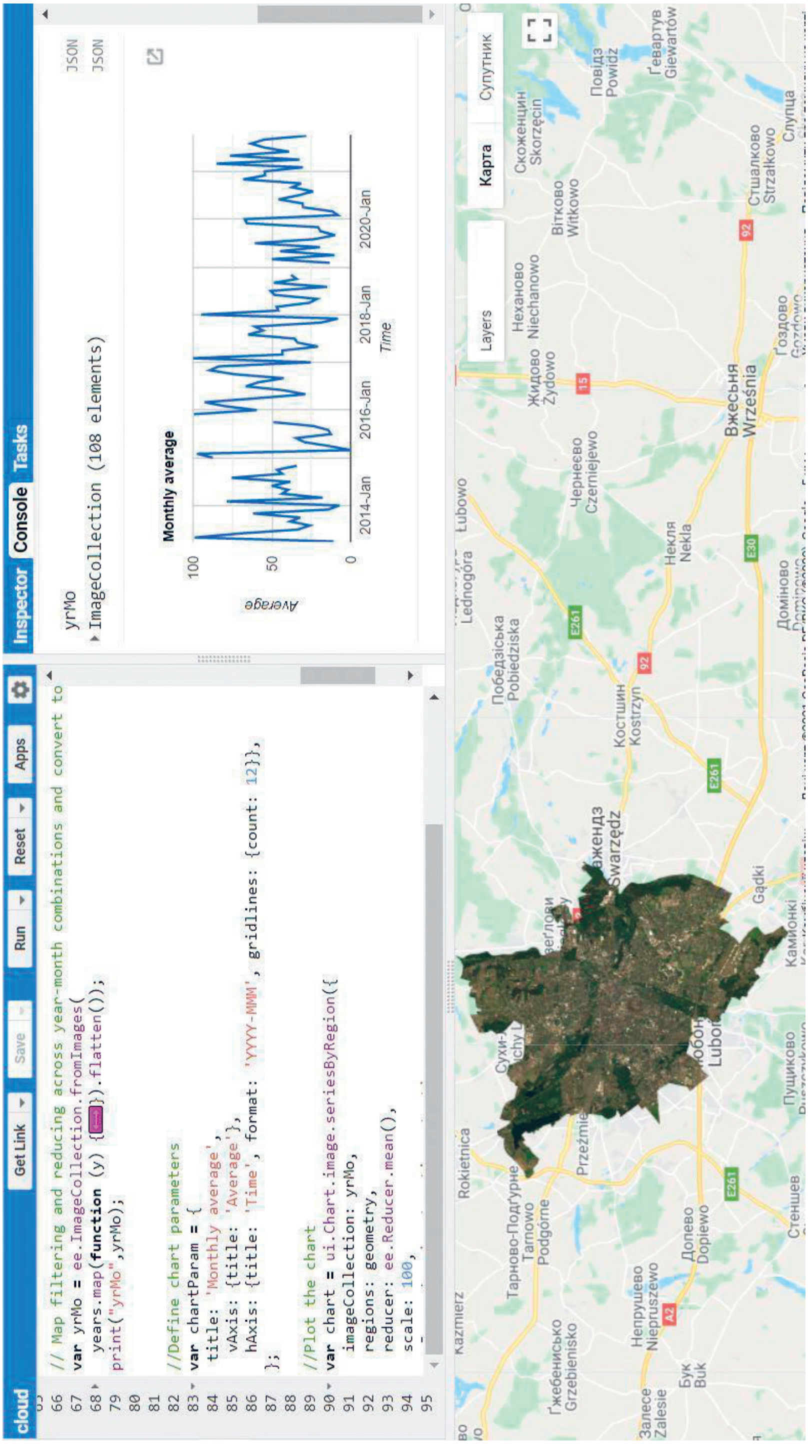

Fig. 5. Downloading data from global climate monitoring systems using the Google Earth Engine API

Source: own study based on available data [44]

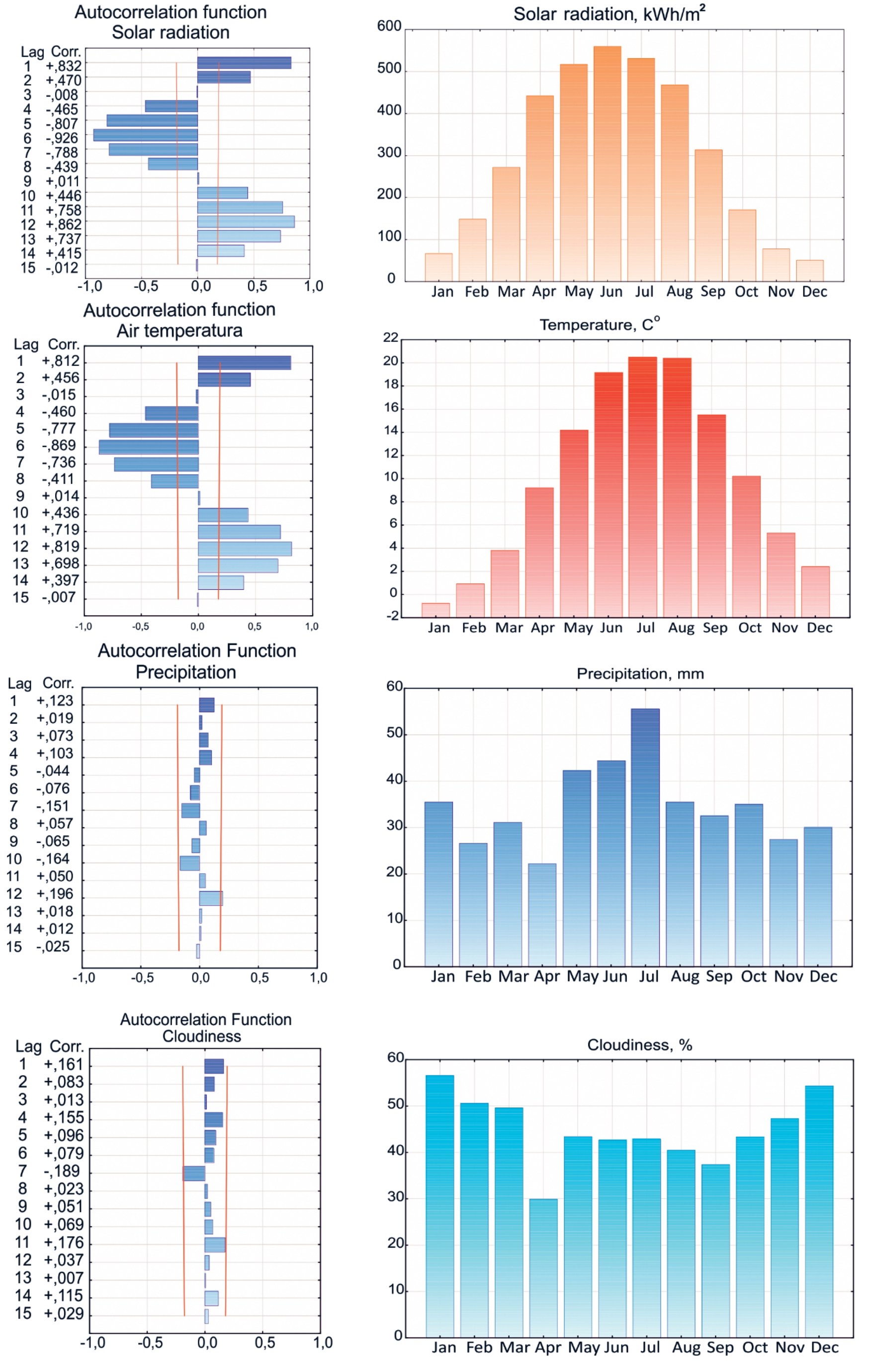

Fig. 6. Graphs of the autocorrelation function and variability of factors over the year (calculated for observational data in 2013–2021)

Installation design

The next step is import the file of obstructions into HelioScope Advanced Solar Design Software, which is an online app for designing and engineering of rooftop photovoltaic (PV) systems. The software provides access to a huge database of different solar panels and other components of PV systems and allows the panel angle, orientation, raw spacing and azimuth to be changed automatically.

Due to the current wide range of solutions for photovoltaic installations, we limit our overview to a few basic pieces of information about them influencing the course of this study:

– photovoltaic roof installations consist of modules (i.e. sets of cells) connected to panels [1, 6] properly arranged on the roof, then electrical installations connect the panels in series, parallel or hybrid wiring, and transfer voltage to inverters converting the generated DC current into AC used by electricity network installations [4];
– modules consist of a regular grid of PV cells made of silicon – mono- or polycrystalline, or linked in pairs of minerals from blocks III and V of the table of chemical elements, or of other combinations of minerals, including rare minerals [20];
– the panels are combined with metal profiles and placed directly on the roof or mounted on racks – fixed or rotating towards the Sun (heliotropes).

Monocrystalline quartz panels predominate in Poland, occupying about 60% of the market – they are most effective concerning the price [4]. For this reason, they were taken as the basis for the spatial analyzes presented here – one-piece monocrystalline SunPower Maxeon 3 (400 Wp) modules [47] with dimensions of 1690 mm × 1046 mm and efficiency of 22.6% were used (in the case of using the 60 kW 3 F 90 A Suntrio Plus inverter).

Simulations of PV installations with different orientations and tilt angles are performed for the parameters of the selected model of solar panels. Finally, the calculation of the expected system energy losses and performance analysis of the photovoltaic installations have to be conducted.

3. Results

3.1. GIS-based Estimation of Solar Irradiance for the Roof

Figure 7 shows the results of the solar radiation analysis for different places of the roof in the two extreme visible positions of the Sun. The daily insolation here ranges from 0.01 kWh/m^2 in winter (Fig. 7b) to about 5.7 kWh/m^2 in summer (Fig. 7a). The summary annual solar radiation is approximately 750–1045 kWh/m^2 (Fig. 7c), except for shaded roof fragments.

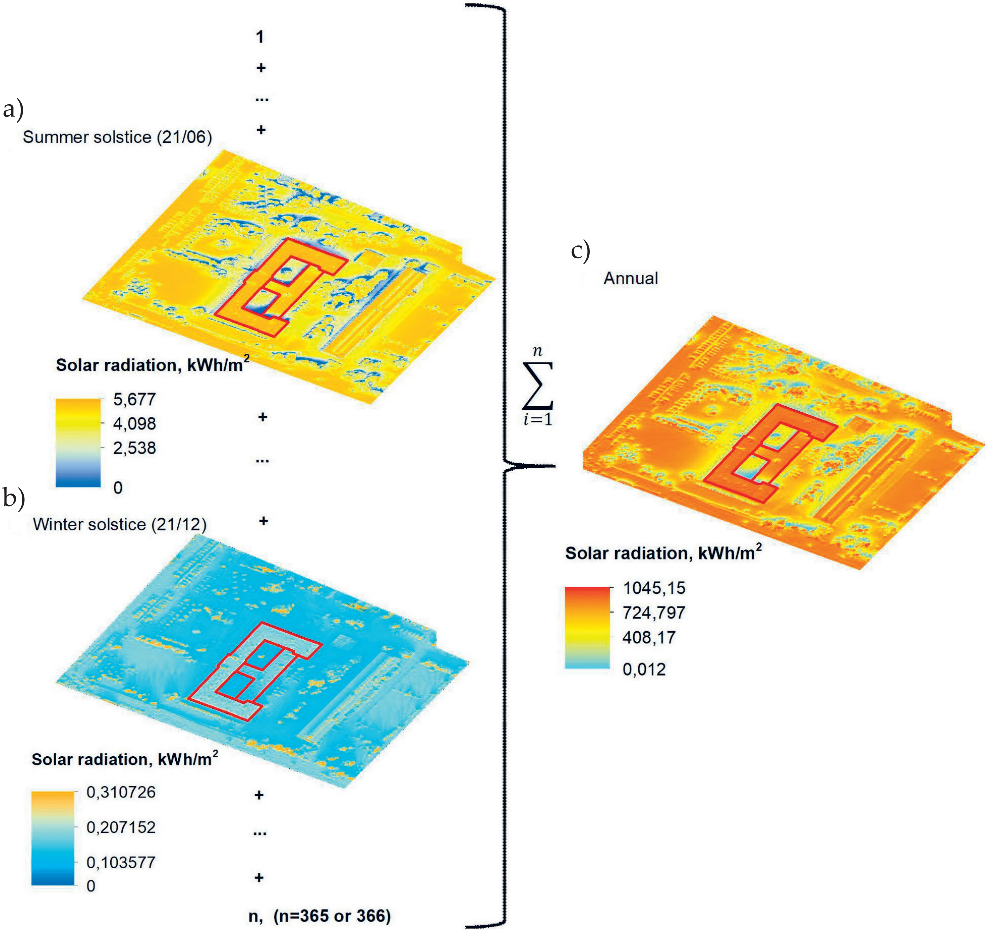

Fig. 7. The daily sum of solar radiation reaching the roof surface during the days of summer (a) and winter solstice (b) and the annual solar radiation reaching the surface (c)

Parts of the roof where the panels can be placed have been identified, given the level of insolation, existing obstructions, and shaded areas. These data not only allow the amount of solar radiation and shading of some roof surfaces for a particular day or period to be determined but also to conduct an accurate analysis of existing superstructures, ventilation systems, chimneys, antennas and others, which constitute obstructions to installing solar panels and sources of additional shading. To eliminate the existing obstructions and the most shaded areas, a raster classification of the total annual insolation was carried out on the principle: <800 kW/m^2/year – the area is unsuitable for the installation of solar panels; ≥800 kW/m^2/year – the area is suitable for the installation of solar panels. Given the shape and position of the roof of the lower part of the building (6.6 m in height) relative to the upper part (15.0 m in height), this one was excluded from further analysis as unpromising.

3.2. Arrangement of Panels

As a rule, designs for solar roof installations assume their arrangement on racks located directly on the roof slopes, rarely on a frame at a certain angle to the roof covering. The first solution relates mainly to slope roofs, and the second one – to flat roofs (according to the "wind standard" PN-77/B-02011/Az1:2009, it was assumed that these roofs have a slope of up to 5°), thus this value was omitted in further analysis. In the second solution, two approaches are presented in the literature:

1) Panels placed on frames with an angle of inclination optimal due to the recovery of solar energy – for medium latitudes it is usually between 39° and 41°. The optimal value for the tilt angle was calculated by an application from the geographic information portal PVGIS [48], which also provides access to databases of meteorological data and solar radiation based on three components of lighting – direct, diffused and reflected in clear skies under the real global lighting conditions for flat as well as sloping surfaces.
2) Panels folded flat on the roof or at a slight angle, 10° to 15° inclination. This solution is supported by limiting the risks to the roof structure due to wind gusts, as well as the unequal load of the roof with the PV installation by itself. Moreover, the smaller the angle of inclination of the panels, the greater the possibilities of their orientation (facing) – while the inclined surfaces must face south (or turned only a little to the sides), the horizontal ones can be oriented completely arbitrarily. Thus, the inclination (and the angle of orientation) of the panels is the first criterion considered for the arrangement of PV installations on flat roofs.

At the latitude corresponding to the location of the tested building ($\varphi \approx 53.4°$ N), the Sun rises above the horizon from 13.2° at noon on the winter solstice (December 21) to 61° in summer (June 21) [49]. The panels have a mounting dimension of about 1.0 m × 1.7 m, so when they are oriented with their long side at the base and with the slope of 15°, the opposite longer side will be got up to 0.26 m. Such a setting is favourable due to the influence of wind, but it can be problematic in the case of significant snowfall. Snowfall and the residual snow cover after it solidifies may require periodic maintenance. When the panels are placed at an angle of 40°, the elevation of the back edge relative to the front edge is 0.64 m.

3.3. Shadows

Direct (or indirect, diffused light) illumination of the entire surface of the panel is the basis for the effective operation of a PV installation. Incomplete lighting results in the almost complete shutdown of the entire chain (series connection) of panels [50]. Therefore, it is necessary to arrange the panels in such a way that will avoid their mutual shading and influence on other installations sticking out from the roof. Mutual shading analyzes generally apply to panels installed on a sloping frame on flat roofs (panels lying flat on the roof surface do not cast a shadow). Usually, the shadows are analyzed at extreme positions of the Sun concerning the Earth's surface, i.e. on the summer solstice (June 21–22) and winter solstice (December 21–22), and sometimes also on the equinox days. The apparent position of the Sun at noon local time is also considered. The relative position of the Sun to the selected place can be calculated based on quite simple geometric relationships or using one of the internet applications available. Figure 8 shows a graph of the apparent movement of the Sun in relation to the test object (coordinates 52.4N and 16.9E), as presented on the website of the University of Oregon, USA [49].

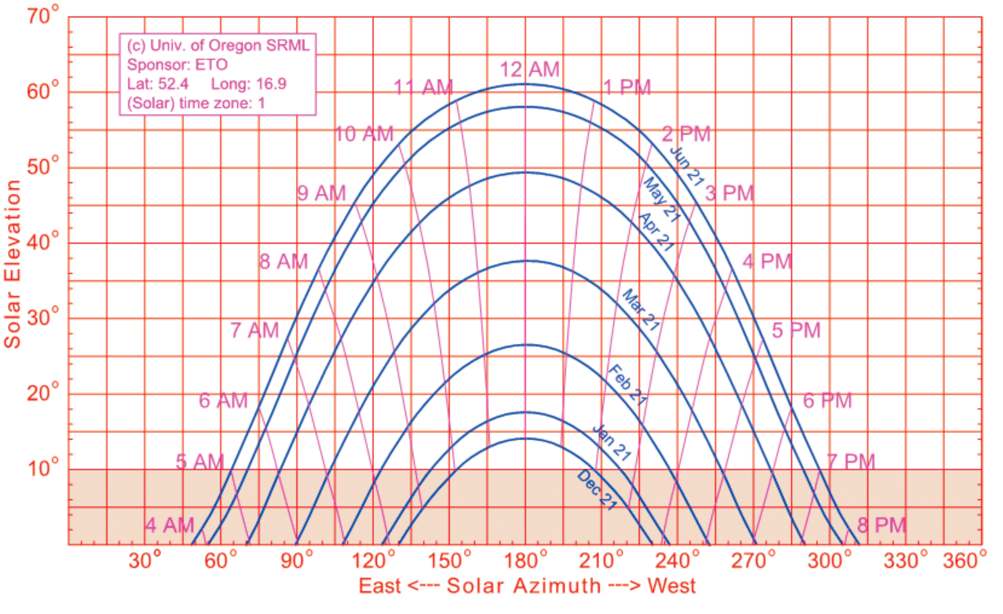

Fig. 8. The apparent movement of the Sun in the sky for the location of the tested object on selected days of the year. The highlighted (darkened) first 10° of the height of the Sun above the horizon corresponds to the minimum efficiency of electricity production by the PV installation

Source: own study based on [49]

Converting the results from Figure 8 to the length of shadows (the function $d = h/\tan \alpha$, where d – length of the shadow, h – the height of the obstacle, α – the angle of incidence of sunlight), we obtain an illustration of the shadow variability in subsequent hours of local time in selected and characteristic days of the year (Fig. 9). For an object with a height of $h = 1$ m, the longest shadow at noon on December 21 is almost 4.0 m long, and at 9:00 or 15:00 reach almost 12.0 m. Limiting the operation time of the panels to the lower limit of the angle of incidence of light (i.e. 10°), we obtained the shadow, which reaches 5.8 m. Taking into account the orientation of the Sun to the panel line, the maximum shadow lengths of the object of 1 m height are 4.0 m and 9.1 m respectively, and for an angle of 10° above the horizon is 5.1 m.

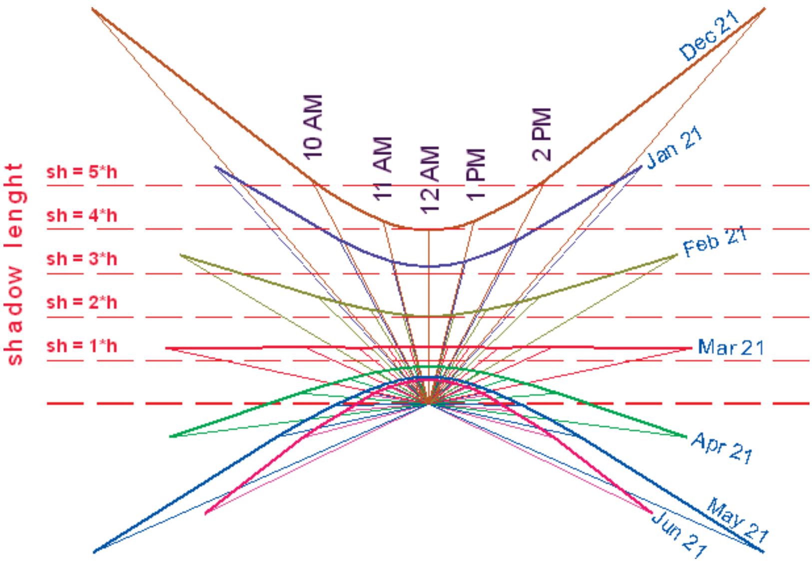

Fig. 9. Shadows projected by a vertical element (gnomon) on a horizontal roof due to sunlight on selected days of the year. The distance *sh* is the length of the shadow calculated as a multiple of the height of the illuminated element (*h*)

Source: own study based on [49]

In the variants considered in this analysis (40° and 15° inclination of panels), it corresponds to the following parameters of the height of the obstacle resulting from the inclination of the panel: a) shadow length on December 21 at 12:00, b) shadow length on December 21 at 10:00 or 14:00:

- 0.64 m (40°): a) 2.6 m; b) 3.7 m;
- 0.26 m (15°): a) 1.0 m; b) 1.5 m.

On the longest day of the year (i.e. June 21), most of the shadows are turned towards the south and do not interfere with the installation, while at noon they are 0.55 m long.

Ultimately, it was concluded that for the effective use of the installation, panels should be inclined at an angle of 15° and their rows should be moved from each other at about 1.5–2.0 m. In the case of inclination at the angle of 40°, the rows of modules should be moved at about 3.5 m. The above-given parameters are close to the results obtained by specialized software used for designing photovoltaic systems. For further analysis, these two variants of panel inclination were adopted (with corresponding sizes of spacing between the rows), as well as two versions of the orientation of the rows of panels: a) in the east-west direction ($\varphi = 180°$) or b) under the azimuth of the southern elevation of the analyzed building ($\varphi = 211.6°$). Further calculations also took into account – according to the above analysis – shadows cast by lofty roof installations.

3.4. Visibility of the Panels

For the analysis, the extent of the panels from the roof edge was calculated to ensure their invisibility from the surrounding public places. In the beginning, it was assumed that for safety reasons the panels should be at least 1 m away from the edge of the roof. With this assumption, the rear edges of the outer rows of panels are moved away from the edge of the roof – similarly to the calculations of shadows – with the value $b = h/\tan \alpha$ (where b is the panel's projection onto the roof surface). For panels inclination angle of 15° $b = 0.97$ m, their rear walls are almost 2.0 m away from the roof edge, and for the panel inclination angle of 40° – $b = 0.31$ m, and their distance from the edge roof respectively 1.31 m.

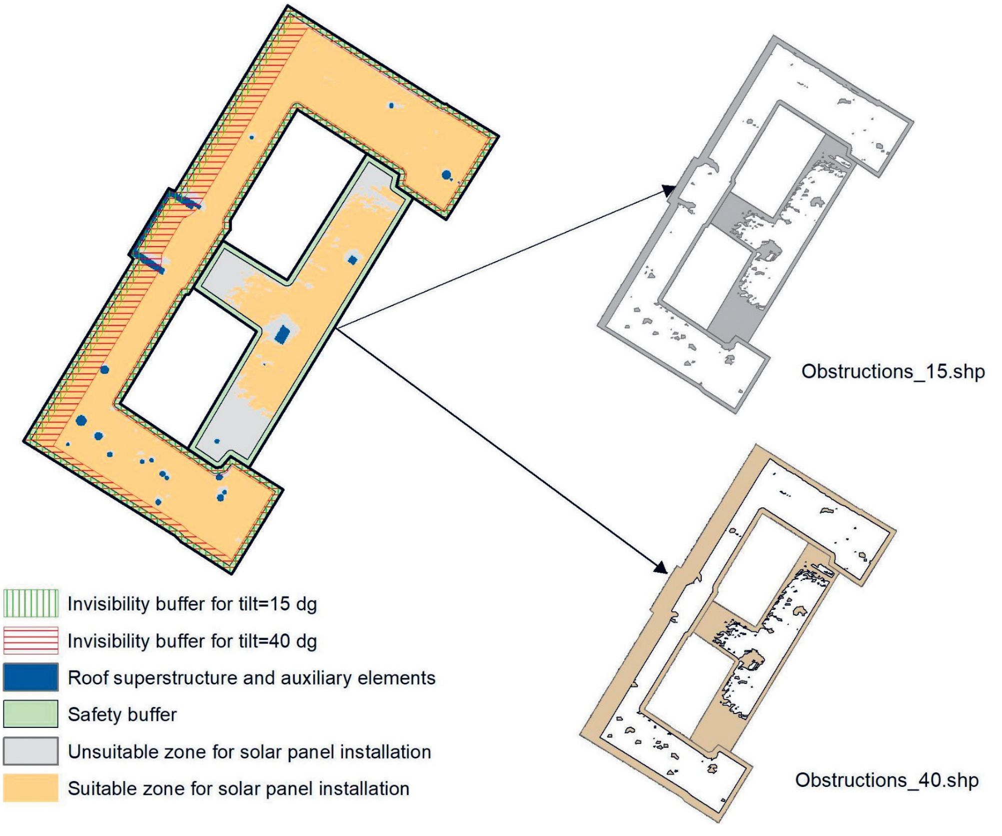

Fig. 10. Standardization of the obstruction layers

For a three-storey building (with an attic, as in the case of the considered object), the edge of the roof rises above the ground to the height of about 15 m. Therefore – according to the above given trigonometric rules – panels 0.26 m in height, remoted from the edge for 2.0 m are not visible from a distance of 100 m (for the observer's eye at the level of 2.0 m above the base of the tested building), while for panels 0.64 m in height, separated from the edge for 1.3 m, equals a distance of 26.5 m. To hide these panels from the eye of an observer who is 100 m away from the building, they should be at least 4.9 m away from the edge of the roof (their higher edge), and for the distance of 50 m (the maximum actual distance for an observer) it is 2.4 m, which corresponds to the offset of the front line of these panels from the edge of the roof for 2.1 m – in our analysis, we will assume a minimum distance of 4.0 m to the edge of the roof along the front wall, and 2.0 m to the edge of the southern wall, less visible for longer distances. The remaining edges of the roofs are not visible at greater distances than the predetermined 26.5 m.

The above-calculated values were used as parameters for the design of the arrangement of the PV installation on the roof of the tested building.

Based on the calculations described in the previous chapters, the heights of the rear edges of the panels and the minimal spacing distance between modules were determined for tilt angles 15° and 40° for two options of the orientation of panels: south (azimuth 180°) and parallel the edge of the roof (azimuth 211.6°). The obtained layers, including the perimeter security buffer zone, the visibility area of the panels, and the shaded areas, were combined into two vector layers, Obstructions_15.shp and Obstructions_40.shp, correspondingly for tilt angles 15° and 40° (Fig. 10).

3.5. Detailed Design of the PV Installation

At the next step CAD models were built for shadow analysis, calculation of shading losses and energy performance in the PV system and assessment of general financial indicators in the HelioScope Advanced Solar Design Software platform [51].

Primarily, after converting obstruction layers to the *.kml exchange format, they were imported into the HelioScope environment to fill the KeepOuts information block and for further design.

For both variants of the tilt angle, the possibilities of placing the modules strictly to the south and parallel to the edge of the roof were designed (Fig. 11). The summary results of the assessment are presented in Table 2. Calculations and models allow the determination of the possibility of installing a solar power plant with a capacity of about 40–99 kW on the roof of the A2 building of Poznan University of Technology with an estimated average energy output of 41–100 MWh/year.

The projected distribution of expected system losses and the distribution of energy production are shown in Figures 12 and 13, respectively. Shading losses are minimized, their values are less than the losses due to the technical parameters of the PV system, and are approximately 3% for the 40° tilt and less than 1% for the 15° tilt (Fig. 12). The created prognostication graphs of energy distribution (Fig. 13) show a significant variability in the amount of energy produced during the year, due to the impact of the natural seasonality of the meteorological factors.

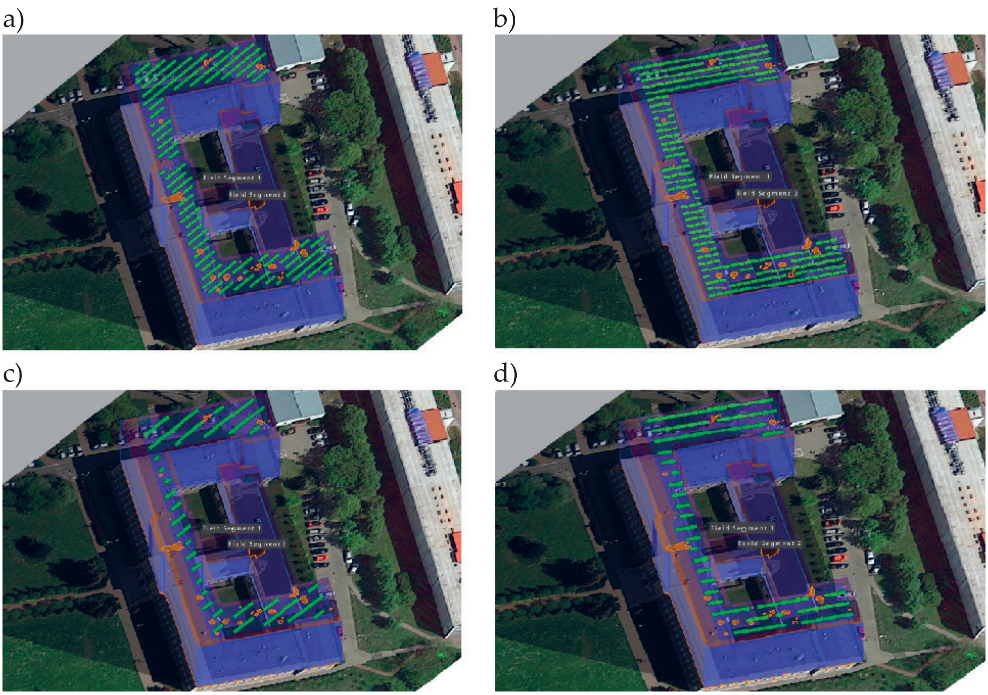

Fig. 11. Options for the photovoltaic installations for: a) tilt angle 15° (azimuth 180°); b) tilt angle 15° (azimuth 211.6°); c) tilt angle 40° (azimuth 180°); d) tilt angle 40° (azimuth 211.6°) (created using the HelioScope Software)

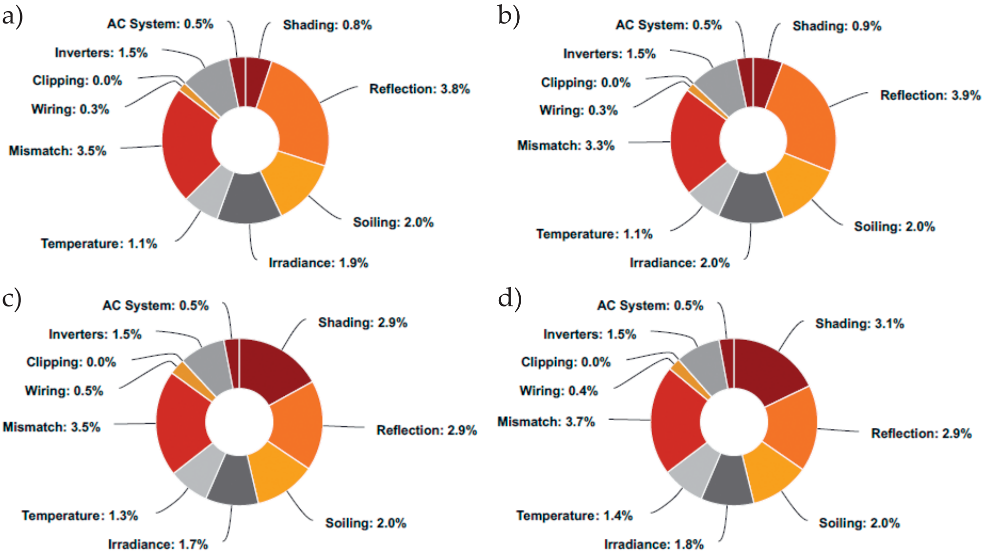

Fig. 12. Distribution of the expected system energy losses for: a) tilt angle 15° (azimuth 180°); b) tilt angle 15° (azimuth 211.6°); c) tilt angle 40° (azimuth 180°); d) tilt angle 40° (azimuth 211.6°)

Fig. 13. Potential distribution of energy produced for:
a) tilt angle 15° (azimuth 180°); b) tilt angle 15° (azimuth 211.6°);
c) tilt angle 40° (azimuth 180°); d) tilt angle 40° (azimuth 211.6°)

Table 2. Possibilities and results of the placement of modules (photovoltaic panels – SunPower Maxeon 3 (400 Wp), inverter – Suntrio Plus 60 kW)

Tilt [°]	Azimuth [°]	Row spacing [m]	Modules	Nameplate [kW]	Annual shading [%]	Performance ratio [%]	Annual energy [MWh]
15	180.0	1.5	226	90.4	0.8	85.5	91.4
	211.6	1.5	248	99.2	0.9	85.5	99.9
40	180.0	3.4	97*	38.8	2.9	84.4	41.4
	211.6	3.4	120**	48.0	3.1	83.9	49.9

* An inverter with a capacity of 40 kW was used due to the less number of panels.
** An inverter with a capacity of 50 kW was used due to the less number of panels.

4. Discussion

This publication presents the applied spatial analysis procedure for the selection and proper placement of photovoltaic panels on flat roofs, taking into account the above-mentioned requirements (criteria) resulting from the need for safe usage of the designed PV installations, as well as the elements of the roof structure and objects existing on them, and their shadows. Due to the historic nature of the building, it was also necessary to take into account another criterion, namely hiding the panels from observers at the street level. Assuming that the designer does not influence the lighting conditions that get weaker with increasing latitude, an important task was to find the best option to place the solar panels on the roof of the building to achieve the maximum possible efficiency.

A review of previous research [6, 10, 12, 15–19, 24, 26–31] and existing practical solutions [33–39] confirms the feasibility of combining GIS and CAD tools (with their decision-making modules), using high-precision spatial models to address issues, concerning the design and optimization of photovoltaic systems, evaluation of their effectiveness, planning and development of solar energetics.

The basis of the presented analysis is a spatial model of land cover developed based on low-altitude aerial photographs (drone) correlated with the necessary data available on internet portals [33, 43]. The analyses were preceded by a review of the available PV panel systems and the design and implementation of studies for rooftop PV installations gathered in the literature on the subject. Selected functions of the programs mentioned in the text were used for the analysis. The final effect was presented in the form of a 3D decision map showing the optimal distribution of panels on the roof.

The best option allows the placement of the maximum number of solar panel modules and at the same time, minimize energy losses due to mutual shading.

Considering the possibility of technology development is also essential. Currently, opportunities for development in the design of photovoltaics are mainly considered in the technology of manufacturing cells. The technology of multi-transition cells stands out among the various solutions. In this technology, each of the layers works independently and regulates productivity under the energy of solar radiation, which reaches a single cell, depending on the current wavelength of light. Moreover, silicon is being replaced by materials of greater efficiency and productivity. One of them is perovskite, a mineral consisting of calcium, titanium and oxygen ($CaTiO_3$). Investigations have shown that it absorbs much more solar energy and in addition, is characterized by high conversion efficiency of solar radiation into electricity, even 1/3 greater than silicon [52].

Another solution is to use polymers in which more electrons excited by light move faster. This increases the efficiency of solar cells by as much as 15% [5]. Techniques for increasing the amount of absorbed solar light using lenses printed on cells with gallium arsenide are also being developed. Such a system will be much lighter and relatively cheaper, it can be installed on old roofs that are sensitive to overloading due to the reduced weight. In the field of miniaturization and load reduction, research is being conducted on the production of amorphous [a-Si] or micromorphous [a-Si/c-Si] silicon cells, which will be one micrometre thick. It is also possible to make hybrid or even dye (DSSC) cells, enriched with a special dye, actively involved in electricity production. When these solutions enter the production phase it will be possible to cover the entire roof surface and facades [27, 30] of facilities such as the A2 building of Poznan University of Technology with solar panels without fear of their visibility from the sidewalk, mutual shading and consequently without previous comprehensive analysis for their effective placement.

Analysis of the content and interactive tools of existing solar data geoportals, both for Poznan and other cities in Poland and Europe [32–39], shows the possibility of developing and supplementing the geoportal with simulation results (obstructions, layouts of solar panel modules, graphs of potential energy produced) that can be performed according to the proposed algorithm involving data with greater spatial coverage. Input data can be obtained using drone photography or LIDAR [28, 39, 40, 46].

An additional issue that needs to be addressed when the study area of the model is expanded concerns the development of special GIS plugins to automate routine tasks, including the formation of unified files of obstructions, preparing them for import, as well as integration of CAD tools in the GIS environment. The results of modelling can be added to the solar data portal for the city and used in the tasks of land and energy management.

5. Conclusion

The purpose of the research was to use geomatics methods to place a photovoltaic installation on a specific roof of a historic public building, which requires consideration of certain spatial constraints. In addition to the standard placement criteria, the state of visibility/invisibility of panels from the surrounding communication spaces was taken into account. Methods for designing photovoltaic installations on roofs using specialized SDSS software and data models were considered. Original visibility and shading analysis were performed using GIS tools.

Based on the results of the analysis, the expected implementation effectiveness of the designed solution was calculated. The obtained results confirmed the hypothesis that the best solution was to install panels with a tilt angle of 15° parallel to the south-eastern edge of the roof. This option is expected to generate 99.9 MWh of electricity per year, while the least efficient solution is to install panels with an angle of 40° and an azimuth of 180°, which will produce 41.4 MWh of electricity per year. All parameters were evaluated for specific types of photovoltaic modules and inverters.

Installing photovoltaic panels on the roof of a historic building may require reinforcement, which should also be taken into account in such an analysis. It would require a preliminary inventory of the load-bearing structure and the necessary strength calculations.

The current study is limited by the spatial coverage of input data, which includes only one tested object. Expansion of the input database with the involvement of aerial photography or LIDAR with high accuracy, as well as automation of routine data processing tasks using specialized plugins, will create relevant models with greater spatial coverage (district, city). The results of modelling, in their turn, can be used to supplement and improve the functionality of the solar data portal for the city.

Author Contribution

Lidiia Davybida: conceptualization, methodology, data curation, formal analysis, visualization and writing – original draft.

Ireneusz Wyczałek: conceptualization, supervision, project administration, formal analysis, visualization and writing – original draft.

Artur Plichta: methodology, validation, supervision, writing – reviewing and editing. All authors approved the final version of the manuscript and agree to be held accountable for the content therein.

Acknowledgements

This research was prepared with the support of the Centre for East European Studies (University of Warsaw) in the frame of the Ivan Vyhovsky Award (2020/2021) under the patronage of the President of Poland.

References

[1] Green M.A.: *Silicon Photovoltaic Modules: A Brief History of the First 50 Years.* Progress in Photovoltaics: Research and Applications, vol. 13, 2005, pp. 447–455. https://doi.org/10.1002/pip.612.

[2] Jastrzębska G.: *Ogniwa słoneczne: budowa, technologia i zastosowanie.* Wydawnictwa Komunikacji i Łączności, Warszawa 2013.

[3] Soumya C., Deepanraj B., Ranjitha J.: *A review on solar photovoltaic systems and its application in electricity generation.* [in:] *AIP Conference Proceedings*, 2396, 020011, 2021. https://doi.org/ 10.1063/5.0066291.

[4] Mirowski T., Sornek K.: *Potencjał energetyki prosumenckiej w Polsce na przykładzie mikroinstalacji fotowoltaicznych w budownictwie indywidualnym* [*Potential of prosumer power engineering in Poland by example of micro PV installation in private construction*]. Polityka Energetyczna, t. 18, z. 2, 2015, pp. 73–84.

[5] Mughal Sh., Sood Yog R., Jarial R.K.: *A Review on Solar Photovoltaic Technology and Future Trends.* National Conference on Recent Advances in Computer Science and IT (NCRACIT). International Journal of Scientific Research in Computer Science, Engineering and Information Technology, vol. 4, no. 1, 2018, pp. 227–235.

[6] Dondariya C., Porwal D., Awasthi A., Shukla A.K., Bhimte A.: *Performance simulation of grid-connected rooftop solar PV system for small households: A case study of Ujjain, India.* Energy Reports, vol. 4, 2018, pp. 546–553. https://doi.org/10.1016/j.egyr.2018.08.002.

[7] Bonomolo M., Di Lisi S., Leone G.: *Building Information Modelling and Energy Simulation for Architecture Design.* Applied Sciences, vol. 11, 2021, 2252. https://doi.org/10.3390/app11052252.

[8] Yankiv-Vitkovska L., Peresunko B., Wyczałek I., Papis J.: *Site selection for solar power plant in Zaporizhia city (Ukraine).* Geodesy and Cartography, vol. 69, no. 1, 2020, pp. 97–116. https://doi.org/10.24425/gac.2020.131076.

[9] Yushchenko A., de Bono A., Chatenoux B., Kumar Patel M., Ray N.: *GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa.* Renewable & Sustainable Energy Reviews, vol. 81, 2018, pp. 2088–2103. https://doi.org/10.1016/j.rser.2017.06.021.

[10] Romero Rodríguez L., Duminil E., Sánchez Ramos J., Eicker U.: *Assessment of the photovoltaic potential at urban level based on 3D City models: A case study and new methodological approach*. Solar Energy, vol. 146, 2017, pp. 264–275. https://doi.org/10.1016/j.solener.2017.02.043.

[11] Khan J., Arsalan M.H.*: Estimation of rooftop solar photovoltaic potential using geo-spatial techniques: A perspective from planned neighborhood of Karachi – Pakistan*. Renewable Energy, vol. 90, 2016, pp. 188–203. https://doi.org/10.1016/j.renene.2015.12.058.

[12] Fuentes J.E., Francisco D.M., Oscar D.M.: *Method for Estimating Solar Energy Potential Based on Photogrammetry from Unmanned Aerial Vehicles*. Electronics, vol. 9, no. 12, 2020, 2144. https://doi.org/10.3390/electronics9122144.

[13] Zambrano-Asanza S., Quiros-Tortos J., Franco J.: *Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load.* Renewable and Sustainable Energy Reviews, vol. 143, 2021, 110853. https://doi.org/10.1016/j.rser.2021.110853.

[14] Bujarkiewicz A., Sztubecka M., Sztubecki J.: *The Study of Using GIS Tools in Sustainable Management of Solar Energy.* Civil and Environmental Engineering Reports, vol. 28, 2018, pp. 26–39. https://doi.org/10.2478/ceer-2018-0003.

[15] Chow A., Alan S.F., Songnian L.: *GIS Modeling of Solar Neighborhood Potential at a Fine Spatiotemporal Resolution*. Buildings, vol. 4, no. 2, 2014, pp. 195–206. https://doi.org/10.3390/buildings4020195.

[16] Iñaki P., Izkara J.L., Usobiaga E.: *The Application of LiDAR Data for the Solar Potential Analysis Based on Urban 3D Model*. Remote Sensing, vol. 11, no. 20, 2019, 2348. https://doi.org/10.3390/rs11202348.

[17] Redweik P., Catita C., Brito M.: *Solar energy potential on roofs and facades in an urban landscape.* Solar Energy, vol. 97, 2013, pp. 332–341. https://doi.org/10.1016/j.solener.2013.08.036.

[18] Thebault M., Clivillé V., Berrah L., Desthieux G.: *Multicriteria roof sorting for the integration of photovoltaic systems in urban environments.* Sustainable Cities and Society, vol. 60, 2020, 102259. http://doi.org/10.1016/j.scs.2020.102259.

[19] Stachura T., Krzyś M.: *GIS-based assessment of the feasibility of solar energy applications, in the case of Łazy village*. Geomatics, Landmanagement and Landscape, no. 1, 2017, pp. 65–79. http://doi.org/10.15576/GLL/2017.1.65.

[20] Beseničar J., Trstenjak B., Setnika D.: *Application of geomatics in photovoltaics.* The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 37(B4), 2008, pp. 53–56.

[21] Guaita-Pradas I., Marques-Perez I., Gallego A., Segura B.: *Analyzing territory for the sustainable development of solar photovoltaic power using GIS databases.* Environmental Monitoring and Assessment, vol. 191, 2019, 764. https://doi.org/10.1007/s10661-019-7871-8.

[22] Ostapenko O., Koval V., Olczak P., Hren L., Matuszewska D., Postupna O.: *Application of Geoinformation Systems for Assessment of Effective Integration of Renewable Energy Technologies in the Energy Sector of Ukraine.* Applied Sciences, vol. 12, 2022, 592. https://doi.org/10.3390/app12020592.

[23] Bukowski M., Majewski J., Sobolewska A.: *Macroeconomic Electric Energy Production Efficiency of Photovoltaic Panels in Single-Family Homes in Poland.* Energies, vol. 14(1), no. 126, 2021. https://doi.org/10.3390/en14010126.

[24] Gassar A.A.A., Cha S.H.: *Review of geographic information systems-based rooftop solar photovoltaic potential estimation approaches at urban scales.* Applied Energy, vol. 291, 2021, 116817. https://doi.org/10.1016/j.apenergy.2021.116817.

[25] Pawłowska M., Pawłowski L. (eds.): *Advances in Environmental Engineering Research in Poland.* 1st ed. Routledge, London 2021. https://doi.org/10.1201/9781003171669.

[26] Bremer M., Mayr A., Wichmann V., Schmidtner K., Rutzinger M.: *A new multi-scale 3D-GIS-approach for the assessment and dissemination of solar income of digital city models.* Computers, Environment and Urban Systems, vol. 57, 2016, pp. 144–154. https://doi.org/10.1016/j.compenvurbsys.2016.02.007.

[27] Saretta E., Bonomo P., Frontini F.: *A calculation method for the BIPV potential of Swiss façades at LOD2.5 in urban areas: A case from Ticino region*. Solar Energy, vol. 195, 2020, pp. 150–165. http://doi.org/10.1016/j.solener.2019.11.062.

[28] Brito M., Redweik P., Catita C., Freitas S., Santos M.: *3D Solar Potential in the Urban Environment: A Case Study in Lisbon*, *Energies*, vol. 12, no. 18, 2019, 3457. https://doi.org/10.3390/en12183457.

[29] Sánchez-Aparicio M., Jimenez Jose A., Del Pozo S., González E., Lagüela S.: *Ener3DMap-SolarWeb roofs: A geospatial web-based platform to compute photovoltaic potential.* Renewable and Sustainable Energy Reviews, vol. 135, 2021, 110203. https://doi.org/10.1016/j.rser.2020.110203.

[30] Desthieux G., Carneiro C., Camponovo R., Ineichen P., Morello E., Boulmier A., Abdennadher N. et al.: *Solar energy potential assessment on rooftops and facades in large built environments based on LIDAR data, image processing, and cloud computing. Methodological background, application, and validation in Geneva (solar cadaster).* Frontiers Built Environment, vol. 4, 2018, 14. https://doi.org/10.3389/fbuil.2018.00014.

[31] Stendardo N., Desthieux G., Abdennadher N., Gallinelli P.: *GPU-Enabled Shadow Casting for Solar Potential Estimation in Large Urban Areas. Application to the Solar Cadaster of Greater Geneva.* Applied Sciences, vol. 10, 2020, 5361. https://doi.org/10.3390/app10155361.

[32] Bieda A., Cienciała A.: *Towards a Renewable Energy Source Cadastre – A Review of Examples from around the World.* Energies, vol. 14, no. 23, 2021, 8095. https://doi.org/10.3390/en14238095.

[33] SIP Poznan. http://sip.poznan.pl/model3d/#/legend [access: 1.12.2021].

[34] Solar cadaster of Grand Genève. https://apps.sitg-lab.ch/solaire/ [access: 9.04.2022].

[35] Map of solar potential in Munich. https://geoportal.muenchen.de/portal/solarpotenzial/ [access: 9.04.2022].

[36] The London Solar Opportunities Map. https://maps.london.gov.uk/lsom/?_gl=1%2a13sqp4w%2a_ga%2aMTY4OTIzNzMzOC4xNjQ5NTEzODc4 [access: 9.04.2022].

[37] Solar atlas of Amsterdam. https://www.zonatlas.nl/amsterdam/ontdek-de-zonatlas/ [access: 9.04.2022].

[38] Map of solar potential in Wrocław. https://gis.um.wroc.pl/en/maps/solarna/ [access: 9.04.2022].

[39] Mapping solar energy resources in San Francisco. http://app.dumpark.com/sunlight/sf [access: 9.04.2022].

[40] *Energy Efficiency and Historic Buildings: Solar Electric (Photovoltaics).* Historic England, Swindon 2018.

[41] Kandt A., Hotchkiss E., Walker A., Buddenborg J., Lindberg J.: *Implementing Solar PV Projects on Historic Buildings and in Historic Districts.* National Renewable Energy Laboratory, Colorado 2011.

[42] Global Solar Atlas. https://globalsolaratlas.info/download/poland [access: 8.12.2021].

[43] Geoportal Poland. https://www.geoportal.gov.pl/ [access: 8.12.2021].

[44] Google Earth Engine. A planetary-scale platform for Earth science data and analysis. https://earthengine.google.com/ [access: 8.12.2021].

[45] Solar Energy – Introduction to SEBE. https://umep-docs.readthedocs.io/projects/tutorial/en/latest/Tutorials/SEBE.html [access: 9.04.2022].

[46] Garcia R., Polo J.: *Evaluating the Solar Potential of Rooftops on Campus San Joaquín, Santiago – Chile using Opensource GIS*. [in:] *EuroSun2020 – ISES Conference Proceedings*, International Solar Energy Society, 2020. https://doi.org/10.18086/eurosun.2020.01.12.

[47] SunPower. https://sunpower.maxeon.com/uk/solar-panel-products/maxeon-solar-panels [access: 8.12.2021].

[48] PVGIS – Photovoltaic Geographical Information System. https://ec.europa.eu/jrc/en/pvgis [access: 8.12.2021].

[49] University of Oregon. Solar Radiation Monitoring Laboratory. http://solardat.uoregon.edu/SunChartProgram.html [access: 8.12.2021].

[50] Fialho L., Melicio R., Mendes V.M.F., Figueiredo J., Collares-Pereira M.: *Effect of Shading on Series Solar Modules: Simulation and Experimental Results.* Procedia Technology, vol. 17, 2014, pp. 295–302. https://doi.org/10.1016/j.protcy.2014.10.240.

[51] HelioScope. Advanced Solar Design Software. https://www.helioscope.com/ [access: 8.12.2021].

[52] Green M., Ho-Baillie A., Snaith H.: *The emergence of perovskite solar cells.* Nature Photon, vol. 8, 2014, pp. 506–514. https://doi.org/10.1038/nphoton.2014.134.