GIS estimated potential of rooftop PVs in urban areas – case study Wrocław (Poland)

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Abstract. The authors attempted to determine the amount of a roof's surface required for the installation of PVs panels, in terms of the type of building, roof shape, slope, exposition and potential shading of the structure. The area selected for the study was the city of Wrocław, Poland.

Photovoltaics are perceived to be a viable option for reducing the environmental impact of energy production while simultaneously increasing local energy security. Exploiting the potential of cities in generating energy from photovoltaics is increasingly evident; in particular, to provide the individual needs of cities, estates or buildings. Due to the diversity of the construction of buildings' roofs, as well as the impact of neighbouring buildings, determining the technical potential at the stage of preliminary analyses is necessary. For these aims, it seems almost obvious to use high–resolution LiDAR data and a GIS spatial analysis.

The LiDAR data in the form of a classified points cloud (12 pt/m^2) and the Database of Topographic Object from which information on the building class was taken was used. A digital surface model of roofs with a spatial resolution of 1 m was created from the LiDAR data. A slope and a roof exposition models were created, and the roofs were finally counted in 90 categories. The authors have also analysed the conditions for the shading of their own and neighbouring objects with regard to the vertical and horizontal angle of the sunlight for Wrocław, Poland, on characteristic dates: the March and September equinox, the summer and winter solstice, and analysing the period from 8 am to 4 pm in one hour intervals. Analyses of the available areas were made regarding the building's class.

1 Introduction

Cities are centres of human activities. They not only create opportunities for progress in various areas, but also contribute heavily to the degradation of the local and global environment. The volume of goods, especially the energy consumed in cities (in a relatively small area), is so immense that this environmental burden [1] cannot remain neglected, especially in the context of observed climate changes [2].

Cities consume various forms of energy, the majority of which is generated in distant power plants and processing facilities. Electricity is a specific form as it generally has to be used when produced, and can be stored for a limited time and volume [3].

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Considering the above, it is of vital importance to investigate whether cities can limit their impact on the environment by generating electricity in the place of its consumption. One of the most socially acceptable forms of energy harvesting [4] is photovoltaics (PV) which directly convert sunlight (irradiation) into electricity. PVs are believed to have a significant potential in reducing the city's impact on the environment [5] and increasing the city's energetic self-sufficiency and storage demand (by an appropriate management) [6]. It is recommended that PVs be applied into areas of low value (examples) as they are characterized by a relatively low power density [7]. In the case of the urban environment, PVs can be used as Building Applied Photovoltaics or Building Integrated Photovoltaics; both of which over recent years drew significant scientific and market attention [8]. One of the ways to install PVs panels is to install them on the roofs of buildings. This variant does not interfere with the spatial order of the urban area, nor does it limit it, it additionally uses undeveloped surfaces, which are at the same time the most exposed to sunlight.

In order to estimate the potential of urban areas in terms of the surface of roofs potentially available for the installation of PVs panels, GIS tools, LiDAR data (Light Detection and Ranging) and a digital roof model (DSM) created from LiDAR can be used. High–resolution LiDAR data, including those for urban areas, is available free of charge in many countries [9], and in the case of Poland, for example, such data is available for a fee or for without a fee if it is for scientific purposes. Similar research, although each having a different aspect and purpose, were conducted, among others, in Slovenia [10], South Korea [11], the USA [12] and other countries.

The authors aim was to determine the possibilities of using high–resolution LiDAR data and GIS tools to analyse the potential of rooftop PVs in urban areas`, using the example of the city of Wrocław, Poland. Simultaneously, the aim of the research was to estimate the availability of `the surfaces of roofs in terms of building class, slope, exposition and shading condition for the installation of PV panels.

2 Material and methods

2.1 Site description

Analyses in terms of determining the roof surfaces of various functions buildings available for the installation of PVs panels were conducted for the city of Wrocław area (coordinates: GPS: N: 51°12'52.4"–51°2'19.8", E: 16°48'43.4"–17°10'18.9"; PL–92: N: 354722–373570, E: 346655–372361), Poland (Fig. 1). Wrocław is a city with county rights, the seat of the Wrocław County council and the Lower Silesian Voivodeship capitol. It is located in south–west Poland in the Silesian Lowland at an altitude of 105–156 m ASL. Wroclaw is the fourth largest city in Poland in terms of population (ca. 640,000), and the fifth in terms of area (ca. 292.5 km^2). Wrocław is located in a temperate climate zone of medium latitude, in the type of transitional climate subject to oceanic and continental climate influences. Annual sunshine is 41 days, mostly in September; annual cloud cover is 206 days, mostly in November; while the annual duration of sunshine is 1556 hours.

The analysis concerned buildings, practically the roofs of these buildings (ca. 65,500 buildings). The buildings have been classified into five categories: single–family; multi–family; industrial, economic; general, commercial, service; and monuments.

The analysis also considers solar conditions, including the vertical and horizontal angle of sunlight on four characteristic dates of the year: the March equinox (March 21), the summer solstice (June 22), the September equinox (September 23) and the winter solstice (December 22). Information on the angle of sunlight was used to analyse the shading conditions of roofs.

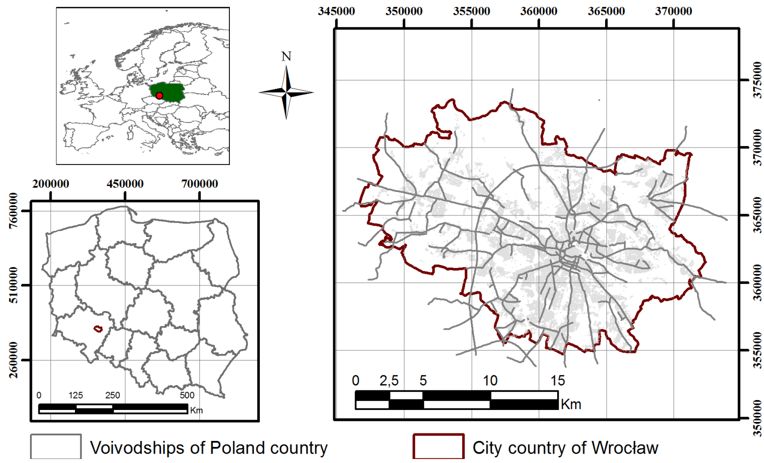

Fig. 1. Location of the research object – the city of Wrocław, Lower Silesian Voivodeship, Poland.

2.2 Data

The main basis of the performed analyses, in terms of materials and data, was high–resolution LiDAR data. The data used was obtained from the Polish governmental project ISOK (IT system of the Country's Protection Against Extreme Hazards). During the July–August 2011 period, aerial laser scanning (ALS) was performed, with the final product being a classified points cloud with a density of 12 pt/m^2. The points cloud is saved in the .las file format ver. 1.2, compliant with the American Society for Photogrammetry and Remote Sensing . Each point in the cloud contains information about its location, which is stored in the PL–92 coordinate system (EPSG code: 2180), as well as information about the altitude at sea level. According to the classification, each point in the cloud has information on belonging to one of the classes, including the class of ground, low, medium and high vegetation, and the class of buildings. The points cloud was used to develop numerical models that were the basis for the analysis on the available roof area of buildings.

The LiDAR data, in the form of the classified points cloud (Fig. 2), does not reveal information on the type of object and its function. In order to categorize objects (buildings), data from the Database of Topographic Object prepared in the 1: 10000 scale (BDOT10k) was used. BDOT are data developed in 2012–2013 according to the standards of the Ministry of Interior and Administration and managed by the Head Office of Geodesy and Cartography.

Fig. 2. Points cloud: with RGB mask, selected building class and highest points of rooftop.

From the BDOT data (Fig. 3), information about the category of buildings (single–family; multi–family; industrial, economic; general, commercial, service; monuments) was obtained. BDOT was developed on the basis of the vectorization of topographic maps and orthophotomaps. The topicality of the BDOT data may in some places be lower than the content of the LiDAR data, therefore in the analysis process data were limited to objects included in the BDOT database.

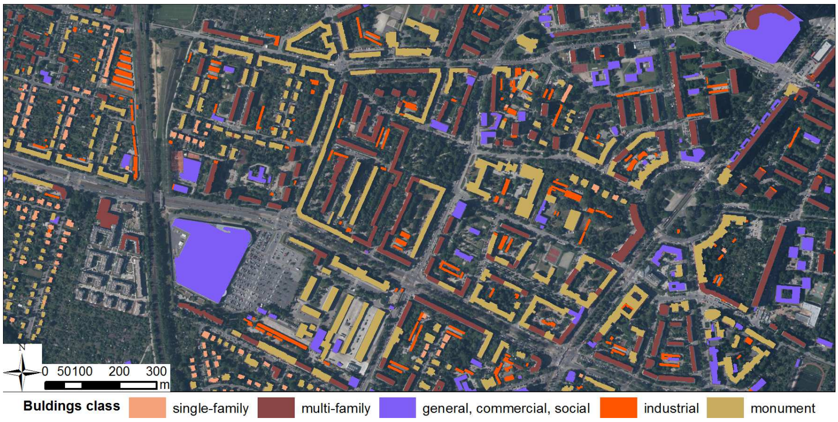

Fig. 3. Classification of buildings based on the Database of Topographic Object.

The analysis included the conditions of sunlight for four characteristic dates of the year (the March and September equinox, the summer and winter solstice). The analysis of shading conditions was conducted for the period from 8 am to 4 pm each day, while considering both the vertical and horizontal angle of sunlight. Detailed values of the angles of sunlight and the analysed variants are shown in Table 1. The study includes an 8-hour time interval for the multivariate analysis of angles of sunlight, including two-direction sun movement on the horizon.

Table. 1. The values of the angles of sunlight.

Date	Hour	Horizontal angle (azimuth) [°]	Vertical angle [°]	Date	Hour	Horizontal angle (azimuth) [°]	Vertical angle [°]
March 21	8 am	114	19	June 22	8 am	99	38
	9 am	128	27		9 am	113	47
	10 am	143	33		10 am	131	55
	12 pm	180	39		12 pm	182	62
	2 pm	217	33		2 pm	233	53
	3 pm	232	27		3 pm	250	45
	4 pm	246	19		4 pm	264	36
September 23	8 am	117	20	December 22	8 am	129	0
	9 am	132	28		9 am	141	7
	10 am	148	34		10 am	154	12
	12 pm	185	39		12 pm	182	16
	2 pm	220	31		2 pm	210	10
	3 pm	235	24		3 pm	222	5
	4 pm	249	16		4 pm	234	-

2.3 Methods of analysis

From the LiDAR data in the form of a classified points cloud, and considering only the points belonging to the building class, a digital surface model of roofs in the GRID format was created. The DSM of rooftops (Fig. 4) was created from the points of the first return feature and the maximum cell assignment type was used in the DSM creation process. Although the ISOK points cloud density for the city of Wrocław area is 12 pt/m^2, which would allow building a DSM with a resolution of at least 0.5 m, a rooftop`s DSM with 1 m resolution was created. It was assumed that such a resolution of the model would eliminate the irregularity of roofs` surfaces and roofing elements.

Fig. 4. Rooftop DSM.

The ALS LiDAR data for this area was obtained in 2011. BDOT was developed in 2012–2013, but based on topographic maps made in the 1990s and also orthophotomaps made in recent years. The orthophotomap used in the backgrounds of Fig. 3 and Fig. 4 was made in 2016 and its higher content is obviously visible. In order to eliminate the heterogeneity of data, it was decided that the rooftops DSM be clipped to the extent of the BDOT, due to the occurrence of objects included in the LiDAR data.

In the next steps, the roof slope model and the roof exposition (aspect) model were made using the slope and aspect function in ArcGIS, respectively. The slope and the exposition models have a 1 m spatial resolution according to the resolution of the basic DSM model. The slope of the roofs was divided in the range of 0–90° into 18 classes every 5°. The exposition of roofs was divided into 5 classes according to the azimuth, in the range of 90–270°, from the eastern to western exposition. It was adopted, according to the geographical location of the city, that the sun would never illuminate the roofs of the north, north-east and north-west expositions. The roofs' exposition was divided into the following classes: E (90–112.5°), SE (112.5–157.5°), S (157.5–202.5°), SW (202.5–247.5°), and W (247.5–270°).

Finally, shading models (hillshade function in ArcGIS) with 1 m spatial resolution were made based on the values of vertical and horizontal angles of the sunlight for the 4 characteristic dates (Table 1).

In order to obtain results – the area in a given category, the models were reclassified according to the accepted ranges and the appropriate areas in the given class were counted.

3 Results

For the city of Wrocław, the roofs' area from BDOT is ca. 16.30 km^2, but as a result of the compilation of data from the BDOT and the ALS LiDAR from the ISOK project, the area of buildings' roofs is ca. 11.86 km^2. In Wrocław, the buildings having the largest area are roofs of industrial and economic (3.38 km^2), monuments (2.34 km^2), general, commercial and service (2.22 km^2), then multi–family (2.03 km^2) and single–family (1.79 km^2). Residential buildings comprised of single and multi–family together make up 32% of all roofs. The rest of the objects contained in the BDOT (ca. 4.44 km^2) is not covered by the LiDAR data.

Based on the slope of the roofs on the buildings (Fig. 5) and the exposition models (Fig. 6), the roofs' area were calculated depending on their slope and their exposition (Table 2). Most roofs have a slope of up to 5° (ca. 30%) and 5–10° (ca. 14%). Roughly 53% of the roofs' area are those with a slope of up to 15°. The roofs of the eastern to western exposition (azimuth of 90–270°) is ca. 63% of buildings resulting from the BDOT and LiDAR data compilation. In these terms, the roofs exposition distribution is similar (1.36–1.62 km^2). The remaining roofs have an exposition towards the north (azimuth 0–90° and 270–360°).

Table. 2. Exposition and slope of the roofs.

Exposition	Area [km^2]	Area [%]	Slope [°]	Area [km^2]	Area [%]
N	1.63	14%	< 5	3.58	30.2%
NE	1.35	11%	5–10	1.65	13.9%
E	1.58	13%	10–15	1.13	9.5%
SE	1.36	11%	15–20	0.85	7.2%
S	1.62	14%	20–25	0.74	6.2%
SW	1.36	11%	25–30	0.69	5.8%
W	1.58	13%	30–35	0.66	5.6%
NW	1.38	12%	35–40	0,64	5,4%
			40–45	0.61	5.1%
			45–50	0.44	3.7%
			50–55	0.30	2.5%
			55–60	0.20	1.7%
			60–65	0.13	1.1%
			65–70	0.09	0.8%
			70–75	0.06	0.5%
			75–80	0.04	0.3%
			80–85	0.04	0.3%
			85–90	0.01	0.1%

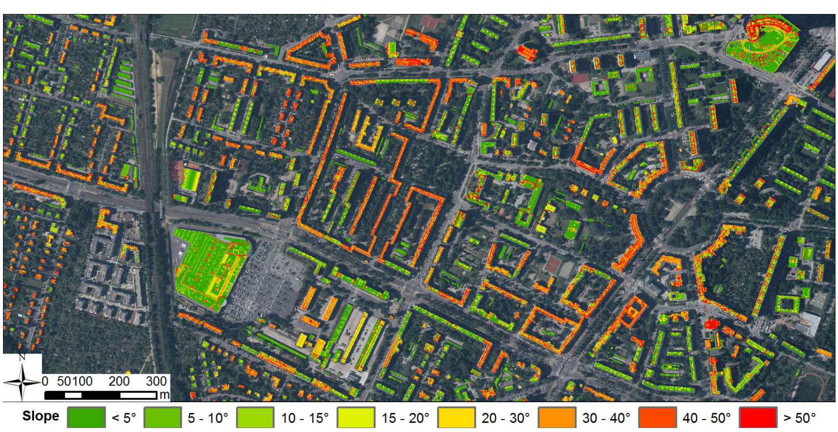

Fig. 5. Slope model of rooftops.

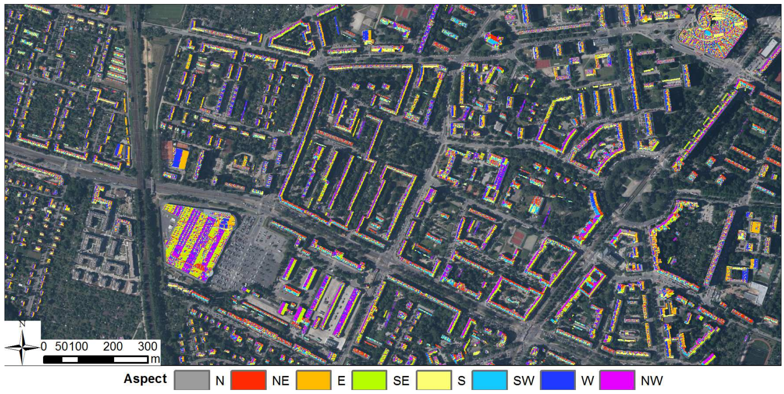

Fig. 6. Exposition model of rooftops.

Based on the rooftop DSM and the data of the angle of sunlight, models of roofs surface shading were created (Fig. 7). Both their own shading as well as that from neighbouring objects is included. The analyses of the shaded and unshaded roof's surface at a given time are summarized in Table 3.

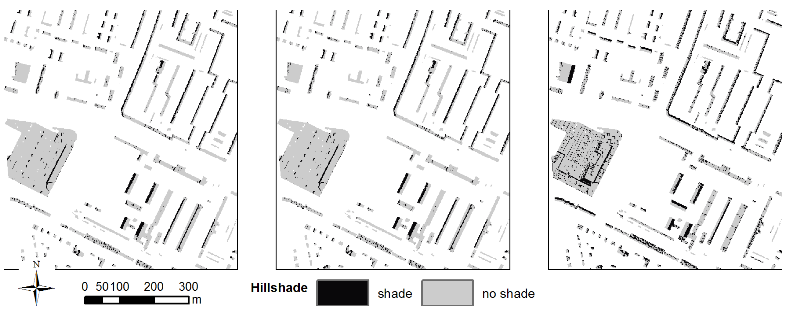

Fig. 7. Shading model of rooftops – March 21, 8 am; June 22, 12 pm and December 22, 3 pm.

Table. 3. Shaded and unshaded roofs surface.

Date	**Hour**	**Shade [km^2]**	**No shade [km^2]**	**No shade [%]**	**Date**	**Hour**	**Shade [km^2]**	**No shade [km^2]**	**No shade [%]**
March 21	8 am	1.49	10.37	87%	June 22	8 am	0.56	11.30	95%
	9 am	1.05	10.81	91%		9 am	0.28	11.58	98%
	10 am	0.76	11.10	94%		10 am	0.15	11.71	99%
	12 pm	0.51	11.35	96%		12 pm	0.08	11.78	99%
	2 pm	0.76	11.10	94%		2 pm	0.16	11.70	99%
	3 pm	1.10	10.76	91%		3 pm	0.31	11.55	97%
	4 pm	1.65	10.21	86%		4 pm	0.64	11.22	95%
September 23	8 am	1.43	10.43	88%	December 22	8 am	6.11	5.75	48%
	9 am	1.01	10.85	91%		9 am	2.93	8.93	75%
	10 am	0.71	11.15	94%		10 am	2.25	9.61	81%
	12 pm	0.51	11.35	96%		12 pm	1.74	10.12	85%
	2 pm	0.86	11.00	93%		2 pm	2.38	9.48	80%
	3 pm	1.30	10.56	89%		3 pm	3.32	8.54	72%
	4 pm	1.89	9.97	84%		4 pm	6.10	5.75	48%

The results were counted for the entire scope of the exposition. As a result of the location of the city of Wrocław it was found that at noon, regardless of the season, over

95% of the roofs' area is unshaded. The exception is winter, when 85% of roofs are unshaded. Generally, in the non–winter period, between 8 am and 4 pm, not less than 84% of the roofs' surface (not less than 9.97 km^2) is unshaded. In winter, this percentage decreases to 48% (5.75 km^2) in the morning and afternoon.

4 Conclusions

The high–resolution LiDAR data can be successfully used to create a DSM of the roofs for urban areas. Thus, the availability of LiDAR data and GIS tools provide the possibility of and ease of data processing and analysis to determine the potential of cities for the installation of PVs panels. GIS analyses provide opportunities for the analysis of metropolitan areas in order to determine their potential, for example in urban development strategies, as well as the analysis of individual objects at the stage of project preparation.

The analysis allowed determining that in a large city with an area of almost 300 km^2, there are over 11 km^2 of roofs, of which over 60% have an exposition favouring the installation of PVs panels, over 50% have a slope (up to 15°) allowing for easy PVs installation, over 30% of buildings are residential buildings.

Favourable exposure promotes better use of available solar energy. The prevalence of roofs with a relatively low slope is predisposed for PVs installed in rows rather than placed directly on roofs – this enables some flexibility when it comes to modules orientation, however reduces the capacity installed per available surface.

Beneficial is also the distribution of available roof surfaces depending on the building type, as the perspective of new PVs installations can be located directly near the sources of energy consumption (industrial facilities, single and multi-family). An analysis of shading conditions indicates that on each day of the year, at least approx. 50% of the roofs' surfaces does not get shade. In the cold season, the area of shade on roofs is smaller.

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