The potential of roofs in city centers to be used for photovoltaic micro-installations

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Abstract. Currently in Poland, power engineering based on hard coal and lignite plays the dominant role. This significantly impedes the attainment of 15% share of energy produced from renewable sources by 2020 and has a negative impact on air quality in Poland. A solution to this unfavourable situation may be to develop renewable dispersed energy with particular emphasis on installations using photovoltaic. Strongly urbanized areas have high electricity demand, and at the same time low availability of areas where it is possible to locate renewable energy sources. In this study, the possibility of using roofs of buildings in city centres for the purpose of photovoltaic micro-installation was analysed. A case study was carried out for two selected districts of the city of Opole. Opole has sunshine conditions which are representative for Poland. The analysis of photovoltaic potential of roofs in urbanised areas was carried out using geographical information systems (GIS). The analysis showed a high photovoltaic potential of the two selected districts of Opole: the potential to generate locally almost 25% of the electrical energy required. The proposed method of determining the photovoltaic potential of roofs in city centres can be used in Polish conditions, as well as in Central Europe.

1. Introduction

As the analysis of the energy market in Poland shows, hard coal and lignite power plants play a dominant role in power engineering. This significantly hinders the ability to achieve by 2020 a 15% share of energy produced from renewable sources [1]. At the same time, such a situation has a very negative impact on the quality of air in Poland, which is considered to be one of the most polluted in Europe.

One of the possible solutions to improve this negative situation could be that of dispersed renewable energy, with a particular focus on installations using photovoltaic cells. Promoting sustainable energy systems, in particular photovoltaics (PV) is recommend to the EU Member States by the EU Directive 2009/28/EC of the European Parliament and of the Council of 23 April, 2009 on the promotion of the use of energy from renewable sources [1]. However, it must be noted that PV involves high investment costs and without the state support (e.g. through a system of subsidies or non-repayable loans) the share of PV in total energy production will fail to increase [2]. Increased share of PV in the national electrical power generation is beneficial for the environment, as it is one of the cleanest methods of electrical power generation. What is more, it is possible to generate energy using PV locally (even in urban areas), without the need to transmit electricity over long distances [3].
Cities, as highly urbanized areas have a high demand for electricity and low availability of land for installation of renewable energy sources. Roofs of high-rise buildings in urban areas are particularly advantageous locations for PV installations, as they are not shaded, e.g. by trees. Flat roofs of residential buildings (or roofs with a slope angle of up to 30º) also allow to position the panels in a most advantageous position so as to obtain the best angle of incidence of sunlight [4]. Therefore, this paper analyses the potential of using the rooftops of buildings in the city centres for micro-installations of photovoltaic cells. The analysis used spatial databases of urban areas [5].

Section 2 presents the research object and the methodology according to which this type of analysis can be carried out using the geographical information system and orthophotomaps. Section 3 presents the results of the analysis of the photovoltaic potential for the case study presented. There will also be proposed a formula for calculating photovoltaic potential (PVP), using coefficients determined during the study. It also presents the average monthly amount of electricity that can be produced in the area under study using a reference polycrystalline panel. The percentage of meeting the area’s electricity demand by photovoltaic installations on roofs of buildings will also be determined.

2. Methods
The methodology of research on the energy potential of roofs in urban area is presented through a case study of two districts of the city of Opole - the Old Town and the City Centre (marked as 1 and 2 in Fig. 1). These districts exhibit building density and geometric characteristics (buildings heights, roof types and their inclinations) typical of medium and large cities in Central and Eastern Europe. Furthermore, the location of Opole is characteristic of sunshine conditions which are representative for Poland.

The analysis of photovoltaic potential of roofs of buildings was made using geographic information systems (GIS), which is a widely used solution used by researchers to analyse geographical areas [6,7]. The distribution of rooftops in the area of the two administrative districts of the city of Opole was executed in several stages. In the first stage, a field inspection was carried out in order to identify the types of roofs used for buildings in this part of Opole. Shed and gable types of roofs were taken into account, which were further classified as:

a) flat or almost flat roofs (with a small, minimum pitch), and roofs with an inclination angle of up to 30º;

b) steep roofs with an inclination angle > 30º.

An initial mapping of the terrain location of rooftops of the specific type was carried out on the working base of the orthophoto map.

The next stage was site-specific works where an orthophoto map base was prepared (for two districts whose borders were marked) in the ArcGIS program, the ArcInfo v.10.6 package using the WMTS service from the Spatial Information System of the City of Opole [8], setting the coordinate system as mapped, rectangular, PUWG 1992 (EPSG 2180). The orthophoto map was covered with a layer of buildings obtained from the basic map in order to precisely determine the location of the buildings. On the underlay prepared in this way, the screen vectorization of the outlines of flat roofs and roofs with an inclination angle of up to 30º was carried out, trying to eliminate the fragments unsuitable for use in PV installations. Analysis of the roof inclination was made with the help of pictures available in the public domain [9]. Oblique aerial photographs of the study area of Opole were used, available on the website www.ukosne.pl [10], as well as the results of field research in the analysed area.

On-site inspections of selected roofs were also carried out in the selected districts of Opole in order to determine the average share of the active roof area. i.e. the area permitting installation of photovoltaic panels [11]. Those analyses took into account the shape of the roof, the orientation, and the building facilities located on the roof surface [12]. For the purpose of the research, 50 buildings, typically built in the city centre, with different architectural arrangements of roofs were selected as a representative sample in each analysed district.
In order to be able to determine the amount of electricity that can be produced on rooftops in the city centre using photovoltaic panels (for the conditions of sunlight typical of Opole), research was carried out for a period of 1 year. During the studies, the average monthly value of solar radiation intensity was determined with the use of a pyranometer LB-900 [13]. At the same time, a reference polycrystalline photovoltaic panel with a capacity of 250 Wp and dimensions of 1650 x 990 mm was used to measure the average monthly amount of electricity produced by a single PV panel on one of the rooftops located in the area under study (on one of the buildings of the University of Opole).

3. Results and discussion

As a result of field research and analysis with the use of geographic information systems (GIS), for the two districts of Opole, types of buildings’ rooftops were selected allowing installation of PV panels to ensure efficient production of electricity. Rooftops with the potential for arrangement of photovoltaic micro-installations (flat roofs, or roofs with an inclination of up to 30°) in the centre of Opole (within the areas under study marked in blue) are marked red in Figure 1.

![Figure 1. Distribution of roofs suggested for the PV installations in the area of districts: 1 - the Old Town, and 2 - the City Centre in Opole.](image)

For the districts of the Old Town and the City Centre, the numbers of flat roofs or roof slope inclination up to 30°, with the potential for PV panels' installation, were determined. Their total area, as well as the average area of a flat roof in each district were determined. For each district, the district area, and the total surface area of all roofs measured by their outlines were also determined. The results are shown in Table 1.

As can be seen in Table 1, in the districts under study in Opole, whose area in total is 463.26 ha, there are 2399 buildings with flat roofs, or roof slope inclination up to 30°. It can therefore be assumed
that these buildings, with a total rooftops area of 532700 m² have the potential for photovoltaic installations.

Table 1. The number and surfaces areas of rooftops with potential for PV installation in the centre of Opole

| The Old Town                                      |          |          |
|--------------------------------------------------|----------|----------|
| Surface area of flat roofs, and up to 30° [ha]   | 23.46    |          |
| by the outline of the building                    |          |          |
| Surface area of all roofs [ha]                   | 32.79    |          |
| Average roof area [m²]                           | 206.37   |          |
| District surface area [ha]                       | 173.09   |          |
| Number of flat roofs                             | 1137     |          |

| The City Centre                                   |          |          |
|--------------------------------------------------|----------|----------|
| Surface area of flat roofs, and up to 30° [ha]   | 29.81    |          |
| by the outline of the building                    |          |          |
| Surface area of all roofs [ha]                   | 49.53    |          |
| Average roof area [m²]                           | 236.22   |          |
| District surface area [ha]                       | 290.17   |          |
| Number of flat roofs                             | 1262     |          |

In order to estimate the rooftops' PV potential, an indicator was proposed to determine the amount of electricity that can be generated on the roofs of PVP buildings (photovoltaic potential), which can be determined from the equation (1):

\[ PVP = \sum_i \left( A_{EI} \cdot RA_i \right) \cdot E_y \ [kWh/y] \] (1)

where: 
- \( A_{EI} \) - efficiency factor of the roof surface [-].
- \( RA \) - the area of rooftops by the outline [m²],
- \( i \) - roof type: flat, or with a slope inclination up to 30°,
- \( E_y \) - the yearly production of electricity for 1m² surface of the PV panel [kWh/m²•y].

The proposed efficiency factor of the roof surface \( A_{EI} \) is expressed as a percentage of the active surface of the roof, i.e. permitting installation of PV panels. Based on the statistical analysis of the results obtained during field studies in both districts, it was established that the coefficient for flat roofs \( A_{EI} \) is 0.74, and for roofs with slope inclination up to 30°, it is 0.26.

In order to determine the value of \( E_y \) for sunlight conditions characteristic for Opole for a period of one year, the intensity of solar radiation was measured so as to determine the average values for individual months. The results (shown in Figure 2) were compared with the monthly average values of solar radiation determined through measurements carried out for a period of 10 years at Legnica actinometrical station (closest to the city of Opole). The comparison showed high correspondence (characterized by the determination factor \( R^2 = 0.93 \)), which meant the determined monthly mean values of the intensity of solar radiation were reliable.

A study was also carried out on the amount of electricity that could potentially be generated yearly by a reference PV panel installed on a rooftop in the centre of Opole (in the Old Town district). Based on the analysis of the production of electricity by a power 250 Wp polycrystalline panel (using 1.63 m² of the roof surface), a chart of electricity production in different months of the year was drawn up (shown in Figure 2).

Based on the data from the actinometrical station in Legnica, it was assumed that the average insolation, i.e. the number of sunny hours per year in Opole is 1765 hours. For insolation conditions in the area under analysis, the annual electricity production value for 1m² of PV panel area, \( E_y \), was determined as 161.96 kWh/m²•y.
As a result of the research, the amount of electricity that can be generated on the rooftops of residential buildings $PVP = 30714288.75$ kWh/y was determined for the two selected districts in the centre of Opole.

![Figure 2. Average monthly electricity yield by 1 panel - 250 Wp and average solar radiation intensity.](image)

For the number of inhabitants of the analysed districts, determined on the basis of statistical data obtained from the Town Hall of Opole, the average annual electricity demand for residential buildings was estimated for two selected districts of the city centre. For the purpose of the analyses, standard values (for multi-family residential buildings) of electricity demand were adopted for the following purposes: lighting, heating, hot water heating, and power supply for household appliances and consumer electronics [14]. The analysis conducted led to the conclusion that the potential of electricity generation on the rooftops in the two selected districts in the centre of Opole can meet the electricity demand of residential buildings up to almost 25%.

The above research methodology can make an integrated assessment tool for researchers, investors or local authorities in implementation of energy policy in the urban areas.

4. Conclusions
In the course of the study, the following were determined: the values of the efficiency coefficient of roof surface - $A_E$, roof surface with the potential for PV installations - $RA$, as well as the yearly electricity production for $1m^2$ area of the PV panel - $E_y$ for local conditions in the centre of Opole (as the reference object for south-western Poland).

The research and analysis of the results showed a high photovoltaic potential in the two selected districts of Opole. The PV potential value was determined, expressed as the amount of electricity which can be produced on the rooftops of residential buildings in the two districts in the centre of Opole, $PVP = 30714288.75$ kWh/y. This leads to the conclusion that there is a possibility of producing locally nearly 25% of the electricity consumed by residential buildings in the area under study.

The study also showed that the proposed methodology for assessing the rooftops for their photovoltaic potential in various city districts can be used in other urban areas by extrapolating local estimates and spatial databases of urban areas. The proposed method can be used both in Polish conditions and in other countries of Central and Eastern Europe.
Local electricity production (using PV installations on the buildings’ rooftops) allows to reduce air pollutants which are emitted by conventional power plants using hard coal or lignite; this can positively influence the improvement of air quality in Poland.

This paper does not analyse the issue of storage of electricity generated, assuming that these issues remain to be decided individually by each property administrator. In addition to local energy storage, it is also possible to transfer the generated energy to the grid, and then to offset the transferred energy against the consumed energy as part of settlements with the local energy distributor.

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