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THE USE OF PHOTOVOLTAIC MICRO-INSTALLATIONS IN SELECTED REGIONAL CITIES IN POLAND

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ABSTRACT: The aim of the paper is to assess the use of RES, i.e. solar energy (through investment in PV installations) in selected regional cities in Poland. We focused on the area of five regional capital cities, selected in terms of representativeness and fulfilling regional administrative or administrative and self-governmental functions. The research hypothesis is that installations are mainly mounted on new buildings, while income is a factor that determines the choice of PV. The methodological part features an analysis of the literature in the selected area. This was followed by an analysis of the statistical data available in the public statistics (Statistics Poland's data) and on the basis of primary data collected from the main electricity distributors (Tauron Dystrybucja S.A. and ENEA). The data for the analysis comes from before the COVID pandemic and the war in Ukraine, as these were characterised by a relative stabilisation of electricity prices and consumption in Poland. A correlation analysis based on the Pearson coefficient was carried out to investigate a possible relationship between the number of micro-installations in the cities reviewed and the other variables. An econometric model was built to analyse the variables studied, which have a significant impact on the number of PV micro-installations in the urban areas studied. The article fills a gap in the literature concerning the identification of conditions responsible for location preferences for renewable energy in the existing settlement patterns of fast-growing cities, dispersed in external zones, as well as in the urbanising rural environment. Research on prosumer energy in these areas is completely new. An in-depth analysis of the behaviour of prosumers and their preferences regarding photovoltaic installations may be the basis for optimising the economic instruments used in Poland to encourage investment in renewable energy sources.

KEYWORDS: renewable energy, solar energy, photovoltaic micro-installations, cities policy, urban development

Introduction

It is estimated that almost 70% of the world's population will live in cities by 2050 (United Nations, 2018). Cities, especially the largest ones, are economic drivers and have a positive impact on labour-market processes. For this reason alone, their development should be of particular importance to the country as a whole.

Creating the right conditions for living and doing business in cities requires the right energy input. In Poland, coal is still the most important raw material for electricity generation (Bankier.pl, 2021). Adamkiewicz and Matyasik (2019) note that both coal and wood are widely used, including for the direct heating of single-family homes, which contributes significantly to a high level of so-called low-stack emissions.

In 2012, Poland implemented Directives of the European Parliament and of the Council (Directive, 2004; Directive, 2008) important in the topic of pollution reduction. The ordinance sets pollution standards applicable in Poland, which are identical to those in force in the European Union, although for PM10 and PM2.5 particles, they are higher than those recommended by the WHO (2006).

Table 1. Permissible pollution levels in Poland (EU) and pollution levels suggested by the WHO

L.p.	Chemical Abstracts Service Registry Number (CAS)	The averaging period for measurement results	Permissible levels of substances in the air Poland/EU	Permissible levels of substances in the air WHO
1	Suspended particulate matter PM 2.5	Calendar year	25 $\mu\text{g}/\text{m}^3$	10 $\mu\text{g}/\text{m}^3$
2	Suspended particulate matter PM10	Calendar year	40 $\mu\text{g}/\text{m}^3$	20 $\mu\text{g}/\text{m}^3$
3	Benzo(a)pyrene(b) (50-32-8)	Calendar year	1 ng/m^3	

Source: authors' work based on Directive (2004) and Directive (2008).

Kuchcik and Milewski (2018) found that, in general, each air pollutant has a negative impact on human health, but benzo(a)pyrene (B[a]P), which is recognised as the determinant of all PAHs (polycyclic aromatic hydrocarbons) in Poland, is the most carcinogenic and toxic compound. Its main sources are the use of coal for individual heating (especially in detached houses), biomass and uncontrolled waste incineration. B[a]P is also found in cigarette smoke, diesel exhaust, grilled food and industrial waste.

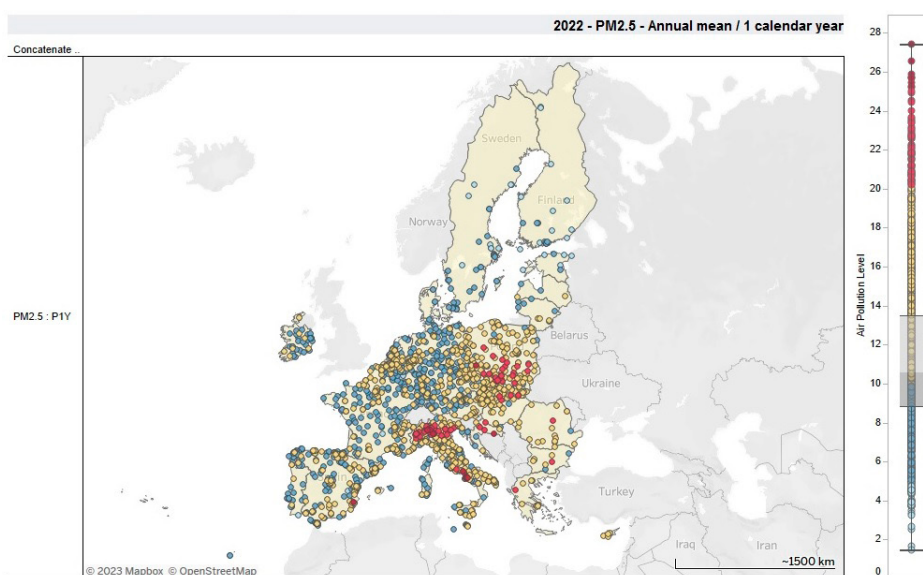


Figure 1. PM2.5 in EU (annual/1 calendar year)

Source: EEA. Air quality statistics. <https://www.eea.europa.eu/en/analysis/maps-and-charts/air-quality-statistics-dashboards> [02-02-2024].

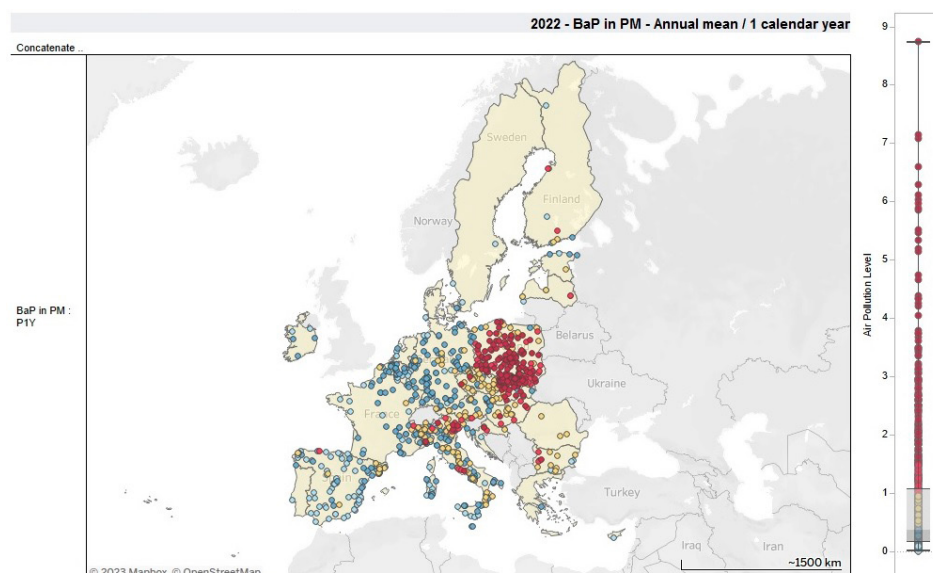


Figure 2. Benzo[a]pyrene in PM in UE (annual / 1 calendar year)

Source: EEA. Air quality statistics. <https://www.eea.europa.eu/en/analysis/maps-and-charts/air-quality-statistics-dashboards> [02-02-2024].

Poland is one of the most polluted countries in Europe. According to the European Environment Agency (EEA), Poland has the highest exceedance rates, especially for B[a]P (Figure 1). For other compounds, such as PM_{2.5}, Poland has average exceedances (Figure 2).

For some time, attention has been drawn to the association between exposure to B[a]P and lung cancer incidence. This association has been demonstrated and extensively described in the literature (Widziewicz et al., 2017; Porwisiak et al., 2023; Bukowska et al., 2022). B[a]P can chemically influence the modification of genetic material (epigenetics), breast cancer cells and cancer cells in general (Bukowska & Sicińska, 2021). One of the main reasons is the burning of coal and banned substances. Some case studies from Poland show that public authorities reflect health issues in strategic documents, but they are relatively seldom related to the issue of environmental changes (Klemens, 2024).

Achieving climate neutrality by 2050 will require a transformation of the energy sector. The energy transition is becoming a crucial and necessary driver for changes in the economy, technology and social behaviour. The Paris Agreement, signed by EU member states in December 2019, requires the implementation of policies that support societal engagement in this process (Burningham et al., 2015; Zecca et al., 2023). We are currently witnessing a shift from viewing society as passive consumers of centralised energy systems to inclusive citizen energy (Rabe et al., 2023), which stems from the theory of energy citizenship (Ryghaug et al., 2018). Azarova et al. (2019) note that state-owned energy companies are no longer the sole producers of energy, but are beginning to share this activity with citizens. Devine-Wright (2007) states that citizen energy is manifested in the use of renewable energy technologies in the energy market with active participation of citizens, whether acting independently or in groups.

An alternative to conventional energy sources is the use of Renewable Energy Sources (RES), which include solar, wind, hydro, geothermal and biomass. RES are seen as an opportunity to combat the negative effects of climate change, reduce smog levels, reduce low-level emissions, protect natural and environmental resources and promote sustainable development. Climate policy anticipates a significant increase in the use of renewables in energy production by 2030 (Güney, 2022; Directive, 2018). Renewable energy sources are characterised by very low or zero pollutant emissions.

In general, the potential to use renewable resources depends on a number of factors, including: a) geographical factors, such as altitude, slope, urban extent, population distribution and proximity to the electricity grid; b) meteorological factors, e.g. solar radiation, average temperature; c) location factors, e.g. distance from urban areas (Szewczyk & Szeliga-Duchnowska, 2022).

Kurowska et al. (2022) also argue that the energy sector has become an important topic of public debate in Poland in recent years. According to Poland's Energy Policy Until 2040, more than 50% of

installed electricity will be generated from emission-free sources by 2040. However, due to the legal and political conditions in Poland, there is still a lot to be done in the field of renewable energy. Kurowska et al. (2022) identify the main barriers to the development of renewable energy as limited funding, lack of legal support, complex administrative procedures, insufficient capacity of the national grid, lack of support mechanisms, environmental barriers, urban sprawl and mentality. The renewable energy market in Poland is booming, aided by programmes providing financial support for the installation of renewable energy sources in single-family homes (Kuźmiński et al., 2023), and solar energy plays a key role (Szewczyk & Szeliga-Duchnowska, 2022), but the potential of solar energy has never been fully exploited.

Micro-scale PV installations (on single-family homes or small buildings) not only replace traditional heating systems (coal, wood) that contribute to urban pollution, but also make residents less dependent on solid fuels, reducing maintenance costs, improving quality of life and reducing energy poverty.

In general, a factor hindering PV deployment and development is the increasing dispersal of buildings in larger cities and their surrounding rural areas: a) limited roof areas suitable for PV installation, b) lack of large-scale PV areas due to the dispersal of buildings. Rabe et al. (2022) state that the problem of dispersed development or inadequate grid can be solved by energy storage systems, but in Poland, these are still inefficient and very costly, far beyond the financial capacity of individual investors in Polish conditions.

As theoretical studies have shown, low emissions and compliance with climate policy goals associated with the deployment of renewable energy depend heavily on small-scale investments that are decentralised but not dispersed within the settlement pattern. They are located in both urban and rural areas (Streimikiene et al., 2021; Blaszkę et al., 2021), and compact settlement structures enable the resolution of local energy storage and transmission-network operation issues, as well as the optimisation of local and regional renewable energy supply needs. In particular, the article fills a gap in the literature regarding the identification of determinants that account for locational preferences for renewable energy in existing settlement patterns of rapidly developing cities scattered in outer zones, as well as in urbanising rural environments (suburbanisation and semi-urbanisation) (Heffner & Twardzik, 2022; Heffner, 2016). Addressing the locational determinants of the complex issues related to the development of renewable energy in cities and their urbanising rural surroundings should initiate a debate on shaping the spaces associated with urban centres towards reducing electricity demand, limiting emissions, reducing energy network operating costs, and achieving local self-sufficiency of urban and suburban communities in energy management.

Many studies focus on the role of energy clusters, the creation of urban cogeneration (CHP) systems and the importance of prosumers in distributed energy (Hansen et al., 2022; Worek et al., 2021; Kordas et al., 2019; Adamek et al., 2018; Błażejowska & Gostomczyk, 2018; Sołtysik et al., 2018). Numerous works focus mainly on issues related to social acceptance, stimulation of local and regional energy consumers' interest in renewable sources, organisation of production and consumption, creation of communities (Becker et al., 2017), introduction of innovations, massification of their use and production, as well as economic and environmental impacts of these phenomena (Lazanyuk et al., 2023; Mir-Artigues & del Rio, 2021; Wittmayer et al., 2021).

Lorek (2011) and Lorek (2019) note that attention is often drawn to the importance of legislative solutions that effectively block both the application of the latest RES technologies and the modernisation of already operating sources. The instability and impermanence of legal and economic solutions related to individual production and consumption of renewable energy, as well as support mechanisms for the renewable energy system, result in significant fluctuations in interest in them.

In addition, the generally poor technical condition and operational problems of transmission and distribution infrastructure exacerbate the difficulties associated with the need to invest in networks to connect new, dispersed renewable energy sources (Rabe, 2018).

The purpose of this paper is to assess the use of renewable energy, namely solar energy (through investment in PV installations), in selected voivodeship cities in Poland. The research hypothesis is that the installations are mainly installed on new buildings, while income is a factor determining the choice of PV.

The detailed analysis focuses on the area of five voivodeship cities in Poland, selected in terms of representativeness and fulfilling regional administrative or administrative and self-governing func-

tions. A correlation analysis based on the Pearson coefficient was carried out to investigate a possible relationship between the number of micro-installations installed in the cities studied and the other variables (i.e. average monthly salary, total number of micro-installations). An econometric model was built to identify of the variables studied which have a significant impact on the number of PV micro-installations in the urban areas analysed.

Risks in Urban Development Related to Energy Supply – Literature Review

Urban development is a multi-dimensional and complex process influenced by various stakeholders and potential factors. Forecasting and planning processes should be based on skilfully identifying changes, identifying risks and creating scenarios to counteract and transform negative processes.

In urban development, in addition to endogenous factors, such as technological innovation (Gorzelak, 2000; Zygmunt A., 2017), entrepreneurship (Zygmunt J., 2017), leadership authority (Tuziak, 2016) or public participation (Sowada, 2019), it is important to make decisions for the benefit of environmental quality, such as the improvement of local climate, the expansion of urban green areas, the reduction of: low-level emissions, heat islands, smog, etc. (Budner & Gorynia, 2021). The research conducted demonstrates the impact of environmental and energy factors on regional sustainable development (Klemens et al., 2022).

Urban areas are responsible for significant GHG emissions. The IPPC report (Seto et al., 2014) provides estimates of the contribution of cities to GHG emissions. According to the International Energy Agency (2008) and Mitchell et al. (2022), urban emissions accounted for 71% of total emissions in 2006. In addition, dispersed suburban areas often have significant emissions and exceedances of many pollutants, commonly referred to as smog, due to the use of fossil fuels for heating. Residents in these areas often have to rely on personal transport due to poor transport links. According to IRENA (2016), cities are responsible for more than two-thirds of global energy consumption and a corresponding amount of CO₂ emissions. Decarbonising urban energy consumption is crucial to reducing local air pollution (Coninck et al., 2018), and this process cannot be achieved without renewable energy.

Phdungsilp (2009) notes that the carbon footprint of individual cities depends on many variables, including the level of industrialisation, spatial structure of cities, level of socio-economic development, income of residents, lifestyle, functions performed, transport system, energy and heating system, and local climatic factors. Zusman et al. (2012) suggest that municipal authorities can implement or promote more efficient urban, transport or network systems through legal regulation. Colenbrander et al. (2015) argue that changing mindsets and complying with legal restrictions can help developing cities avoid higher development costs due to higher carbon dioxide emissions.

Typically, electricity supply for cities is provided by external (off-site) generation, mainly due to the need for appropriate transmission and distribution lines for power-plant operation, and negative environmental impacts such as gas emissions (Breeze, 2017). In order to avoid these drawbacks, the generation of electricity in units located within the city area is advocated, while at the same time applying restrictions aimed at environmental protection, such as the use of PV on building roofs, industrial roofs, car parks and other available urban spaces (Katic, 2022), such as shopping centres or industrial service areas.

Rooftop PV systems can be considered the most common form of solar energy production in cities (Aslani & Seipel, 2022; Fakhraian et al., 2021). Some analysis of effective solar installation with the solar potential from rooftops was made, and the findings of the study suggest that there is great potential hidden on the rooftops of the city, which can be utilised to assist the power systems of the city in the long run for a more sustainable future (Ranjgar & Niccolai, 2023).

The implementation of PV systems in cities is generally analysed in the context of individual installations (Lee et al., 2018; Schunder et al., 2020; Martens, 2022), but also installed by solar communities (Nuñez-Jimenez et al., 2023). According to studies by Nuñez-Jimenez et al. (2023), allowing urban communities to use solar energy could significantly increase PV deployment. One obstacle to this process is legal regulations that limit the use of PV in certain urban areas.

One of the most important issues in identifying risks in the development of modern cities is energy security, especially in the context of the ongoing war in Ukraine. Energy security can be described as the absence of threats to the continuous supply of energy (Ang et al., 2015). It is important to ensure adequate resources, means and processes that could guarantee energy supply in case of disruption of production sources (Kryszk et al., 2023) and management of the energy produced (Giglio et al., 2023). Mišík (2022) and Gatto (2022) understand energy security as the absence of concerns about the continuity of electricity supply, the ability to supply energy independently, stable energy in transmission networks, and resources that ensure energy self-sufficiency. An alternative is to move away from expensive fossil fuels and towards renewable energy. Kryszk et al. (2023) state that photovoltaic (PV) systems are the most popular renewable energy sources in Poland.

Energy security is an issue that is closely linked to the phenomenon of blackouts, which particularly affects cities. Krings (2020) highlights that critical infrastructure in cities, including hospitals, power plants, district heating, water and wastewater systems, transportation, and large enterprises, is highly vulnerable to power outages. The inclusion of individual PV systems in energy production can counteract the long-term effects of large-scale blackouts (Knodt et al., 2023). The involvement of citizens in energy production for common needs can be considered in the context of the common-good phenomenon (Salzano, 2013; Ostrom, 1990; Ostrom, 2008; Czornik, 2020; Heffner et al., 2022).

Decentralised energy systems in cities can be based on energy storage, which would support the balancing of supply, demand and energy supply, as well as supporting traditional energy systems during periods of increased renewable energy production and reduced consumption (Bögel et al., 2021).

According to Heffner et al. (2022) and Heffner (2017), Polish cities, including those with functional areas, are not sufficiently competitive in terms of economic innovation, functional links, infrastructure or organisation. Urban potential is not sufficiently used in regional development processes, especially in peripheral and problem areas.

Sobol (2007) suggests that an important determinant of the competitiveness of urban centres is well-developed urban spaces, as they shape the image of cities and are a magnet for new residents, tourists or investors. However, contemporary urbanisation processes in Poland are characterised by suburbanisation, re-urbanisation, increasing spatial chaos (Heffner et al. 2022) and urban sprawl.

From a technical, construction, legal and economic point of view, single-family houses were the best locations for the installation of PV systems in Poland during the reporting period (Kuźmiński et al., 2023). In multi-family dwellings, such installations for apartments would require significant intervention in the building structure, and municipalities/building managers rarely grant permission for such measures. Economic support schemes and subsidy programmes did not provide funding for installations on large multi-family buildings.

The most popular instruments, such as the “My Electricity” programme (mojprad.gov.pl) and the thermal modernisation subsidy, excluded PV installations in non-residential buildings. Legal solutions in Poland are unstable and are constantly being adapted to the current situation and policy through continuous amendments.

On the other hand, scattered PV installations, especially when operating on old, overstretched and inefficient power grids, can cause more failures and “shutdowns” of transmission grids. The following can increase the risk of issues:

- a high number and high output of micro-installations in an area supplied from a single substation,
- micro-installations located at a considerable distance from supply substations,
- low energy demand during hours of maximum insolation (Halama & Majorek, 2022).

Despite attempts to address the problem comprehensively with selected instruments, special caution should be exercised in Central European countries, which are at a very early stage of developing new forms of electricity supply. For example, although the installation of energy storage systems can reduce the economic and environmental costs associated with the forced expansion of power lines in areas affected by urban sprawl, they are very expensive and not yet efficient enough (the technology is still in its early stages of development) to make individual investments in renewable energy attractive.

In the EU as well as in Poland, the development of renewable energy has been widely and exhaustively studied (Jäger-Waldau et al., 2011; Mac Domhnaill & Ryan, 2020). Changes in energy systems

in smart cities are being studied (Wyrwicka et al., 2023). Available studies address the development of renewable energy worldwide and consumer behaviour (Dąbrowska et al., 2023; Grębosz-Krawczyk et al., 2021; Piekut, 2021). The impact of the “My Electricity” programme on the development of photovoltaics for the entire country was also examined (Kulpa, 2022). Few surveys are carried out for separate areas of provinces and local governments (Klepacka & Zalewska, 2016; Kocur-Bera, 2024).

This is because aggregated data on the development of photovoltaic installations at the supra-national and national level are relatively easily available in Europe (Eurostat) and in Poland (CSO). However, there is a lack of data at the urban and rural levels, which significantly hinders reliable analyses.

The article fills a gap in the literature regarding the identification of conditions responsible for locational preferences for renewable energy in existing settlement patterns of fast-growing cities, dispersed in outer zones, and in urbanising rural settings. Research on prosumer energy in the areas in question is a complete novelty. An in-depth analysis of prosumers’ behaviour and preferences for photovoltaic installations can be the basis for optimising the economic instruments used in Poland to encourage investment in specific areas.

Materials, Research Methods and Sample Selection

The research consisted of two parts: preparation for empirical research and empirical research (Figure 3).

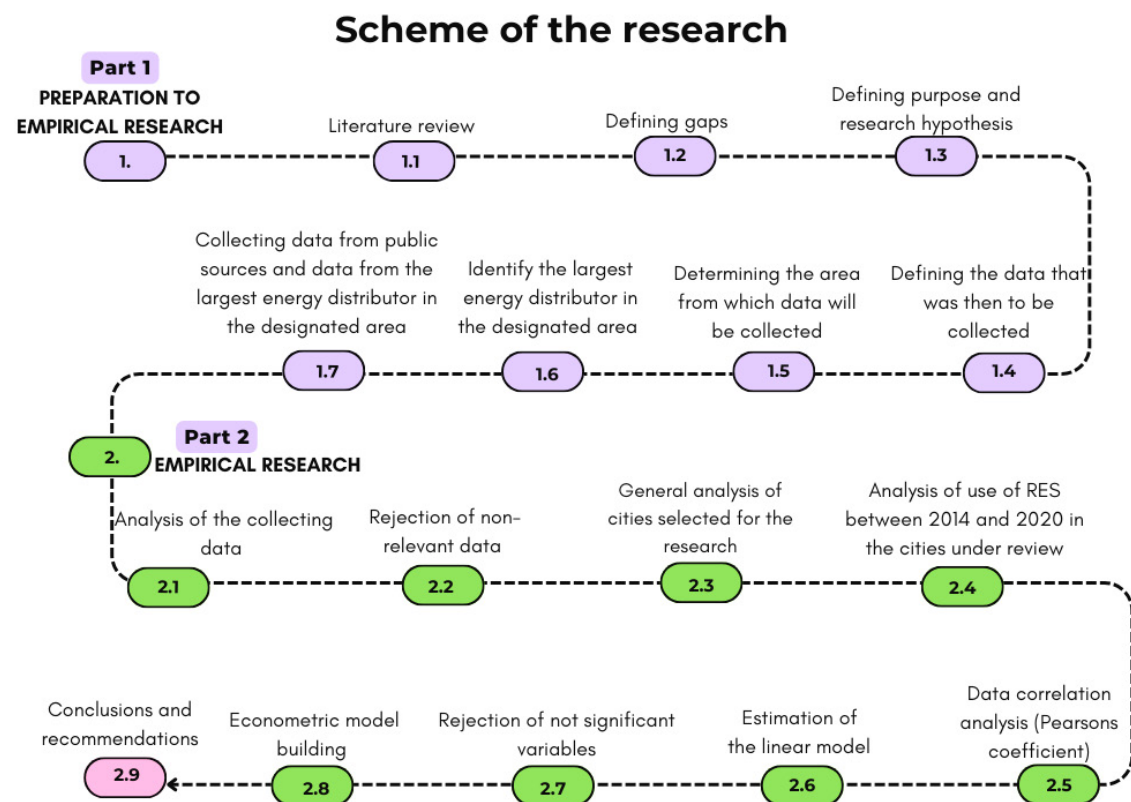


Figure 3. Scheme of the research

The literature review focused on issues related to achieving climate neutrality by 2050 and the importance of renewable energy sources in this process. There was a particular focus on the issue of micro photovoltaic installations and urban development related to energy supply. The literature review made it possible to define the research gaps in this area and, consequently, to define the research objective and research hypotheses.

The purpose of this paper is to assess the use of RES, i.e. solar energy (through investment in PV installations) in selected voivodeship cities.

The research hypothesis is that installations are mainly installed on new buildings, while income is a factor determining the choice of PV. The following assumptions were made:

- the installation of photovoltaic panels is associated with interventions in the building fabric, which means that buildings under construction are the most suitable for such installations;
- legal and economic conditions favour single-family houses (i.e. those with a maximum of dwellings in a building);
- the design of the financial instruments at the time was based on the premise that the investor would first finance all the expenditure and then, after approval and verification of eligibility, the relevant amounts would be reimbursed.

The next step was to define the data necessary for the empirical analysis and to define the geographic area to which the data were to apply. Once the area was narrowed down, the focus was on identifying the main electricity distributors serving the cities studied, and then approaching these distributors indicated by the data.

The research was conducted on a group of five cities in western and southern Poland, which perform regional administrative or self-governing functions and represent the same level in the hierarchy of the spatial settlement system (for their distribution in regional arrangements, see Figure 4). The selection of urban centres for the study is purposeful, as it mainly includes cities with an administrative function (the funding and investment paths using external funds subject to evaluation processes converge in regional institutions located in these cities). The centres selected for the study are large cities (all with more than 100,000 inhabitants) and are highly diversified in terms of population and social and economic potential. The selected sample is therefore diverse in terms of potential – two centres are metropolitan (Poznań, Szczecin), two others are part of metropolitan systems (Katowice, Bydgoszcz), and one (Gorzów Wielkopolski) is a regional centre. In addition, the research sample takes into account both the comparability and the accessibility of the data collected.

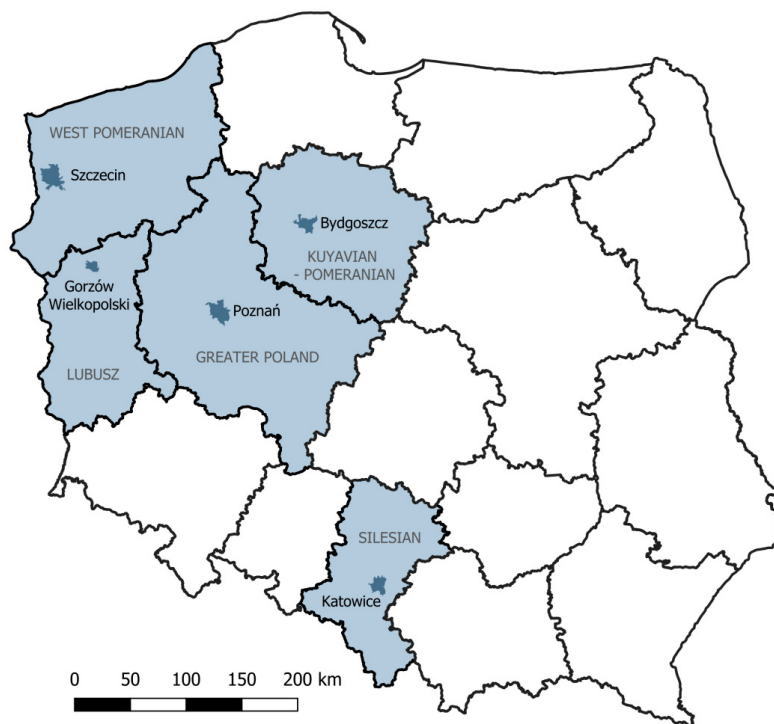


Figure 4. Location of the urban centres under review within the administrative borders of the voivodeships in Poland

It is worth noting that the territorial-administrative system of Poland has two voivodeship-level centres, each in two voivodeships (Kuyavian-Pomeranian and Lubusz), of which centres with the seat of government administration (Bydgoszcz and Gorzów Wielkopolski) were selected for the study, and cities with the seat of local self-government (Toruń and Zielona Góra) were omitted (Heffner & Gibas, 2016).

The main electricity suppliers operating in the study area were identified as Tauron Dystrybucja S.A. and ENEA, which posed an additional challenge as they are different companies collecting data in different formats. For the planned analysis, it was decided to collect data from the period pre-dating the COVID pandemic and the war in Ukraine, as these periods were characterised by a relative stabilisation of electricity prices and consumption in Poland.

In April 2021, in accordance with the Access to Public Information Act of September 6, 2001, requests were made to Tauron Dystrybucja S.A. and ENEA for data on the number of ordinary and “two-way” meters installed, broken down by: a) year from 2015 (base) to 2020, and b) by municipality, as well as c) by individual and company. Unfortunately, due to the spatial dissimilarity of the data (the operators in question only had data from the so-called distribution areas) and after anonymising the data, it was possible to consolidate it at the district level. Data were obtained on the total number of subscribers and prosumers (i.e., owners of PV micro-installations) from 2014 to 2020. Data acquisition lasted from April 2021 to September 2021. In addition, data was collected from public sources, such as: the national public statistical database (Statistics Poland), Topographic Objects Database (geoportal.gov.pl), etc.

After collecting all the data, a selection was made, and non-relevant data was discarded. General analysis of cities selected for the research included: a) main characteristics, such as population, population density, poviát revenue per capita, average monthly salary, electricity consumption; b) residential structure, in particular single-family houses. An analysis was also made of the use of RES between 2014 and 2020 in the cities under review.

As a next step a correlation analysis based on the Pearson coefficient was carried out to investigate a possible relationship between the number of micro-grids installed in the cities under study and the other variables, i.e. municipal revenue per capita, energy consumption per capita and the number of building permits issued. The Pearson correlation coefficient was calculated using the following formula:

$$r_{x,y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (1)$$

where:

x, y – random variables with continuous distributions,

x_i, y_i – random sample values of these variables ($i = 1, 2, \dots, n$),

$\bar{x}, \bar{y}$ – average values of these samples.

An attempt was then made to build an econometric model based on the data to determine the direction of change in the cities when PV is implemented on a larger scale. Three explanatory factors were included in the model: municipal income per capita, energy consumption per capita and the number of building permits.

The classical method of least squares was used to estimate the structural parameters of the linear model.

The detailed analysis involved in building the econometric mainly consisted of estimation of the linear model, rejection of not significant variables and econometric model building. The purpose of building the econometric model was to identify which of the variables studied have a significant impact on the number of PV micro-installations in the cities analysed. The degree of fit of the model to the empirical data was evaluated by estimating the standard error of the residuals calculated according to the formula:

$$S_e = \sqrt{\frac{\sum_{i=1}^n e_i^2}{n - (k + 1)}} \quad (2)$$

where:

e_i – the value of the next non-standardised prediction error in the regression model,

n – number of observations.

An assessment of the degree of explanation of Y variation was made using the R^2 coefficient of determination. It is calculated from the formula:

$$R^2 = \frac{\sum_{t=1}^n (\hat{y}_t - \bar{y})^2}{\sum_{t=1}^n (y_t - \bar{y})^2} \quad (3)$$

where:

y_t – the actual value of the variable Y at time t,

$\hat{y}_t$ – theoretical value of the explained variable (based on the model),

$\bar{y}$ – arithmetical mean of empirical values of the explained variable.

In verifying the constructed model, an assessment of the normality of the residual component was carried out. The Jarque-Bera goodness of fit test was used for this assessment. In this test, the null hypothesis H_0 that the random components have a normal distribution is established.

The value of the Jarque-Bera test statistic is determined from the measure of skewness S and kurtosis K according to the formula:

$$JB = \left[\frac{S^2}{6} + \frac{(K-3)^2}{24} \right]. \quad (4)$$

Measures of skewness and kurtosis are determined using the second, third and fourth central moments μ from the formulas:

$$S = \frac{\mu_3}{\mu_2^{3/2}}; K = \frac{\mu_4}{\mu_2^2}. \quad (5)$$

As part of the model verification process in the econometric model building, the homogeneity of the variance of the random component, also known as the heteroscedasticity of the random component, was also assessed. This assessment was carried out in the Gretl program using the White test. This test checks the significance of the regression obtained for the squares of the residuals with a set of variables from the model, their squares and products. The Gretl program is used for econometric analysis and is part of the General Public License (GPL) software.

The testing procedure for the case of two regressors boils down to the following steps:

Estimate by the method of least squares the output equation of the regression. In the case of two explanatory variables, the equation is of the form:

$$y_i = \beta_1 + \beta_2 x_{2i} + \beta_3 x_{3i} + \varepsilon_i. \quad (6)$$

Determine an auxiliary regression of the form:

$$e_i = \alpha_1 + \alpha_2 x_{2i} + \alpha_3 x_{3i} + \alpha_4 x_{2i}^2 + \alpha_5 x_{3i}^2 + \alpha_6 x_{2i} x_{3i} + u_i. \quad (7)$$

Determination of R^2 for the auxiliary regression

Making the null hypothesis:

$$H_0: \alpha_2 = \alpha_3 = \dots = \alpha_m = 0, \quad (8)$$

which means that random disturbances are homoscedastic.

Verification of the null hypothesis using the statistic having a normal distribution χ^2 with J degrees of freedom, where:

T – number of observations,

R^2 – coefficient of determination of the auxiliary equation.

The final stage of the verification process of the constructed model was the acceptance of the hypothesis of non-linearity of the variables studied. In this regard, non-linearity tests prepared in Gretl program were carried out in three versions by including:

- the logarithmically transformed variables in the model for the residuals (non-linearity test – logarithms);
- the squares of the residuals in the model (nonlinearity test – squares);
- squares and cubes of theoretical values in the original model (Ramsey's RESET specification test, which is commonly used to check whether the linear form of the model is the best choice).

The test of nonlinearity-logarithms requires evaluating the choice of the linear analytical form of the model was also performed in the Gretl program on the basis of White's test for nonlinearity, based on Lagrange multipliers. For this purpose, the auxiliary equation defined by the formula:

$$e_i = \alpha_1 + \alpha_2 x_{2i} + \alpha_3 x_{3i} + \gamma_1 \ln x_{2i} + \gamma_1 \ln x_{3i} + u_i. \quad (9)$$

The null hypothesis H_0 is assumed to be a linear relationship, with the alternative hypothesis H_1 assuming a non-linear, logarithmic relationship. Verification of the null hypothesis is done with the help of statistics, which has a normal distribution χ^2 with J degrees of freedom, where T = number of observations, and R^2 = coefficient of determination of the auxiliary equation

The nonlinearity-squares test requires estimating an auxiliary equation to check the significance of the polynomial, quadratic form. This equation is of the form:

$$e_i = \alpha_1 + \alpha_2 x_{2i} + \alpha_3 x_{3i} + \gamma_1 x_{2i}^2 + \gamma_1 x_{3i}^2 + u_i, \quad (10)$$

third test to verify the linear form of the model is the Ramsey RESET specification test.

For the estimated auxiliary equation:

$$Y_i = \alpha_1 + \alpha_2 x_{2i} + \alpha_3 x_{3i} + \gamma_1 \hat{Y}_i^2 + \gamma_1 \hat{Y}_i^2 + u_i, \quad (11)$$

a validation of the model specification is performed by verifying the null hypothesis:

$$H_0: \gamma_1 = \gamma_2 = 0. \quad (12)$$

We reject the null hypothesis when the calculated Fisher-Snedecor F statistic is greater than the critical value. We calculate the F statistic from the formula:

$$F(2, n - K) = \frac{\frac{(RSS_1 - RSS_2)}{2}}{\frac{1 - RSS_1}{(n - k)}}, \quad (13)$$

where:

RSS_1 – sum of squares of the residuals for the basic model,

RSS_2 – sum of squares of the residuals for the auxiliary model,

$n - K$ – number of observations minus the number of regressors.

The conclusions and recommendations were indicated as a final result of the considerations based on the entire research process described above.

Results of the research

Characteristics of the Cities Under Review

The cities under review are far apart and have a different history and socio-cultural background. Hence they differ in population, area, revenue, average monthly salary and spatial structure. The basic statistical data is presented in Table 2.

Table 2. Characterisation of the cities under review (2021)

City	Population	Population density (population per 1 km ²)	Powiat revenue per capita (PLN)	Average monthly salary (PLN)	Electricity consumption per household (kWh)	Electricity consumption per capita (kWh)
Bydgoszcz	334.026	1897.88	7.617	5848.22	1540.82	712.53
Gorzów Wielkopolski	118.011	1372.22	8.004	5242.27	1678.43	766.88
Katowice	282.755	1713.67	9.014	6924.74	1741.03	935.69
Poznań	545.073	2080.43	9.152	6662.69	1706.25	886.74
Szczecin	394.482	1310.57	8.227	6244.67	1677.34	799.35

Source: authors' work based on the data of the Topographic Objects Database (www.geoportal.gov.pl), the Local Data Bank (bdl.stat.gov.pl), Directive (2004), Directive (2008).

Poznań has the highest population density, while Szczecin and Gorzów Wielkopolski have the lowest. Poznań is also the richest city in this ranking, although Katowice has only slightly lower income. Bydgoszcz, on the other hand, has the lowest income of the cities surveyed. The average revenue of a city is one of the most reliable sources of data on the wealth of its inhabitants, as it is based on the share of personal income tax (PIT in Poland) paid by people living in the city area (Act, 2003). The highest salaries in 2021 were recorded in Katowice, followed by Poznań and Szczecin.

The inhabitants of Katowice consumed the most electricity, both per household and per capita. Poznań came second, followed by Szczecin and Gorzów Wielkopolski. The lowest electricity consumption was recorded in Bydgoszcz.

Poznań has a population of over 545,000, Szczecin over 394,000, Bydgoszcz around 334,000, Katowice just under 283,000 and Gorzów Wielkopolski around 118,000. At the same time, these data show wealthy cities such as Poznań and Katowice, slightly poorer Bydgoszcz and Gorzów Wielkopolski, and Szczecin, which is average in this ranking.

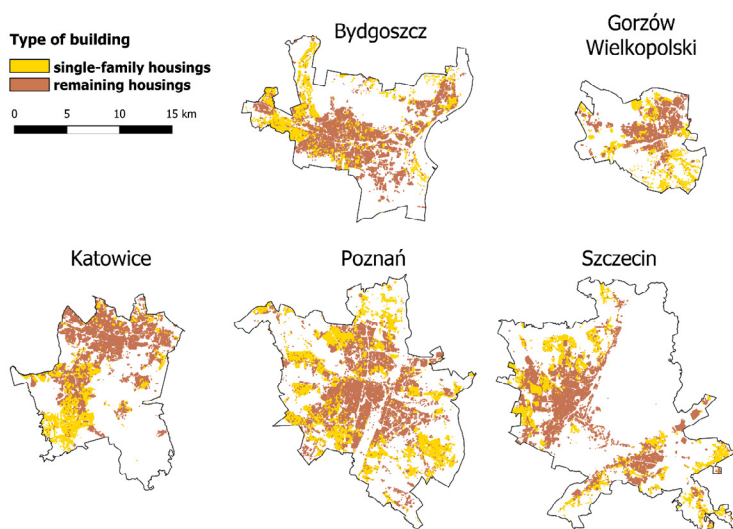


Figure 5. Housing types in the cities under review

Source: authors' work based on the data of the Topographic Objects Database (www.geoportal.gov.pl).

A key element influencing the comparison of cities in terms of the use of PV micro-installations is the analysis of the residential structure, in particular single-family houses (Figure 5).

The single-family housing in Katowice, Bydgoszcz and Gorzów Wielkopolski shows clear clusters. In the case of Katowice, these are the south-western districts, in Bydgoszcz the western parts of the city, and in Gorzów Wielkopolski the concentration is somewhat less pronounced (mainly in the south, but also in the north of the city). In the case of Poznań and Szczecin, single-family dwellings are located in the extended and dispersed suburbs. The reasons for this are also to be found in the cities' surroundings and their specific conditions.

It is also worth noting the difference in size between the cities studied. Administratively, Szczecin has the largest area (more than 300km²), but a significant part of it is occupied by water. Poznań (about 262km²) has the largest area occupied by housing in this list. On the other hand, the smallest city is Gorzów Wielkopolski, which is less than half the size of Poznań (about 86 km²).

The analysis of the housing structure has also been supplemented with data on the number of single-family and two-family dwellings in relation to the total number of residential buildings in the city (Figure 6). In Bydgoszcz, Gorzów Wielkopolski and Szczecin, single-family or two-family dwellings account for around three-quarters of all residential buildings in the city. In the case of Katowice, the proportion is just over 66%, and Poznań has the highest proportion (almost 84%).

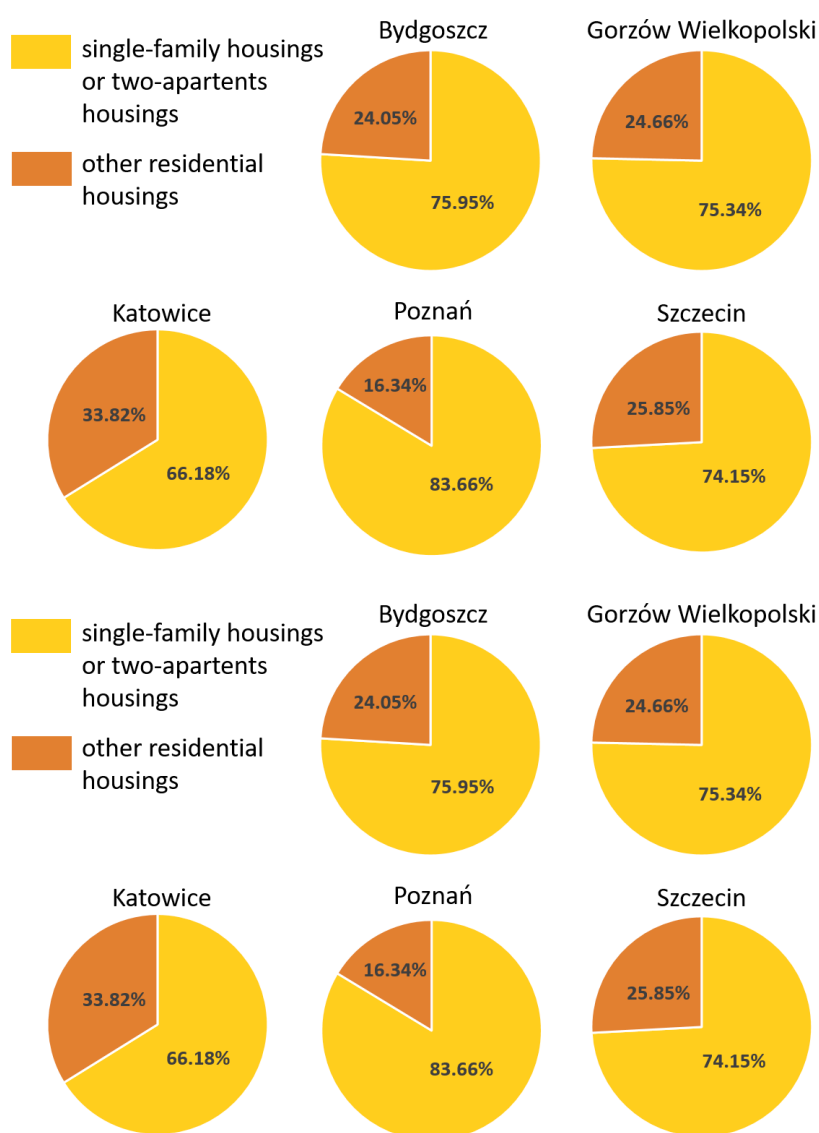


Figure 6. Share of single-family or two-apartment buildings in the total number of residential buildings

Source: authors' work based on the data of the Local Data Bank (Statistics Poland) (bdl.stat.gov.pl).

The development of housing over time was also compared. The analysis included the number of building permits (individual, single-family houses) issued between 2015 and 2021 per 10,000 inhabitants (Figure 7). In the case of Poznań, Szczecin and Bydgoszcz, the number of permits issued in relation to the population remained at a similar level over the period. There was a slight decrease in Katowice, while in Gorzów Wielkopolski, this index doubled. From 2017 to 2018 it increased by more than half (65%), and from 2020 to 2021, it increased again by about 46%, reaching a value of more than 11 permits per 10 000 inhabitants. In 2021, the index will be around 3 in Bydgoszcz and Katowice and around 4.35 in Szczecin and Poznań.

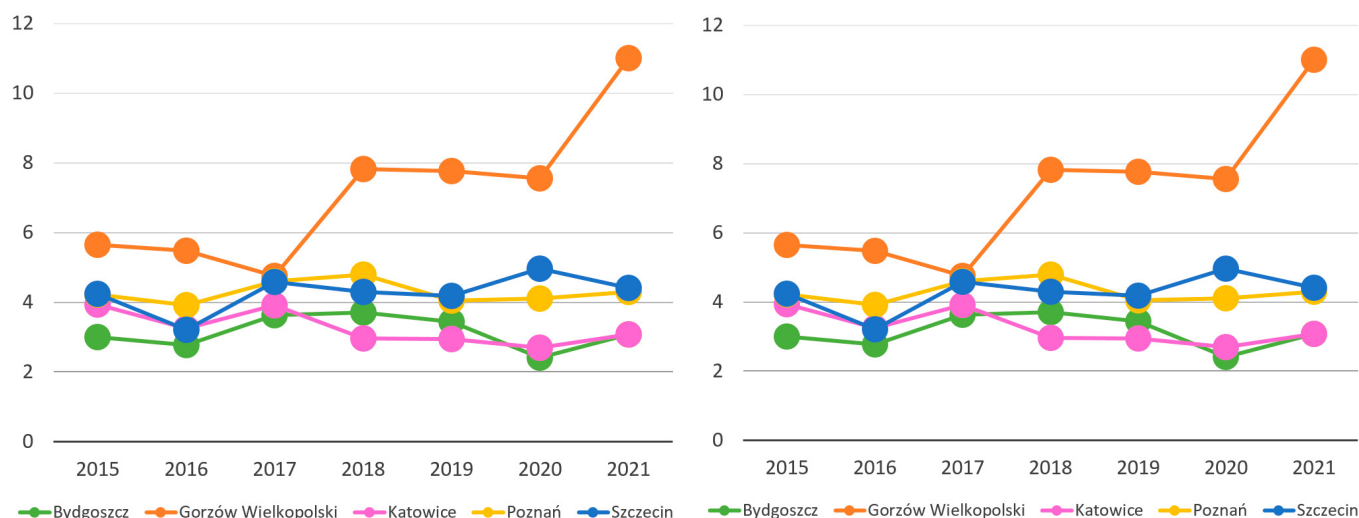
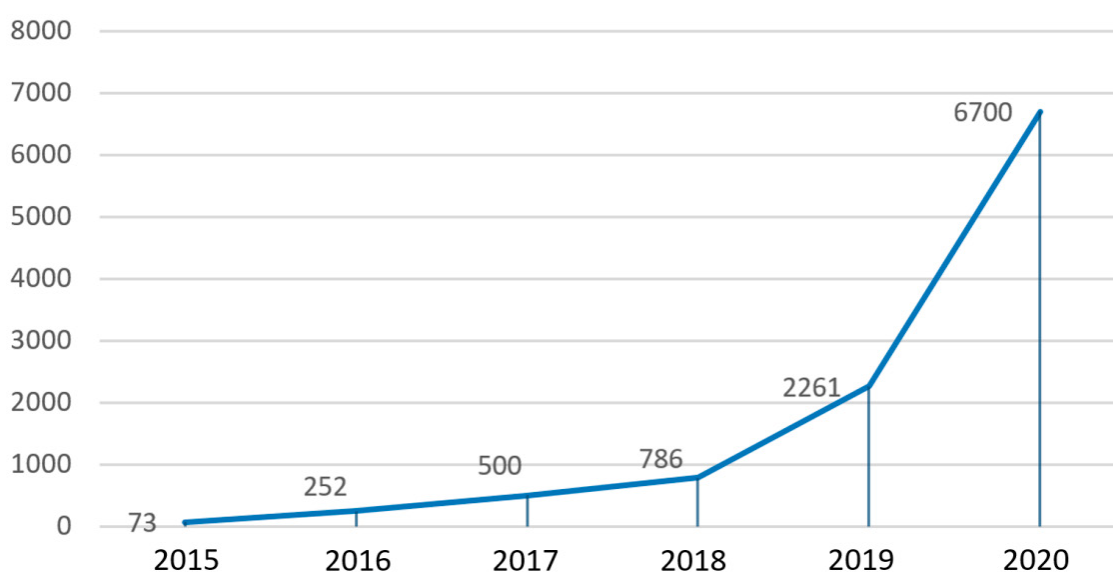


Figure 7. Number of building permits issued (individual, single-family housing) between 2015 and 2021 per 10,000 inhabitants

Source: authors' work based on the data of the Local Data Bank (Statistics Poland) (bdl.stat.gov.pl).

Use of RES between 2014 and 2020 in the Cities Under Review

Between 2015 and 2018, the interest in investment in photovoltaic micro-installations increased slightly but remained relatively low. A significant increase in their number (Figure 8) occurs at the end of the period under review, i.e. 2018-2020.



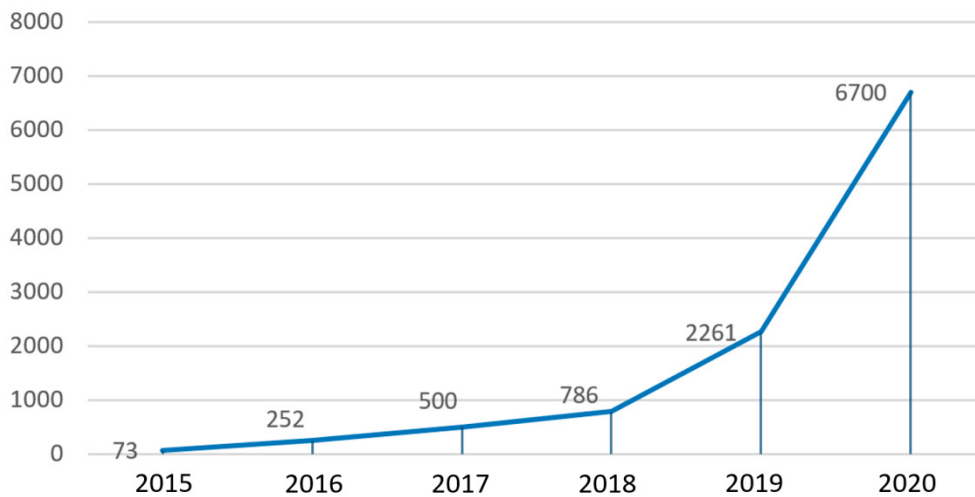


Figure 8. Total number of micro-installations in the cities under review between 2015 and 2020

Source: authors' work based on information provided by Tauron Dystrybucja S.A. and ENEA.

The growth rate of new micro-installations varied between cities in the period 2015-2020 (Figure 9). Initially, Szczecin and Katowice had the highest number of such investments (in 2015). By 2019, Szczecin will have the highest number of recorded micro-installations. Poznań caught up with Katowice in 2017 and then overtook it, catching up with Szczecin in 2019 to become the centre with the highest number of micro-installations. Bydgoszcz and Gorzów Wielkopolski, on the other hand, recorded the largest increase in micro-installations between 2018 and 2020. In Bydgoszcz, a similar number of micro-installations were installed in one year (2019-2020) as in Katowice or Szczecin.

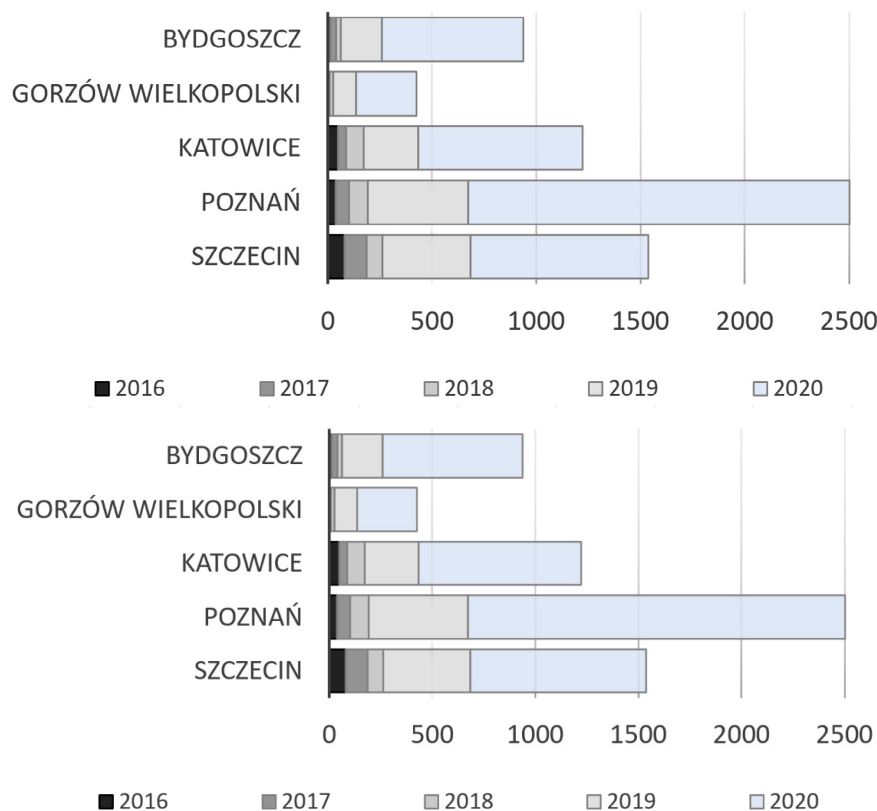


Figure 9. Increase in the total number of micro-installations in the cities under review between 2015 and 2020

Source: authors' work based on information provided by Tauron Dystrybucja S.A.

Poznań has the highest number of PV micro-installations (more than 2,500), followed by Szczecin (more than 1,500) and Katowice (more than 1,200) (Table 3). In Bydgoszcz, fewer than a thousand PV micro-installations were recorded in 2020, and in Gorzów Wielkopolski, only 427. The changes that occurred during the period of the highest growth (i.e. 2018-2020) were taken into account when analysing the growth rate of the number of micro-installations. It turns out that during this period, Gorzów Wielkopolski recorded a more than 15-fold increase in the number of micro-installations: Bydgoszcz more than 13-fold, Poznań more than 12-fold, and Katowice and Szczecin about twice as much (6.5-fold and more than 5-fold, respectively). This means that in Katowice and Szczecin, the change in the number of micro-installations was not as rapid as in the other cities surveyed.

Table 3. Micro-installations data in the cities under review

City	Total number of micro-installations in 2020	Increase in the total number of micro-installations between 2018 and 2020	Total number of micro-installations in relation to the number of single-family buildings in 2020 (%) ¹	Total number of micro-installations in relation to the number of electricity consumers in 2020 (w ‰)
Bydgoszcz	947	13.34	4.77	6.08
Gorzów Wielkopolski	427	15.25	6.50	7.83
Katowice	1,243	6.47	8.23	7.28
Poznań	2,515	12.39	6.16	8.96
Szczecin	1,568	5.37	7.23	8.27

Source: authors' work based on information provided by Tauron Dystrybucja S.A. and the Topographic Objects Database's data.

However, it should be remembered that Poznań is also by far the largest of the urban centres considered. It is therefore worth looking at the other indices. The highest ratio of micro-installations to the number of single-family dwellings was recorded in Katowice (over 8%), followed by Szczecin (over 7%), Gorzów Wielkopolski (6.5%), then Poznań (over 6%) and Bydgoszcz (less than 5%). It therefore appears that although Poznań is the absolute leader in terms of the total number of micro-installations (among the cities surveyed), there are still many opportunities available.

In turn, when analysing the ratio of the number of micro-installations to the number of electricity consumers in 2020, Poznań again recorded the highest index value (almost 9‰), followed by Szczecin (over 8‰), Gorzów Wielkopolski (less than 8‰) and Katowice (over 7‰). The lowest value was again recorded in Bydgoszcz (around 6‰).

Data-Correlation Analysis

The correlation indices of selected variables are presented in Table 4.

Table 4. Correlation indices of selected variables

Selected variable	Correlation index
Number of micro-installations	1
Municipality revenue per capita	0.801502934
Energy consumption per capita	0.331797673
Building permits (individual, single-family housing)	0.072468023

Calculations (Table 4) show that there is a weak and low correlation between the number of micro-installations installed, electricity consumption per capita and the number of building permits issued (see Figures 10-11). However, a high correlation can be observed between the number of

¹ Applies to single-family buildings and two-apartment buildings (classes BUBD01 and BUBD02) in relation to the buildings category (BUBD) in the Topographic Objects Database's classification.

micro-installations installed and municipal revenue per capita, where the correlation coefficient is 0.80, as shown in Figure 12.

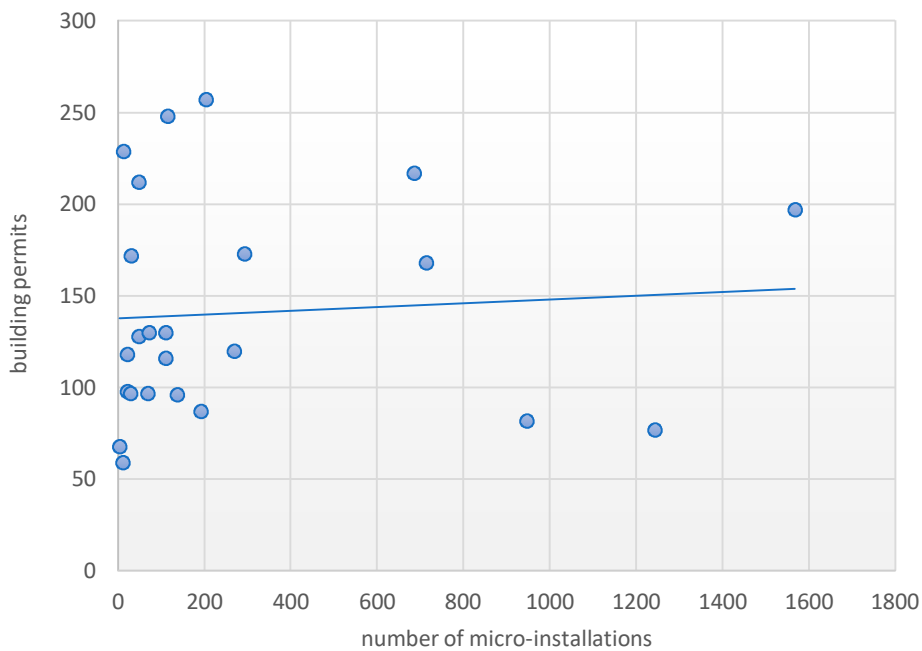


Figure 10. Correlation between building permits and number of micro-installations

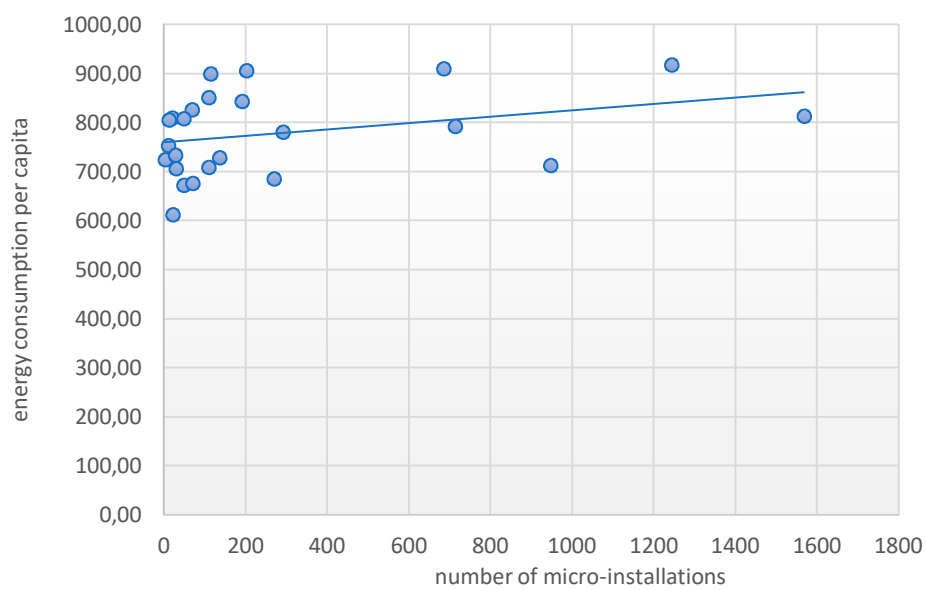


Figure 11. Correlation between energy consumption per capita and number of micro-installations

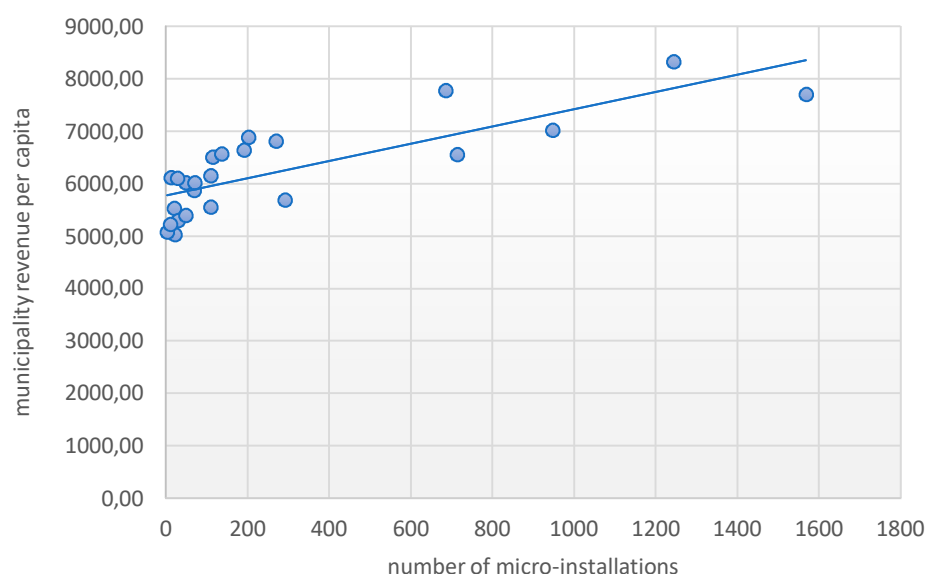


Figure 12. Correlation between municipality revenue per capita and the number of micro-installations

Econometric Model

It was assumed that the dependent variable (Y) is the number of PV micro-installations in cities, while the explanatory variables are: municipal income per capita (X1), energy consumption per capita (X2) and the number of building permits (X3). The results of the estimation of the linear model are presented in Table 5. They have been developed using the Gretl program.

Table 5. Results of estimating the parameters of the linear model

	Coefficient	Std. Error	t-ratio	p-value	
Const	-1672.47	516.690	-3.237	0.0041	***
Municipality_revenue_per_capita	0.462225	0.0771063	5.995	<0.0001	***
Energy_consumption_per_capita	-1.11216	0.867713	-1.282	0.2146	
Building_permits	-0.434179	1.00554	-0.4318	0.6705	
Mean dependent var	289.5000	S.D. dependent var		426.1652	
Sum squared resid	1318400	S.E. of regression		256.7489	
R-squared	0.684381	Adjusted R-squared		0.637038	
F(3, 20)	14.45584	P-value(F)		0.000031	
Log-likelihood	-165.0210	Akaike criterion		338.0421	
Schwarz criterion	342.7543	Hannan-Quinn		339.2922	

Source: authors' work based on data using the Gretl program.

In the estimated model, parameters that are significantly different from zero are marked with additional symbols (*) at the end of the row. In the model analysed, the presence of three asterisks indicates that the variable is significant at the 1% level. Variables that are not significant have therefore been rejected: energy consumption per capita and building permits (Table 6).

Table 6. Results of estimating the parameters of the linear model after excluding insignificant variables

	Coefficient	Std. Error	t-ratio	p-value	
Const	-2146.17	391.067	-5.488	<0.0001	***
Municipality_revenue_per_capita	0.389735	0.0619936	6.287	<0.0001	***
Mean dependent var	289.5000	S.D. dependent var		426.1652	
Sum squared resid	1493733	S.E. of regression		260.5704	
R-squared	0.642407	Adjusted R-squared		0.626153	
F(1, 22)	39.52245	P-value(F)		2.51e-06	
Log-likelihood	-166.5193	Akaike criterion		337.0387	
Schwarz criterion	339.3948	Hannan-Quinn		337.6638	

Source: authors' work based on data using the Gretl program.

The degree of explanation of the variability of Y (dependent variable) was assessed using the coefficient of determination R². In the estimated model, the value of R² is 0.642404. This means that the model explains 64% of the phenomenon under investigation. The fit of the model to the empirical values can be considered above average.

The model, therefore, takes the following form:

$$Y = \alpha_0 + \alpha_1 X_1 = -2146,17 + 0,389735 X_1, \quad (14)$$

where:

Y – quantity of micro-installations,

X₁ – municipality income per capita,

α₀, α₁ – model parameters.

In verifying the constructed model, an assessment of the normality of the residual component was carried out. The Jarque-Bera goodness-of-fit test was used for this assessment (the null hypothesis H₀ that the random components have a normal distribution is established). The value of the test statistic is determined based on the measure of skewness S and kurtosis K.

From Figure 13, which presents the results of the Jarque-Bera goodness-of-fit test (JB = 3.498), compared with the critical value of the chi-square statistic $\chi^2(2) = 9.2104$ for $\alpha = 0.01$, with $s = 2$, it can be seen that there is no basis for rejecting the null hypothesis ($p\text{-value} = 0.1739 > 0.01$), so the residual distribution has characteristics of a normal distribution.

As part of the model verification process, the homogeneity of the variance of the random component, also known as the heteroscedasticity of the random component, was also assessed. The probability of making an error determined in the Gretl program (Table 7) ($p\text{-value} = 0.062221$) indicates that there is no reason to reject the null hypothesis that the random disturbances are homoscedastic. Therefore, it can be concluded that all the outliers are explained by the model.

Table 7. White's test for heteroskedasticity

	coefficient	std. error	t-ratio	p-value
Const	-410841	914676	-0.4492	0.6579
Municipality_rev~	95.6549	283.171	0.3378	0.7389
Sq._municipality_~	-0.00313423	0.0216159	-0.1450	0.8861
Unadjusted R-squared = 0.231422				
Test statistic: TR ² = 5.554123, with p-value = P(Chi-square(2) > 5.554123) = 0.062221				

Source: authors' work based on data using the Gretl program.

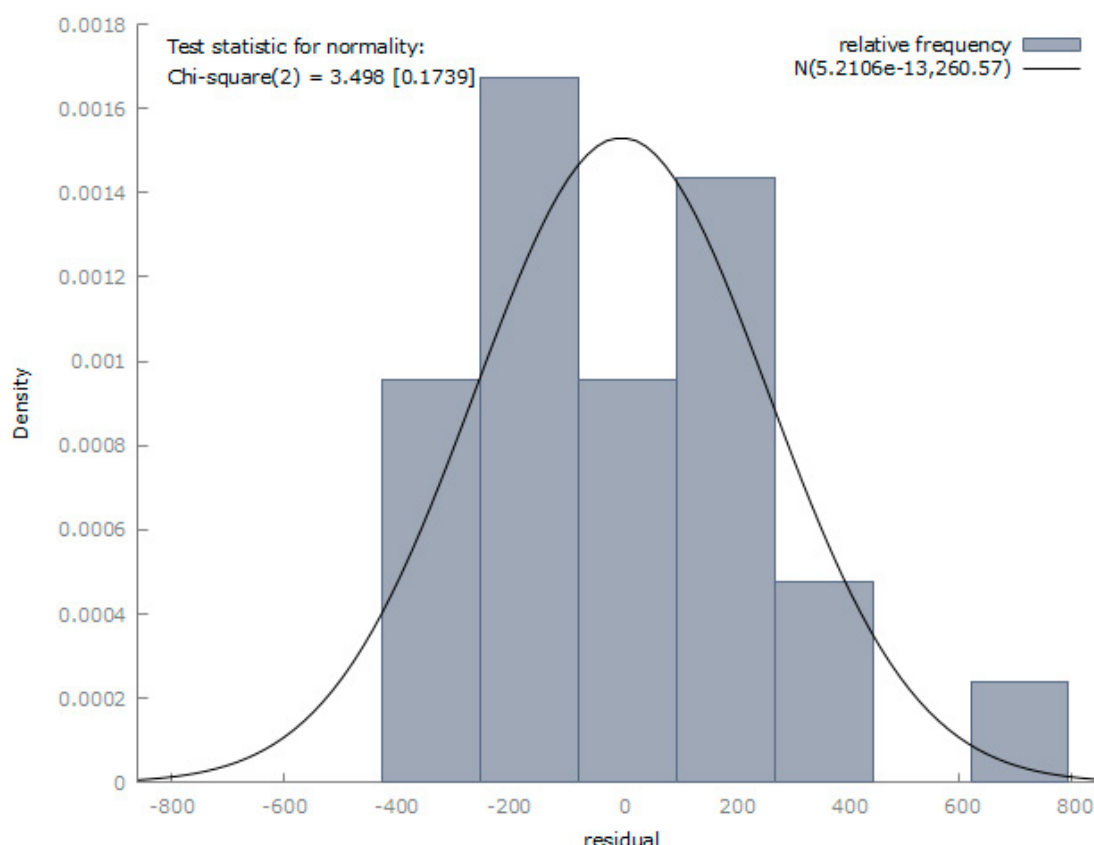


Figure 13. Results of the test for the normality of the residual distribution

Source: authors' work based on data using the Gretl program.

The final stage of the verification process of the model constructed was the acceptance of the hypothesis of non-linearity of the variables studied. In this regard, non-linearity tests were carried out in three versions described in the methodology part.

The results of the tests of the hypothesis of non-linearity of the variables studied are summarised in Table 8.

Table 8. Results of the model non-linearity test.

	Coefficient	Std. error	t-ratio	p-value
Non-linearity test (log terms)				
Const	93660.4	35845.6	2.613	0.0163
Municipality_rev~	1.87444	0.719464	2.605	0.0165
L_ municipality_rev~	-12068.8	4618.74	-2.613	0.0162
Unadjusted R-squared = 0.245359				
Test statistic: $TR^2 = 5.88861$, with p-value = $P(\text{Chi-square}(1) > 5.88861) = 0.0152391$				
Non-linearity test (squared terms)				
	coefficient	std. error	t-ratio	p-value
Const	5820.43	2332.34	2.496	0.0210
Municipality_rev~	-1.81723	0.722060	-2.517	0.0200
Sq_ municipality_rev~	0.000139131	5.51184e-05	2.524	0.0197
Unadjusted R-squared = 0.232783				

Test statistic: $TR^2 = 5.5868$, with p-value = $P(\text{Chi-square}(1) > 5.5868) = 0.0180963$				
RESET specification test Ramsey's				
	Coefficient	Std. error	t-ratio	p-value
Const	117.490	954.920	0.1230	0.9033
Municipality_rev~	-0.0214174	0.172890	-0.1239	0.9026
yhat^2	0.00245772	0.00149744	1.641	0.1164
yhat^3	-1.19918e-06	1.13021e-06	-1.061	0.3013
Test statistic: $F = 3.767801$, with p-value = $P(F(2,20) > 3.7678) = 0.0409$				

Source: authors' work based on data using the Gretl program.

Because:

- in the non-linearity test-logarithms, the value is less than the critical value $\chi^2(1\%, 1) = 6.6349$ with a probability of error $p = 0.0152391$,
- in the nonlinearity test-squares, the value is less than the critical value $\chi^2(1\%, 1) = 6.6349$ with a probability of error $p = 0.0180963$,
- in the Ramsey's RESET specification test, $p = 0.0409 > \alpha = 0.01$.

the analysis carried out indicates that there is no basis for rejecting the null hypothesis, which assumes a linear relationship between the variables under investigation, and replacing it with another function. It can therefore be concluded that the form of the econometric model is correct and it can be used for further analysis and research.

Discussion and Conclusion

The growing demand for electricity can be effectively met by integrating renewable energy sources. Poland is also obliged to reduce the use of non-renewable energy sources in its energy production process. Unfortunately, unfavourable legislation prevents the full use of all types of renewable energy, such as wind energy in wind farms or hydroelectric power in hydroelectric plants (Act, 2016). The most common renewable energy source is solar energy, which is used to generate electricity in photovoltaic modules or to heat water in solar panels.

An important feature of photovoltaic modules is that they can be installed in almost any location (Almeshqab & Ustun, 2019), and in this context, the entire territory of Poland (all cities analysed) is characterised by very similar environmental conditions for PV installations. Moreover, the price of installing PV systems has decreased while their efficiency has increased, which has led to an increase in the number of micro-installations in Poland (Rataj et al., 2021).

The article fills a gap in the literature regarding the identification of determinants counted for locational preferences for renewable energy in existing settlement patterns of rapidly developing cities scattered in outer zones, as well as in urbanising rural environments (suburbanisation and semi-urbanisation).

The connection of a significant number of PV micro-installations in Poland has encountered some technical problems, including instability of the transmission grid (Topolski, 2021). One way of dealing with this problem is to use energy at the point of production, for example, in single-family homes (Kuźmiński et al., 2023).

One problem can be the lack of conditions for the installation of photovoltaic cells (e.g. insufficient roof space). Residents of single-family houses, who usually have such conditions, are in a privileged position. The process of urban expansion, with the dominance of single-family houses in outlying areas, is also an opportunity to increase the number of photovoltaic installations. Similar phenomena occur in the rural areas surrounding the city. However, the significant dispersal of emerging developments poses challenges for prosumers to connect to the grid and hinders the modernisation and improvement of the energy system. This means that energy production and consumption in com-

pact layouts of less intensive urban and suburban development (neighbourhoods and local settlement structures) yield better economic and social outcomes than the use of dispersed development in cities and their rural surroundings (urban sprawl). Such a direction of change in the development of the outer zones of larger cities promotes the transformation of the energy system through renewable energy production, as well as initiating various forms of resident involvement and the creation of networks within broader prosumer ecosystems (Dall-Orsoletta et al., 2022).

There were some limitations in the data analysis, including data availability. Collecting data from the main electricity distributors in Poland was quite a challenge.

The analysis included values for five voivodeship capitals in Poland.

The economic instruments “incentivising” the installation of PV systems were the same throughout the country during the period under review. However, there were significant differences in the number of PV installations in the cities surveyed. The following conclusions can be drawn from the correlation analysis carried out:

- Correlation analysis shows a significant relationship between the number of micro-installations in the regions studied and municipal revenues – the richest cities have the largest number of micro-installations. Investing in PV is the domain of higher-income residents; a question for urban environmental policy is: what measures can be taken to encourage less affluent individuals to invest in prosumer activities?
- The number of new building permits issued does not have a significant impact on the installation of microsystems, nor does the number of buildings – a higher proportion of single-family houses does not mean that there will be more investment in PV. A higher number of prosumer investments is rather associated with the wealth of the inhabitants and the compact nature of the development of the outer zone of the city.
- The increase in electricity consumption per capita is not strongly correlated with the number of new micro-installations. The period under review is the period before the COVID pandemic and the war in Ukraine, which was characterised by a relative stabilisation of electricity prices and consumption in Poland. Prosumer investments tend to stimulate greater control over energy consumption and lead to its reduction, which is an additional benefit (both environmental and economic) for both individual users and the city as a whole.
- Poorer and larger urban centres are “catching up” in terms of investment in renewable energy production, but belatedly (and not necessarily more slowly);

During the period under review, the number of photovoltaic installations has grown very rapidly, which is highly desirable in terms of fulfilling Poland’s climate commitments, among other things. In the long term, the significant and increasing dispersal of development in the outskirts of major cities creates difficulties in the operation and maintenance of the grid, significantly reducing the economic benefits for users. The high correlation with municipal revenues does not seem to be a positive development. The implication is that PV is mainly invested in by people with higher incomes. This suggests that the instruments used should be modified to encourage people with lower incomes to invest in PV. Further in-depth research is needed to assess the relationship between local government revenues and the development of micro-installations. In addition, the relationship between the intensity of the construction movement and the rate of change in the number of new micro-installations should be considered more broadly, in terms of the whole country and between regions, thereby extending the analysis to other Polish regions.

The econometric model verifying the number of PV micro-installations in the urban areas analysed shows that the greatest influence on the increase in the number of PV installations is the municipal income per capita, while the other variables, energy consumption per capita and the number of building permits, did not have a significant influence and were rejected in the model. The analysis carried out allows us to conclude that the proposed form of the econometric model is correct and can be used for further analysis and research in this area. Richer cities with more affluent residents, who are often more aware of the importance of renewable energy, are moving faster and to a greater extent to a power supply from PV micro-installations.

In general, it can be said that PV systems in urban areas require a special approach in a broad context: legislative, social, economic, urban planning, environmental, etc. In particular, the very high level of air pollution in Poland is significant, mainly due to the traditional heating of buildings in low-density areas, which predominate in the outskirts of cities and their urbanising rural surround-

ings. Changing the form of heating and electricity supply can significantly reduce the environmental burden in this zone and improve the quality of life of urban residents, which is one of the main objectives of urban and metropolitan policy supported by European Union funds (Kozera et al., 2022; Słupik et al., 2021; Dembicka-Niemiec et al., 2023).

There is potential for increasing the area dedicated to the practical use of renewable energy production in numerous production, storage and service facilities that are widespread in the outskirts of larger cities, which are almost undeveloped in Poland. Such buildings typically have large roof areas: these include shopping centres, industrial, storage, service and catering facilities, as well as multi-storey car parks.

When it comes to energy in cities, aiming for a radical increase in the number of PV installations can improve living conditions in cities and reduce pollution, which has a positive impact on climate issues.

The contribution of the authors

Conceptualisation, K.H., A.H., A.M.-G., B.K.; literature review, B.K.; methodology, A.H., A.M.-G.; formal analysis, P.M., A.M.-G.; writing, K.H., A.H., A.M.-G., B.K., P.M.; conclusions and discussion, K.H., A.H., A.M.-G., B.K.

The authors have read and agreed to the published version of the manuscript.

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WYKORZYSTANIE MIKROINSTALACJI FOTOWOLTAICZNYCH W WYBRANYCH MIASTACH REGIONALNYCH W POLSCE

STRESZCZENIE: Celem artykułu jest ocena wykorzystania OZE, tj. energii słonecznej (poprzez inwestycje w instalacje fotowoltaiczne) w wybranych miastach wojewódzkich w Polsce. Skupiliśmy się na obszarze pięciu stolic województw, wybranych pod względem reprezentatywności i pełniących regionalne funkcje administracyjne lub administracyjno-samorządowe. Hipoteza badawcza zakłada, że instalacje montowane są głównie na nowych budynkach, a czynnikiem determinującym wybór PV są dochody. Część metodologiczna obejmuje analizę literatury w wybranym obszarze. Następnie przeprowadzono analizę danych statystycznych dostępnych w statystyce publicznej (dane GUS) oraz na podstawie danych pierwotnych zebranych od głównych dystrybutorów energii elektrycznej na danym obszarze (Tauron Dystrybucja S.A. i ENEA). Dane do analizy pochodzą sprzed pandemii COVID i wojny na Ukrainie, ponieważ charakteryzowały się one względną stabilizacją cen energii elektrycznej i zużycia. W celu zbadania ewentualnego związku między liczbą mikroinstalacji w badanych miastach a innymi zmiennymi, przeprowadzono analizę korelacji opartą na współczynniku Pearsona. Zbudowano model ekonometryczny do analizy badanych zmiennych, które mają istotny wpływ na liczbę mikroinstalacji PV w badanych obszarach miejskich. Artykuł wypełnia lukę w literaturze dotyczącą identyfikacji uwarunkowań odpowiedzialnych za preferencje lokalizacyjne dla energetyki odnawialnej w istniejących układach osadniczych szybko rozwijających się miast, rozproszonych w strefach zewnętrznych, a także w urbanizującym się środowisku wiejskim. Badania nad energetyką prosumencką na tych obszarach są zupełnie nowe. Pogłębiona analiza zachowań prosumentów i ich preferencji wobec instalacji fotowoltaicznych może być podstawą do optymalizacji stosowanych w Polsce instrumentów ekonomicznych zachęcających do inwestowania w odnawialne źródła energii.

SŁOWA KLUCZOWE: energia odnawialna; energia słoneczna; mikroinstalacje fotowoltaiczne; polityka miejska; rozwój miast