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# *Optimization of photovoltaic farm locations using GIS tools.*

# *Optymalizacja lokalizacji farm fotowoltaicznych przy wykorzystaniu narzędzi GIS.*

Autor: *Maciej Kulik*
Kierunek studiów: *Energetyka Odnawialna i Zarządzanie Energią*
Opiekun pracy: *dr hab. inż. Artur Wyrwa, prof. AGH*

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## Abstract

In recent years, renewable energy has become very important in most developed countries. In countries such as Germany, the United States, electricity generation using photovoltaic systems is an important element in the structure of energy production and consumption. Most European Union countries, including Poland, are obliged to reduce emissions of harmful substances into the atmosphere. In the document Energy Policy of Poland until 2040, there is a decrease in electricity generation from fossil fuels and an increase in renewable energy sources. An increase in installed capacity is forecast for large ground-mounted photovoltaic farms. Consequently, the use of tools to determine the most suitable locations for solar farms is increasing. The aim of this study was to find such locations in the Malopolska province. The study was based on the use of geographic information system (GIS) in spatial analysis. The methodology and technical and economic aspects were analyzed to achieve the best results. The analysis showed that there are many locations suitable for PV farm development in the study area.



## Streszczenie

W ostatnich latach energetyka odnawialna stała się bardzo istotna w większości krajów rozwiniętych. W państwach takich jak Niemcy, Stany Zjednoczone wytwarzanie energii elektrycznej z wykorzystaniem systemów fotowoltaicznych stanowi ważny element w strukturze produkcji i konsumpcji energii. Większość krajów Unii Europejskiej w tym Polska, zmuszona jest ograniczyć emisję szkodliwych substancji do atmosfery. W dokumencie Polityka Energetyczna Polski do 2040 roku, przewidziany jest spadek wytwarzania prądu z paliw kopalnych a wzrost z odnawialnych źródeł energii. Wzrost mocy zainstalowanej jest prognozowany dla dużych gruntowych farm fotowoltaicznych. W związku z tym rośnie wykorzystanie narzędzi w celu określenia najbardziej odpowiednich lokalizacji dla farm słonecznych. Celem niniejszej pracy było znalezienie takich miejsc w województwie małopolskim. Badanie opierało się na wykorzystaniu systemu informacji geograficznej (GIS) w analizie przestrzennej. Przeanalizowano metodologię i aspekty techniczne oraz ekonomiczne w celu osiągnięcia najlepszych rezultatów. Analiza wykazała, że w badanym obszarze występuje wiele lokalizacji odpowiednich do rozwoju farm PV.

# 1. Introduction

The ever-increasing demand for electricity is the technological challenge of today. Until now, fulfilling demand with energy from fossil fuels has brought us to the point where the continued sustainability of the energy industry is in question. Continued development of conventional power plants can lead to local pollution and carbon emissions at levels that affect the health of the community. In addition, basing electricity generation on fossil fuels decreases the energy security of countries without fossil resources [1]. Energy is a key commodity needed for the development of the economy and the prosperity of the country. Energy sources are divided into two groups: non-renewable and renewable. Renewable energy sources (RES) are those whose usage does not cause a deficit because they renew themselves after a short period of time. The use of non-renewable sources causes a permanent decrease in their resources [2]. As the U.S. Energy Information Administration (EIA) shows in its International Energy Outlook 2021, electricity consumption will increase by 50% by 2050 compared to 2020, mainly due to population and GDP growth. Renewables have the potential to become the main source of energy for this new demand. Fossil fuels are expected to continue to be an important part of the energy mix and ensure that demand is met and that the electricity grid remains stable. The largest growth is expected in solar power as the results of the EIA analysis shown in Figure 1.1 [3].

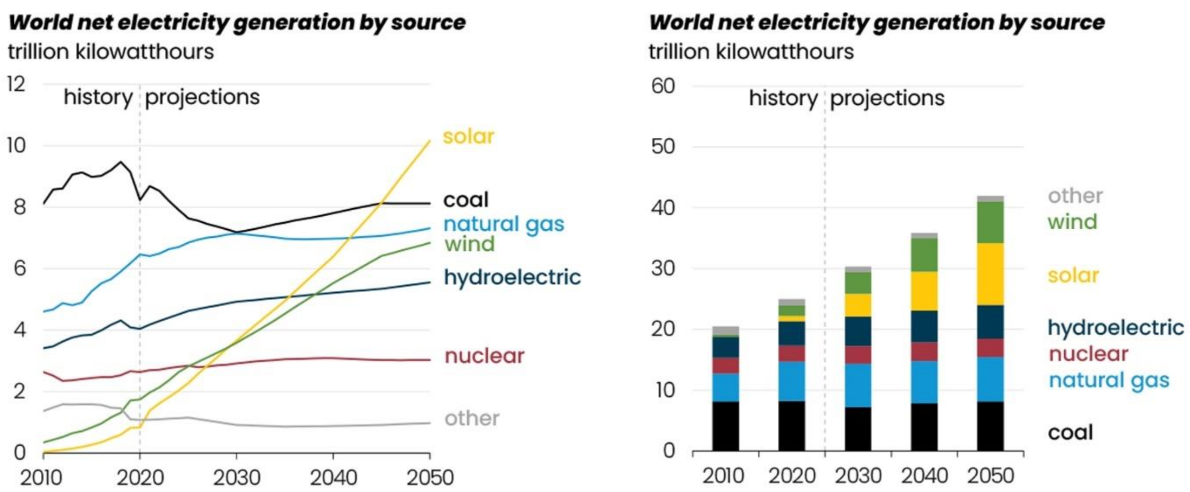


**Figure 1.1** Development and consumption of energy sources
*Source: [3]*

The political transformation and GDP growth in Poland has resulted in a significant increase in electricity consumption over the past 30 years. Back in 1992, per capita electricity consumption was 2961 kWh, while in 2014 it was 3972 kWh, which is an increase of about 34% [4]. Most energy production is based on the combustion of fossil fuels, which is negative for the environment, climate, and human health impacts. Burning fuels causes emissions of pollutants into the atmosphere, including significant amounts of carbon dioxide, which is a greenhouse gas. In 2018, CO2 emissions in Poland were 8235 kg per capita [5]. Due to the European Union (EU) climate and energy policy, the Polish energy sector is changing towards an environmentally friendly energy sector. Achieving the EU goal of climate neutrality by 2050 and reducing greenhouse gas emissions by 55% by 2030 is a major challenge for the energy sector [6]. The Polish government plans to allocate 260 billion PLN for the energy transformation, to support projects implementing the Paris Agreement. This transformation strategy is based on three pillars: fair transition, zero-emission energy system and good air quality [2]. The first effects of the measures can already be seen, in 2020 the energy production from renewable energy sources (RES) increased significantly compared to 2018. Thanks to the subsidies, the increase could be seen especially in solar systems. Photovoltaic installations produced 176% more energy in 2020 than in 2018 [7]. However, the majority of electricity is still obtained in conventional thermal power plants, where fossil fuels are used to generate electricity: hard coal, lignite, natural gas. In 2021 the share of fossil fuels in electricity production was: hard coal 53%, lignite 26%, natural gas 8%. Renewable energy sources (wind, solar, hydroelectric and other power plants) together accounted for 13% of production [8]. According to [2] In 2030 the share of RES is to amount to at least 23% in final energy consumption. Large investments in photovoltaic systems are also planned, with installed capacity of 5-7 GWp in 2030 and 10-16 GWp in 2040. The production of energy from photovoltaic (PV) systems has many advantages, including environmental friendliness (non-emitting energy source), low operating costs, and scalability. Therefore, an increase in investment in PV systems may contribute to the sustainable development of the energy sector in Poland.

It should be noted that one of the limitations of solar development is the dependence on weather conditions. Meteorological conditions are variable and vary with geographic location. In recent years, the selection of a suitable location for photovoltaic systems has been facilitated by the increasing use of Geographic Information Systems (GIS) with multi-criteria decision making process (MCDM). Solar energy is a renewable source with variable availability, so site selection is a key factor in maximizing system performance. With MCDM, decisions can be made based on multiple, often conflicting, criteria. In contrast, GIS is a tool for analyzing, creating and storing geographic data and creating maps. The combination of these two tools makes it possible to solve location problems. Many research papers have used the integration of MCDM and GIS in site selection optimization, especially for solar and wind energy [9].

Photovoltaic systems generate electricity directly from the sun's energy through the photoelectric effect. The amount of energy generated depends mainly on the solar radiation falling on the PV modules, but also on the temperature, the conversion efficiency (depends on type of PV cells) and the module power. The main part of the PV system are the photovoltaic panels, which are called "power generators". They generate DC electricity, which is converted to AC electricity in inverters. There are two main types of photovoltaic installations: on-grid (connected to the electricity grid) and off-grid (isolated). In the first case, the energy generated by the PV plant first covers the electricity demand inside the system, and only the excess energy is sent to the grid. In case of insufficient production from PV, the difference is covered by the grid. In off-grid systems, on the other hand, the excess energy is usually stored in battery banks and when there is insufficient production, the stored energy meets the demand [10].

In Poland, dynamic growth has been recorded in household micro photovoltaic installations (up to 50 kWp), in which panels are most often mounted on the roofs of buildings [7]. Thanks to such investments, households protect themselves against fluctuating electricity prices, increase the value of their properties, save on electricity and contribute to environmental protection. Large-scale PV systems mounted on the ground, so-called solar farms, are becoming increasingly popular. Unlike roof-mounted systems, the key to investing in PV farms is the selection of a suitable location with optimal meteorological and sunny conditions. A major limitation is the relatively small number of climate stations and measurement data of these values. Therefore, some researchers rely on satellite data to assess solar conditions and other factors that determine solar potential. In this way, photovoltaic power potential maps are made (Figure 1.2).

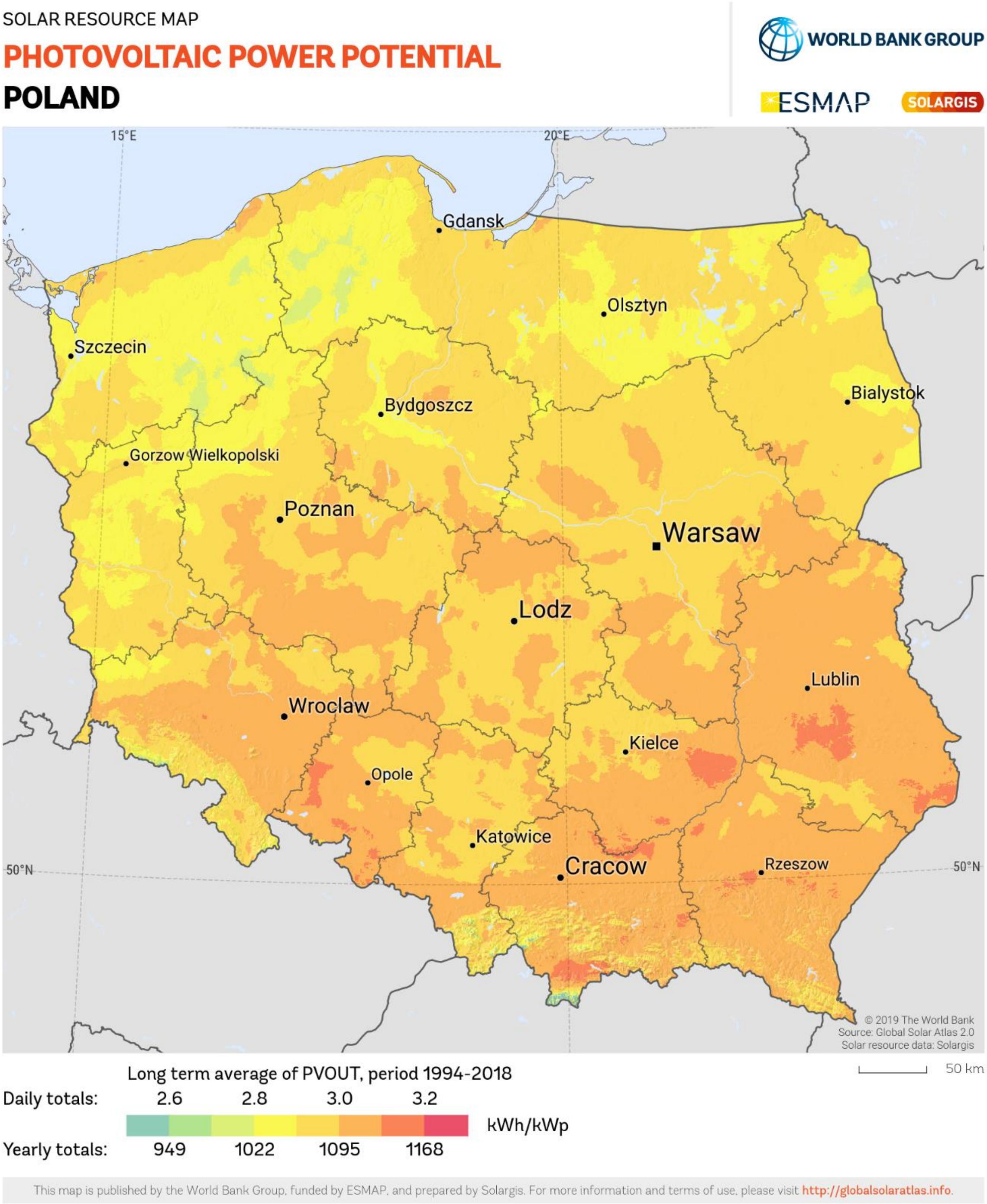


**Figure 1.2** Photovoltaic power potential map of Poland
*Source: [11]*

# 2. Aim and scope of the thesis

The thesis will address the planning of photovoltaic farms (large-scale ground installations) in Poland based on the geo-information tool GIS. It will be based on finding the most optimal locations for ground-mounted PV systems depending on solar radiation, geographical, ecological conditions and urban planning. This thesis is limited to the Malopolska province in Poland, due to the computational power. Considering the diversity of terrain in this region, the research well represents the methodology for selecting locations for PV farms. The aim of this thesis is to identify the best locations for investment in photovoltaic farms in Malopolska province. The focus is on technical and economic issues. Moreover, to estimate the solar potential of given photovoltaic systems and to create a map of possibilities to build such systems.

Therefore, the research on the topic is to answer the following questions:

- What methodology can optimally determine the location of photovoltaic farms?
- How to determine the criteria for evaluating locations?
- What data is required for proper planning of PV systems? What data is available?
- What factors influence the profitability of investments in photovoltaic farms?
- How different potential locations affect the technical and economic aspects of PV farms?

# 3. Description of methodology

Geographic Information System has been used in many scientific works to select a suitable location for solar energy systems. Most of the studies [9], [12]–[17] use a combination of GIS and multi-criteria decision making (MCDM) techniques. MCDM methods can be divided by the way the objective is expressed. The first group is based on solving continuous problems with an infinite number of alternatives. The second group includes techniques that solve discrete problems, i.e., those with a finite number of variants and criteria. To solve such problems one can use the method of superiority relations or utility function [18]. Outperformance relationship methods rely on the relationship between the options and the decision maker's preferences. The most commonly used methods of this subgroup include: Elimination et Choice Translating Reality (ELECTRE), PROMETHEE, TOPSIS, ORESTE. They are suitable for problems with a large number of alternatives, but are not always able to identify the most favorable option. The second subgroup is based on multi-attribute utility theory, in which alternatives are assigned numerical values due to the utility function [19]. The best known techniques are the evaluation method, weighted sum (WSM), weighted linear combination (WLC), analytical hierarchy process (AHP) [13]. In the mathematical AHP method, a hierarchical structure of the problem is created in which the criteria are ordered in terms of importance. The comparison of criteria is made according to the experts' opinions. The criteria are compared in pairs, the relative weight and advantage of one over the other is determined. In this way a matrix of criteria is built reflecting the preferences. In this thesis, the problem of site selection for PV farms was classified as a discrete problem. The AHP method has been used in research [12]–[15], because it is simple, intuitive and reduces process complexity. In this thesis, the decision making process was also based on this method.

## 3.1. Softwares

In order to use GIS, it was decided to use QGIS software. QGIS software is free, open source and allows to work on multiple hardware platforms. It is developed by a group of programmers of Open Source Geospatial foundation and is made available under GNU GPL license. The software allows you to work on spatial data, perform geoprocessing, create your own maps. It is possible to use

GPS data. Thanks to many additional plugins functionality of the program is very high [20].

Microsoft Excel spreadsheet was used for calculations and graphing. This application is widely used in many companies and institutions due to its many mathematical functions and accessible database support. Excel also enables collaboration with QGIS and facilitates attribute analysis [21].

Photovoltaic Geographic Information System (PVGIS) was used to determine electricity production at the study locations. PVGIS is a freely available software developed by the EU science center and allows to check the performance of PV installations. Its high quality data on solar radiation, temperature and wind speed makes it a useful tool in PV systems research [22].

The high-level programming language Python was used to support the API (application programming interface) of the PVGIS program. It is developed by the Python Software Foundation and operates on open-source principles. An undoubted advantage is the readability of the source code, and automatic memory management makes it easy to script applications. [23].

Some calculations were performed through the General Algebraic Modelling System (GAMS). It is a mathematical optimization system designed to model linear, nonlinear and mixed problems. GAMS is a cross-platform system developed by GAMS Development Corporation. It allows users to build large mathematical models and optimize according to parameters. GAMS is widely used in the economics and engineering industries [24].

## 3.2. Proposed framework

Poland is located in the central-eastern part of Europe and lies between longitude 12 and 25 E and latitude 49 and 56 N. This research is carried out for one of the sixteen provinces of Poland (shown in Figure 3.1). Malopolska province is located in the southern part of the country. It covers an area of 15183 $km^2$ , which constitutes 4.9% of the territory of Poland, and its borders are inhabited by approximately 3386 thousand people. Malopolska is characterized by upland and mountainous terrain in the south, and lowland in the north. Due to the natural environment, about 53% of the area is under nature protection, including national parks, landscape parks and reserves. In the region, forests cover an area of 434.3 thousand ha, which is 28.6% of its area. There are 62 cities in the region, and the largest of them is the capital of the province, Krakow. Malopolska is located in a moderate climatic zone, but due to the lay of the land, there is a large temperature amplitude. The average annual temperature ranges from -2.6°C in the mountains in the south to 10.2°C in the north. Global horizontal irradiation, by the same circumstance, varies from about 900 kWh/m$^2$ to about 1200 kWh/m$^2$ [25].

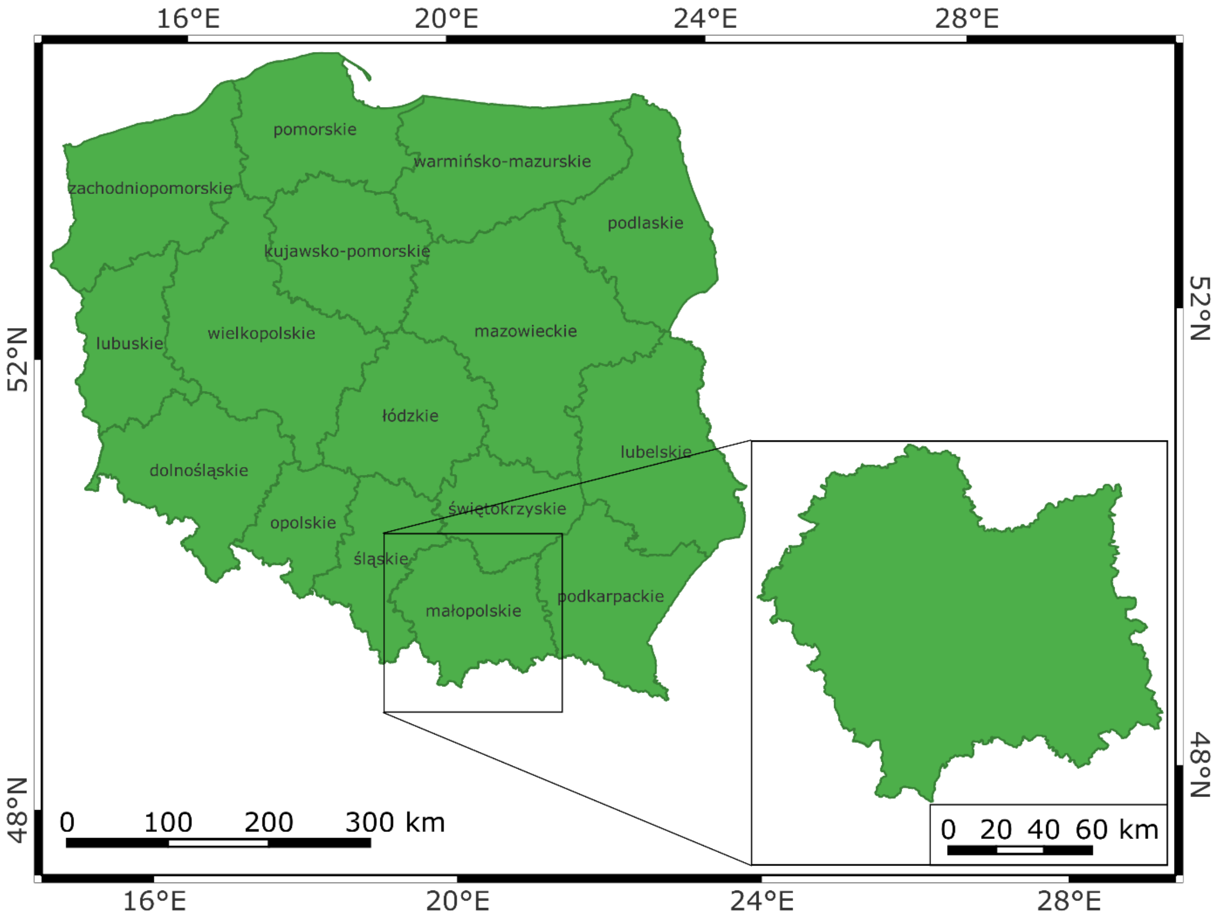


**Figure 3.1** Mapping of Poland and the studied region
*Source: own elaboration*

In the present study, the research was conducted in a stepwise approach, as shown in Figure 3.2. First, the criteria important in site selection for photovoltaic farms were selected. Then, geographic data in different formats were found and adapted into vector layers in QGIS software. AHP decision making process was applied to determine the weights of the criteria. After taking into account the areas not relevant for solar farms, the criteria maps were aggregated and a PV land suitability map was created. The economic suitability analysis was based on the calculation of the levelized cost of electricity parameter for potential locations. An LCOE suitability map was created. The final PV farms development map was created based on the results of technical and economic suitability, and the most appropriate areas were proposed.

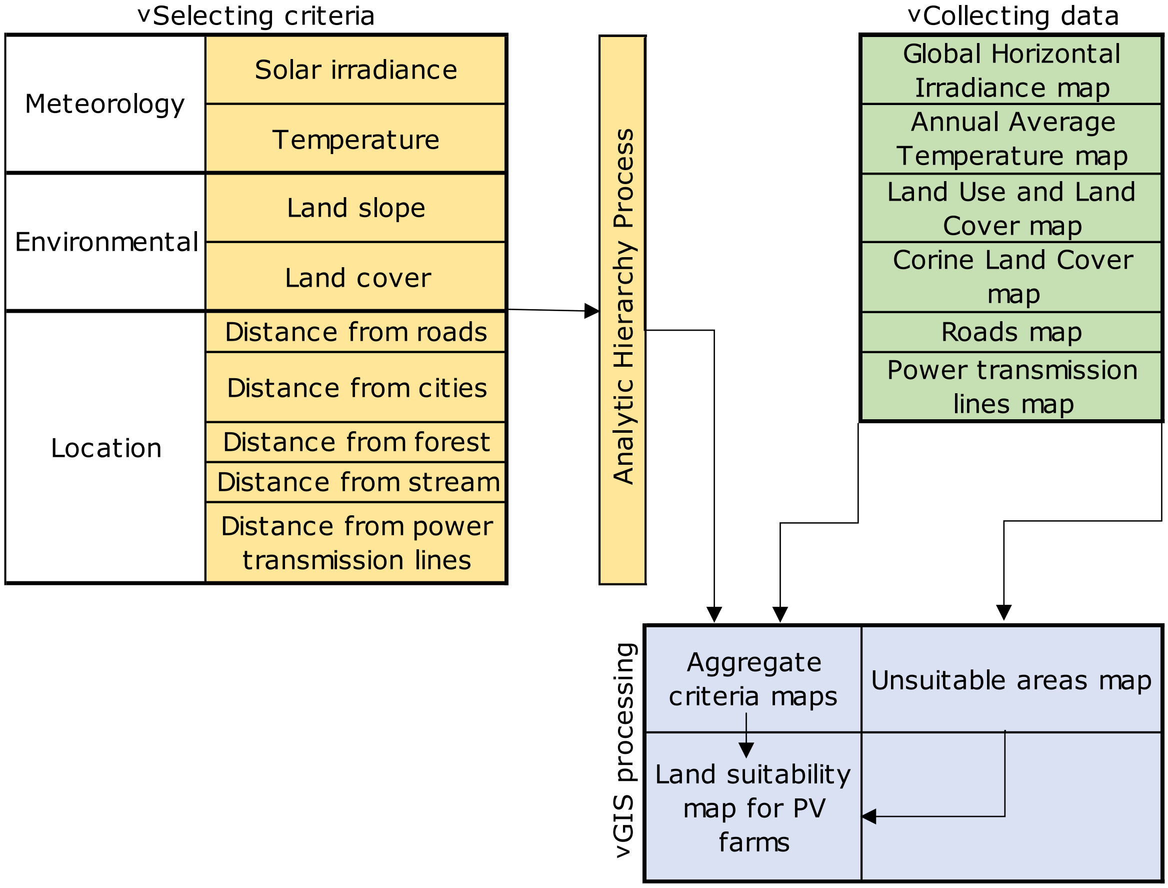


**Figure 3.2** Stages of site investigation for photovoltaic farms
*Source: own elaboration*

## 3.3. Criteria selection

In the thesis, the study used a combination of QGIS software and AHP method. In the first step, the best criteria were selected and assigned weights based on experts' opinion. Then, using GIS, the areas were divided into five ranks according to their suitability for PV farms: very low, low, moderate, high, very high. Decision criteria were selected divided into meteorological, environmental and location. For meteorological categories, solar irradiation data and average temperature during the year are selected. Humidity was omitted due to the low impact and lack of data. In the environmental category, three factors are selected: slope of land, and land cover. In the preliminary analysis, protected ares and cities are excluded from areas with high suitability for PV farms. Five criteria: distance from cities, roads, power lines, forests and waterbodies are selected for the location category [12], [13], [15], [17].

### 3.3.1. Solar irradiance

Solar radiation is defined as the amount of solar energy incident on a plane on the earth's surface. It depends on many factors such as geographic coordinates, humidity, temperature, and evaporation. Solar irradiance plays a key role in selecting location for photovoltaic installations. Higher intensity of solar radiation results in higher open circuit voltage of panels and higher short circuit current. This increases the maximum power point and consequently the energy generated by the PV panel. The amount of solar radiation per unit time is represented by the Global Horizontal Irradiance (GHI) and is usually expressed by average values of few years.

### 3.3.2. Average annual temperature

The average annual air temperature is classified as a meteorological factor and plays a key role in the operation of photovoltaic systems. High temperature negatively affects the operation of PV panels and other system components such as inverters and transformers. As the temperature increases, the efficiency and performance of the modules decreases by lowering the output voltage.

### 3.3.3. Land slope

Slope is an important factor in determining the location for photovoltaic farms. A steeper slope increases the construction costs and creates the risk of shading. Shading of the modules negatively affects the efficiency of energy production. Therefore, flat areas are preferred in site selection.

### 3.3.4. Land cover

Land cover is also an important criterion. It affects not only the costs associated with the construction of a PV system but also legal issues. Due to the law in some places the construction of a PV farm is prohibited or significantly hindered, e.g. urban areas, forests and wetlands preclude the construction of a large PV farm. The most suitable areas are open, uncultivated areas.

### 3.3.5. Distance from roads

The factor included in the location group is the distance from roads. It affects the economic aspect of the investment. The construction of a new access road for construction machinery and people working on PV farm is expensive. Therefore, the preferred locations are those that are close to existing roads to reduce construction costs.

### 3.3.6. Distance from cities

The proximity of PV farms to urban areas is a negative location factor. The construction of PV farm in cities is not recommended. Cities are being developed and the area occupied by them is increasing. In addition, tall buildings may cause shading of the panels. In addition, the construction of a PV power plant near cities is hindered by legal issues, including development plans.

### 3.3.7. Distance from forests

Another important location factor is the distance of the PV farm from forests. The proximity to forests causes a risk of shading of the modules and a decrease in electricity production. In addition, locations away from forests are suitable for fire prevention reasons.

### 3.3.8. Distance from stream/waterbodies

The distance from water bodies and rivers also influences the choice of location. Due to flood risk and catchment areas, it is crucial that the PV farm is far away from water bodies. This can protect the system from failure due to natural disasters.

### 3.3.9. Distance from power grid

Distance from power lines is classified into location criteria and affects the cost of the PV plant and the losses associated with the transmission of electricity. In order to avoid the aforementioned effects, the location of the PV farm should be adjacent to medium voltage lines.

## 3.4. Analytical hierarchy process

Decision making regarding the location of PV farms is subject to some uncertainty, e.g. related to data accuracy. The AHP technique is used to reduce this uncertainty, and to facilitate the selection of a location taking into account several, often conflicting, criteria. In the first step, hierarchical model of the problem is built and the individual decision elements are compared. All factors are compared in pairs in terms of importance on a scale from 1 to 9 (Table 3.1), resulting in the rating matrix (global preference) shown in Table 3.2.

**Table 3.1** Scale of criteria comparisons

| Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Both criteria are equally preferred |
| 3 | Moderate importance | One criterion slightly more preferred |
| 5 | Strong importance | One criterion strongly more preferred |
| 7 | Very strong importance | One criterion very strongly more preferred |
| 9 | Extreme importance | One criterion extremely more preferred |
| 2, 4, 6, 8 | Intermediate values | Intermediate grades for comparisons between the above |

*Source: compiled from* [14]

In the rating matrix, elements are pairwise consistent according to the Equation (3.1). Then the normalized pairwise comparison matrix is created by using Equation (3.2) and shown in Table 3.5. In a further step, the weight vector of each factor is calculated as the arithmetic mean of the normalized values (Equation (3.3)). The maximum eigenvalue of the matrix is calculated according to Equation (3.4). In the AHP method, it is important to study the consistency of the ratings between the alternatives. Therefore, a consistency index is calculated according to Equation (3.5). Due to the difficulty in interpreting the consistency index, a consistency coefficient is determined to check the consistency. Mathematically, it is defined according to Equation (3.6).

**Table 3.2** The pairwise comparison of ground-based photovoltaic systems.

| | Criteria | 1<br>Solar irradiance | 2<br>Distance from roads | 3<br>Distance from cities | 4<br>Land slope | 5<br>Soil type | 6<br>Distance from forest | 7<br>Distance from stream | 8<br>Temperature | 9<br>Distance from power transmission lines |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Solar irradiance | 1 | 5 | 6 | 9 | 6 | 4 | 8 | 3 | 4 |
| 2 | Distance from roads | 0.20 | 1 | 2 | 7 | 3 | 1 | 5 | 0.25 | 0.50 |
| 3 | Distance from cities | 0.17 | 0.50 | 1 | 5 | 1 | 0.5 | 7 | 0.33 | 0.33 |
| 4 | Land slope | 0.11 | 0.14 | 0.20 | 1 | 0.33 | 0.20 | 1 | 0.14 | 0.14 |
| 5 | Soil type | 0.17 | 0.3 | 1 | 3 | 1 | 0.33 | 4 | 0.14 | 0.20 |
| 6 | Distance from forest | 0.25 | 1 | 2 | 5 | 3 | 1 | 7 | 0.50 | 1 |
| 7 | Distance from stream | 0.13 | 0.20 | 0.14 | 1 | 0.25 | 0.14 | 1 | 0.17 | 0.14 |
| 8 | Temperature | 0.33 | 0.33 | 4 | 3 | 7 | 2 | 6 | 1 | 2 |
| 9 | Distance from power transmission lines | 0.25 | 0.25 | 2 | 3 | 7 | 1 | 7 | 0.50 | 1 |

*Source: compiled from [12], [13], [15], [17]*

$$a_{ij} \cdot a_{ji} = 1 \tag{3.1}$$

Where $a_{ij}$ is the preference value in the matrix, i refers to the row number and j refers to the column number.

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_i a_{ij}} \tag{3.2}$$

Where $\overline{a_{ij}}$ is normalized preference value.

$$w_i = \frac{\sum_j \overline{a_{ij}}}{m} \tag{3.3}$$

Where $w_i$ is overall weight vector of each row in the matrix and $m$ refers to number of criteria.

$$\lambda_{max} = \frac{\sum_j \left( \frac{\sum_i a_{ij} \cdot w_j}{w_i} \right)}{m} \tag{3.4}$$

The maximum eigenvalue of the comparison matrix $\lambda_{max}$ is calculated as the average of the sum of the products of the comparison values and their weights in a row divided by the weight of the elements involved.

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{3.5}$$

Where $CI$ is consistency index.

$$CR = \frac{CI}{RI} \tag{3.6}$$

Where $CR$ represents consistency coefficient and $RI$ is a random index taking values depending on the number of criteria according to Table 3.3.

**Table 3.3** The random index

| No. Criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.54 |

*Source: compiled from [15]*

It is assumed that the consistency coefficient in the AHP method should have values:

- $CR \leq 5\%$, for 3x3 matrix
- $CR \leq 8\%$, for 4x4 matrix
- $CR \leq 10\%$, for the others matrix

It is then considered that the consistency coefficient is acceptable and the comparisons are consistent. If the value is greater than the above there is inconsistency between the variants and changes are required [15]. The calculated values of criteria weights, maximum eigenvalue, consistency index and consistency coefficient are presented in Table 3.4. It can be seen that the calculated CR is less than the limit value. Based on this, we can see that the criteria have been paired correctly. The solar irradiance and temperature criteria have the highest weights of 35.9% and 15.7%, respectively, making them the most important factors in site selection for solar farms. On the other hand, the least important are distance to waterbodies and land slope, which have weights of 2.1%.

**Table 3.4** AHP decision making process results

| Criteria | | Criteria weights | $\lambda_{max}$ | $CI$ | $CR$ |
|---|---|---|---|---|---|
| 1 | Solar irradiance | 0.359 | 9.26 | 0.033 | 0.022 |
| 2 | Distance from roads | 0.100 | | | |
| 3 | Distance from cities | 0.071 | | | |
| 4 | Land slope | 0.021 | | | |
| 5 | Land cover | 0.049 | | | |
| 6 | Distance from forest | 0.111 | | | |
| 7 | Distance from stream | 0.021 | | | |
| 8 | Temperature | 0.157 | | | |
| 9 | Distance from power transmission lines | 0.111 | | | |

*Source: own elaboration*

**Table 3.5** Normalized pairwise comparison of criteria

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Criteria | | Solar irradiance | Distance from roads | Distance from cities | Land slope | Land cover | Distance from forest | Distance from stream | Temperature | Distance from power transmission lines |
| 1 | Solar irradiance | 0.384 | 0.571 | 0.327 | 0.243 | 0.210 | 0.393 | 0.174 | 0.497 | 0.429 |
| 2 | Distance from roads | 0.077 | 0.114 | 0.109 | 0.189 | 0.105 | 0.098 | 0.109 | 0.041 | 0.054 |
| 3 | Distance from cities | 0.064 | 0.057 | 0.055 | 0.135 | 0.035 | 0.049 | 0.152 | 0.055 | 0.036 |
| 4 | Land slope | 0.043 | 0.016 | 0.011 | 0.027 | 0.012 | 0.020 | 0.022 | 0.024 | 0.015 |
| 5 | Land cover | 0.064 | 0.038 | 0.055 | 0.081 | 0.035 | 0.033 | 0.087 | 0.024 | 0.021 |
| 6 | Distance from forest | 0.096 | 0.114 | 0.109 | 0.135 | 0.105 | 0.098 | 0.152 | 0.083 | 0.107 |
| 7 | Distance from stream | 0.048 | 0.023 | 0.008 | 0.027 | 0.009 | 0.014 | 0.022 | 0.028 | 0.015 |
| 8 | Temperature | 0.128 | 0.038 | 0.218 | 0.081 | 0.245 | 0.197 | 0.130 | 0.166 | 0.215 |
| 9 | Distance from power transmission lines | 0.096 | 0.029 | 0.109 | 0.081 | 0.245 | 0.098 | 0.152 | 0.083 | 0.107 |

*Source: own elaboration*

## 3.5. Criteria classification

In order to find the most favorable sites for photovoltaic farms, classifications are given for each range of all criteria. The global horizontal irradiation and average annual temperature datasets were obtained from [26],in raster format. However, the other data sets were obtained from [27] and they are in vector format. Thanks to the geoprocessing tools of the QGIS program, the raster data were converted into vector data. First, the Corine Land Cover (CLC) map shown in Figure 3.3 was used to identify excluded, or unsuitable, areas (Figure 3.4). These are urban areas, forests, water bodies and rivers, protected areas such as national parks, landscape parks, reserves, wetlands, roads. Areas with slopes greater than 11% were also excluded. The polygons with the same ranks were then combined and maps of the individual criteria shown further were created.

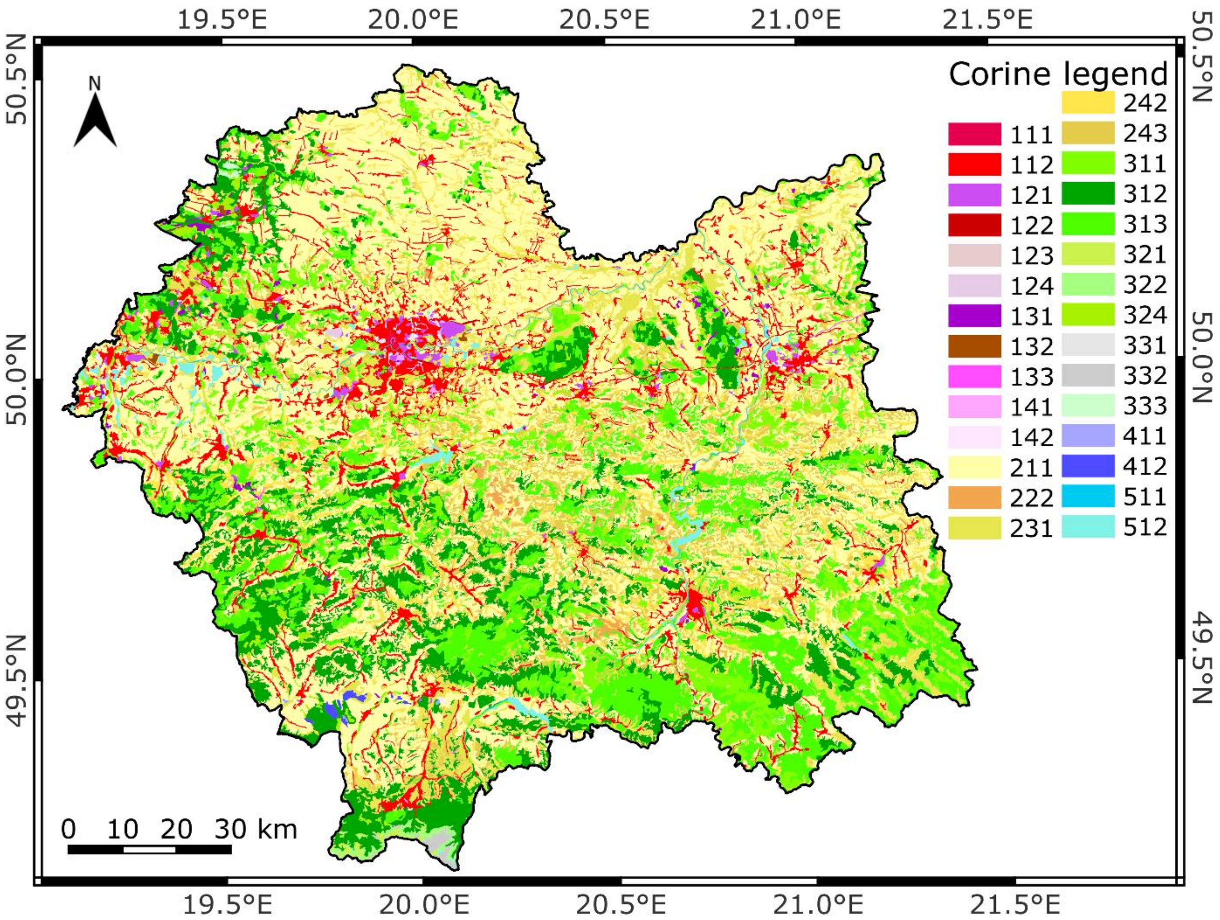


**Figure 3.3** Corine Land Cover map of malopolska
*Source: compiled from [27]*

The above land cover map is hierarchically structured into three classes. The first class refers to the main land cover types: anthropological, agricultural, forests and ecosystems, wetlands and aquatic. The next class is divided into 15 categories, while the most detailed land cover is described by the third class divided into 44 types. This is a standardized system of division used in all European countries. In Malopolska region there are 27 out of 44 types. Codes and colors of Corine Land Cover are shown in Appendix 1 [28].

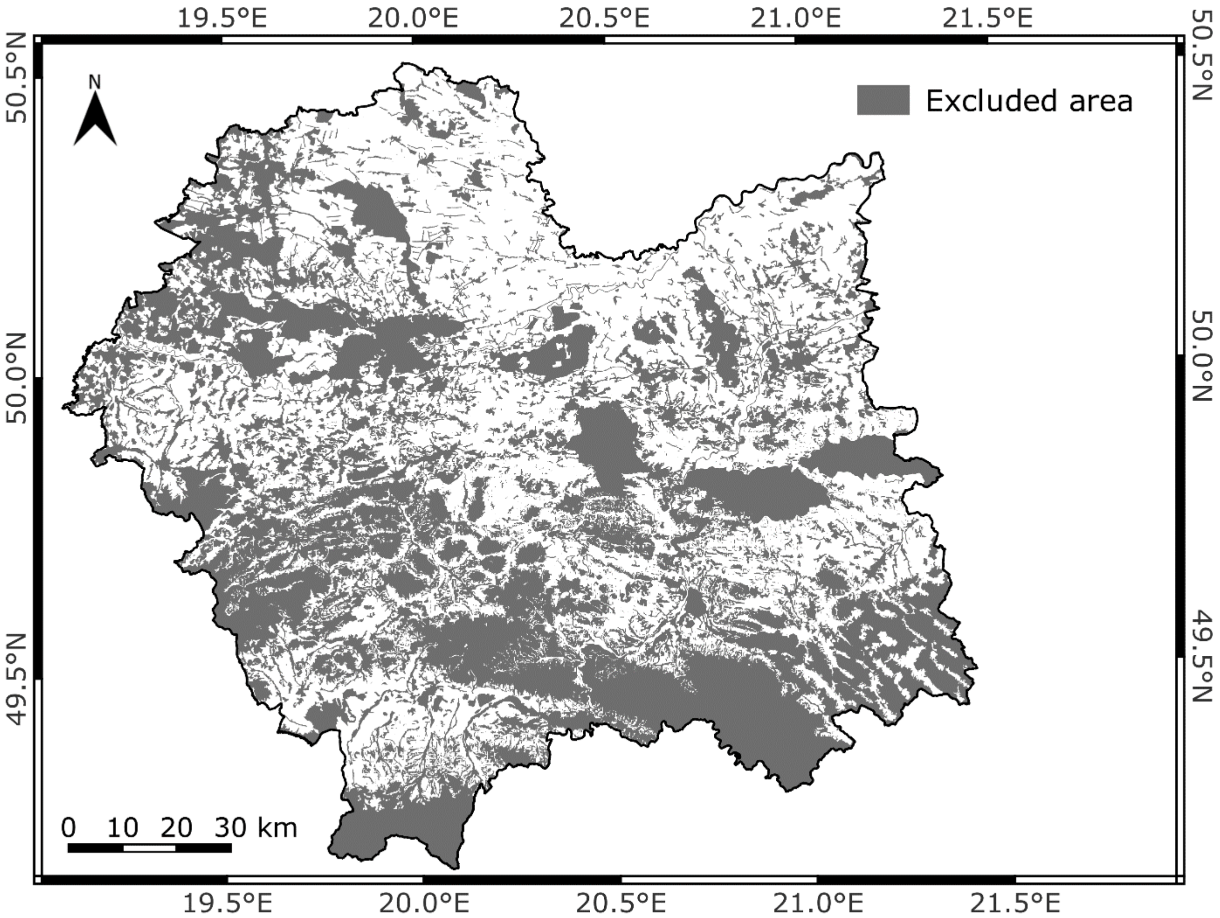


**Figure 3.4** Map of excluded land
*Source: own elaboration*

### 3.5.1. Criteria ranking and mapping

The criteria values were divided into five ranges and ranked to determine the most favorable location for PV power plants. Suitability was ranked as: excluded, very low, low, moderate, high, very high. These ranks correspond to the numerical values respectively: 0, 1, 2, 3, 4, 5.

- Solar irradiation

According to expert opinion, the most important factor in determining the location of photovoltaic farms is solar radiation as defined by Global Horizontal

Irradiance. The GHI represents the annual average irradiance taking into account the shadow effect. The radiation data were taken from surface metrology [26]. Although [3] presents as economically viable locations with a GHI higher than 1300 $kWh/m^2$, it was assumed that changing electricity prices significantly affect the economics. Therefore, the entire GHI range in the study was assumed. In order to select economically justified areas, the irradiation range was divided according to the following classifications: very low (<800 $kWh/m^2$ per year), low (800-900 $kWh/m^2$ per year), moderate (900-1000 $kWh/m^2$ per year), high (1000-1100 $kWh/m^2$ per year), very high (>1100 $kWh/m^2$ per year). The classification is shown in Table 3.6.

**Table 3.6** Solar irradiance classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Solar irradiance (kW/(m2·year)) | Very low | <800 | 1 |
| | Low | 800-900 | 2 |
| | Moderate | 900-1000 | 3 |
| | High | 1000-1100 | 4 |
| | Very high | >1100 | 5 |

*Source: own elaboration*

To create the GHI map, data in raster format were downloaded from [26]. Then the raster was cropped to the region of Malopolska. The raster layer was converted into a vector layer using the vectorization tool in QGIS software. Polygons belonging to the same classifications were identified and then merged. In style properties, rankings were assigned to corresponding colors. The GHI classification map is shown in Figure 3.5.

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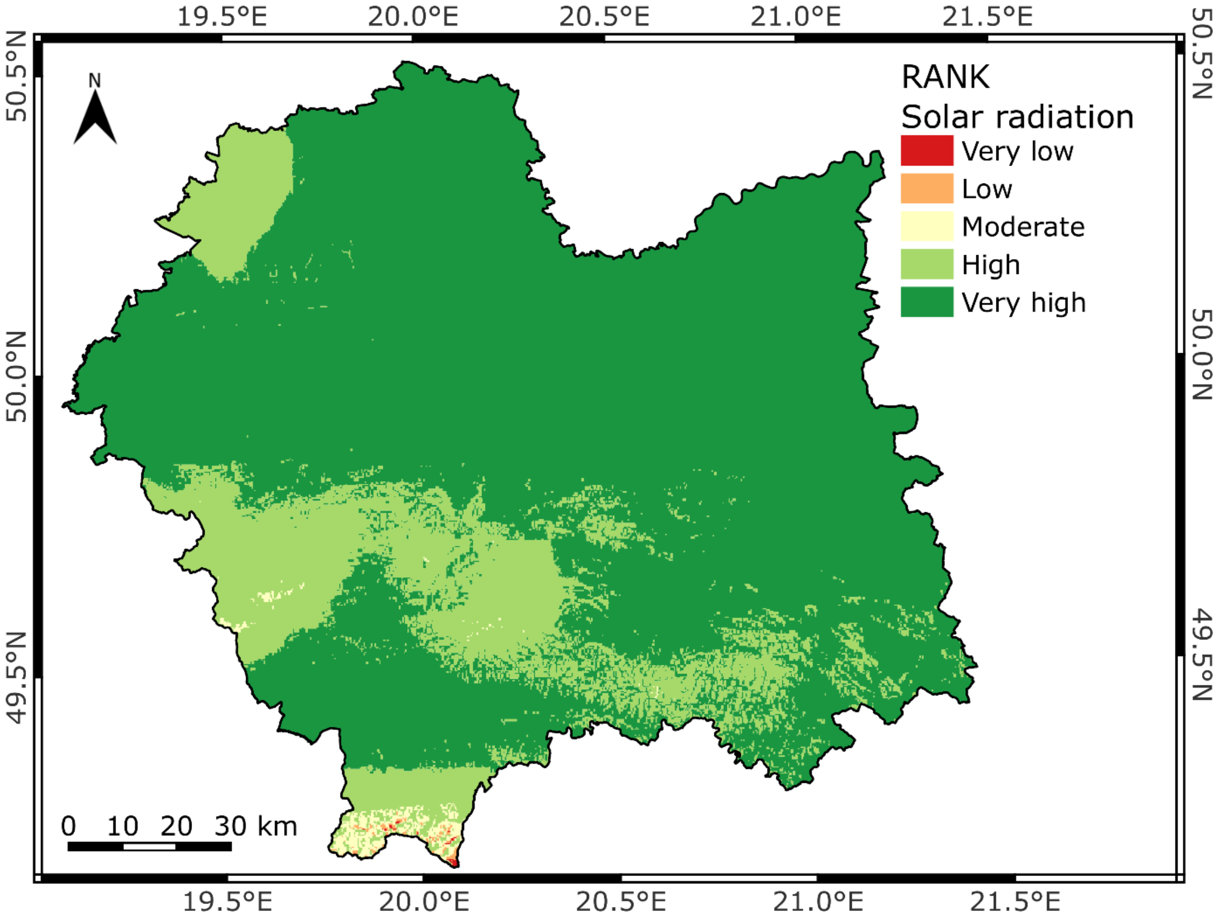


**Figure 3.5** Solar radiation classification map
*Source: own elaboration*

- Average annual temperature

The second most important criterion was chosen to be the average annual temperature. Therefore, temperature ranges were selected to improve the performance of photovoltaic farms. For the studied region, the temperature range was taken from [26]. In this thesis, the selected classifications were selected: very low (>9 °C), low (7-9 °C), moderate (4-7 °C), high (2-4 °C), very high (<2 °C). The classification is shown in Table 3.7.

**Table 3.7** Temperature classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Temperature (°c.) | Very low | >9 | 1 |
| | Low | 7-9 | 2 |
| | Moderate | 4-7 | 3 |
| | High | 2-4 | 4 |
| | Very high | <2 | 5 |

*Source: own elaboration*

To determine the annual average temperature classification map, as with the GHI, data were downloaded in raster format from [26]. The steps were then repeated as for the global horizontal irradiation map. The annual average temperature classification map is shown in **Figure *3.6***.

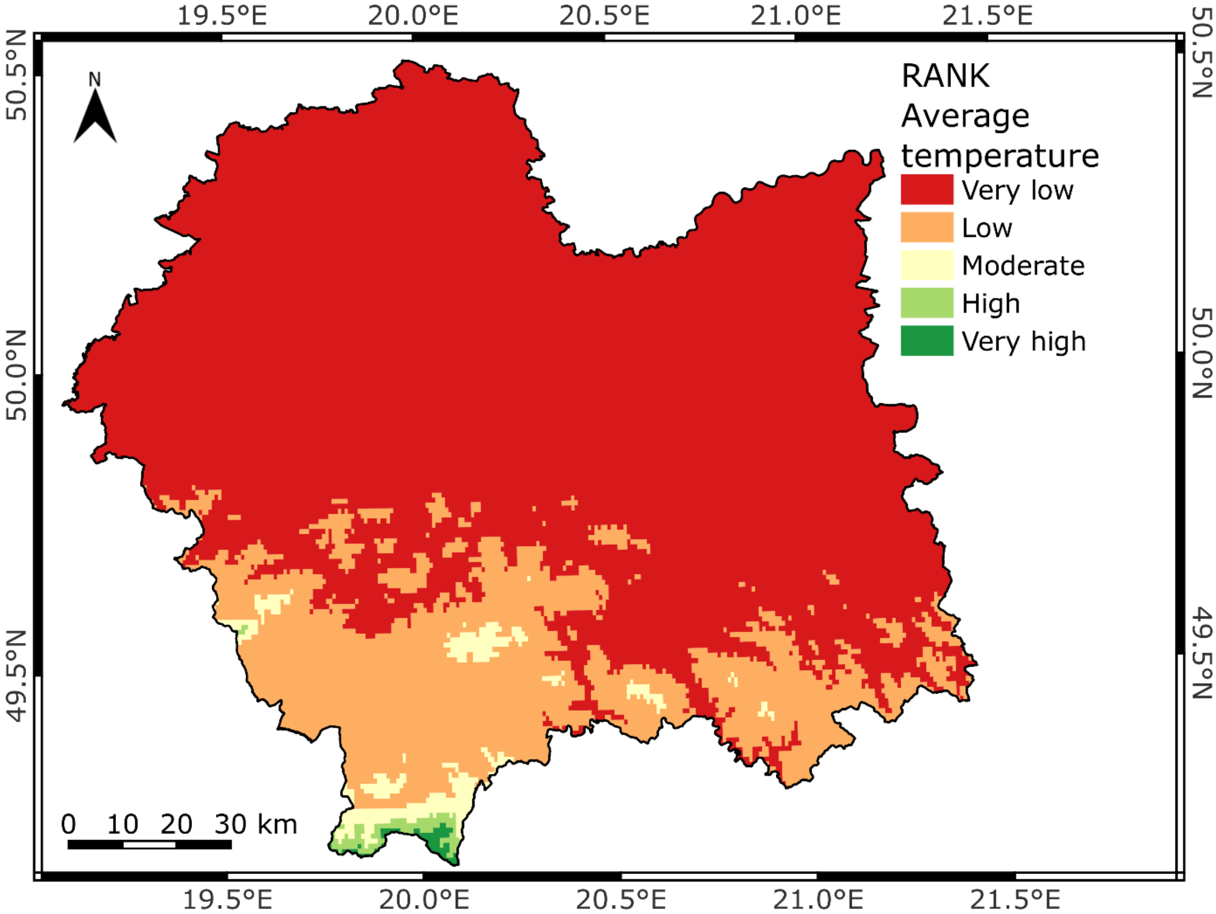


**Figure 3.6** Annual average temperature classification map
*Source: own elaboration*

- Land slope

As mentioned earlier, the construction of photovoltaic farms is mostly carried out on flat land. Sloping ground is technically challenging and increases costs. Different classifications in terms of slope can be found in scientific studies [29]. In this thesis, it was decided to exclude areas with slopes exceeding 11% and assigned the value 0. The remaining land was divided by classification: very low (9-11%), low (7-9%), moderate (5-7%), high (3-5%), very high (<3%). The classification is shown in Table 3.8.

**Table 3.8** Land slope classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Land slope (%) | Excluded | >11 | 0 |
| | Very low | 9-11 | 1 |
| | Low | 7-9 | 2 |
| | Moderate | 5-7 | 3 |
| | High | 3-5 | 4 |
| | Very high | <3 | 5 |

*Source: own elaboration*

The data to create the slope classification map was taken from [27]. A numerical terrain model in raster format was downloaded. The resolution of the downloaded map is 100 m. Then the terrain analysis tool in QGIS software – 'slope' was used. A raster layer was obtained, which was transformed into a vector layer through vectorization. The style was given unique values in terms of ranks. The land slope classification map is shown in **Figure *3.7***. We can see that the northern areas are more lowland, while the southern areas are defined by highlands and mountains.

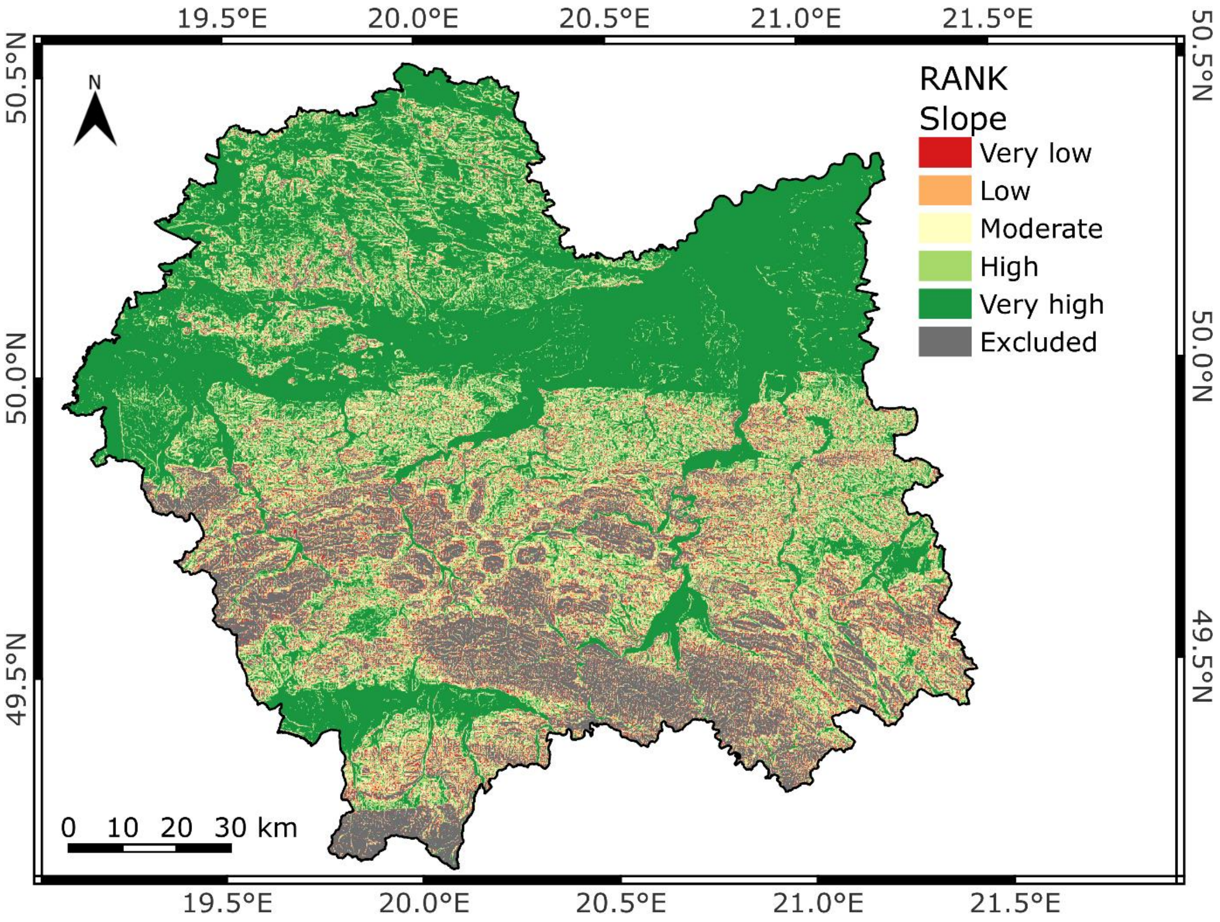


**Figure 3.7** Land slope classification map
*Source: own elaboration*

- Land cover

Another key factor in selecting areas for PV farms is land cover. In Poland, according to the current law, photovoltaic farms can be built on land of class IV, V, VI and on wastelands. In addition, the investment must be approved by the zoning plan. Unfortunately, due to lack of data regarding the land classes in the Malopolska region, the classification was done based on the Corine Land Cover map (Figure 3.3). The range was divided according to the codes (Appendix 1). First, all anthropogenic areas, forests, wetlands and water areas were excluded. They were given values of 0. Exposed rock, which causes technical problems with the mounting system, was considered the least suitable land. Therefore, a rank of very low was assigned and given a value of 1. Due to its agricultural use the low ranking (value 2) includes arable land and orchards and plantations. Grasslands and natural pastures, cropland and allotment systems, woodlands and shrub vegetation in a state of change were classified as moderate (value 3). Land primarily occupied by agriculture with a high proportion of natural areas and land with scattered vegetation was classified as high (value 4). Grasslands and natural pastures and heathlands and rushes were ranked as very high (value 5). The classification with respect to CLC codes is shown in Table 3.9.

**Table 3.9** Land cover classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Land cover (CLC codes) | Excluded | 111, 112, 121, 122, 124, 131, 132, 133, 141, 142, 311, 312, 313, 411, 412, 511, 512 | 0 |
| | Very low | 332 | 1 |
| | Low | 211, 222 | 2 |
| | Moderate | 231, 242, 324 | 3 |
| | High | 243, 333 | 4 |
| | Very high | 321, 322 | 5 |

*Source: own elaboration*

The land cover classification map (***Figure 3.8***) was created based on the Corine Land Cover map. In the attribute table, a coefficient was created according to rank.

Then polygons with the same coefficient values were combined and colors were classified according to the coefficient.

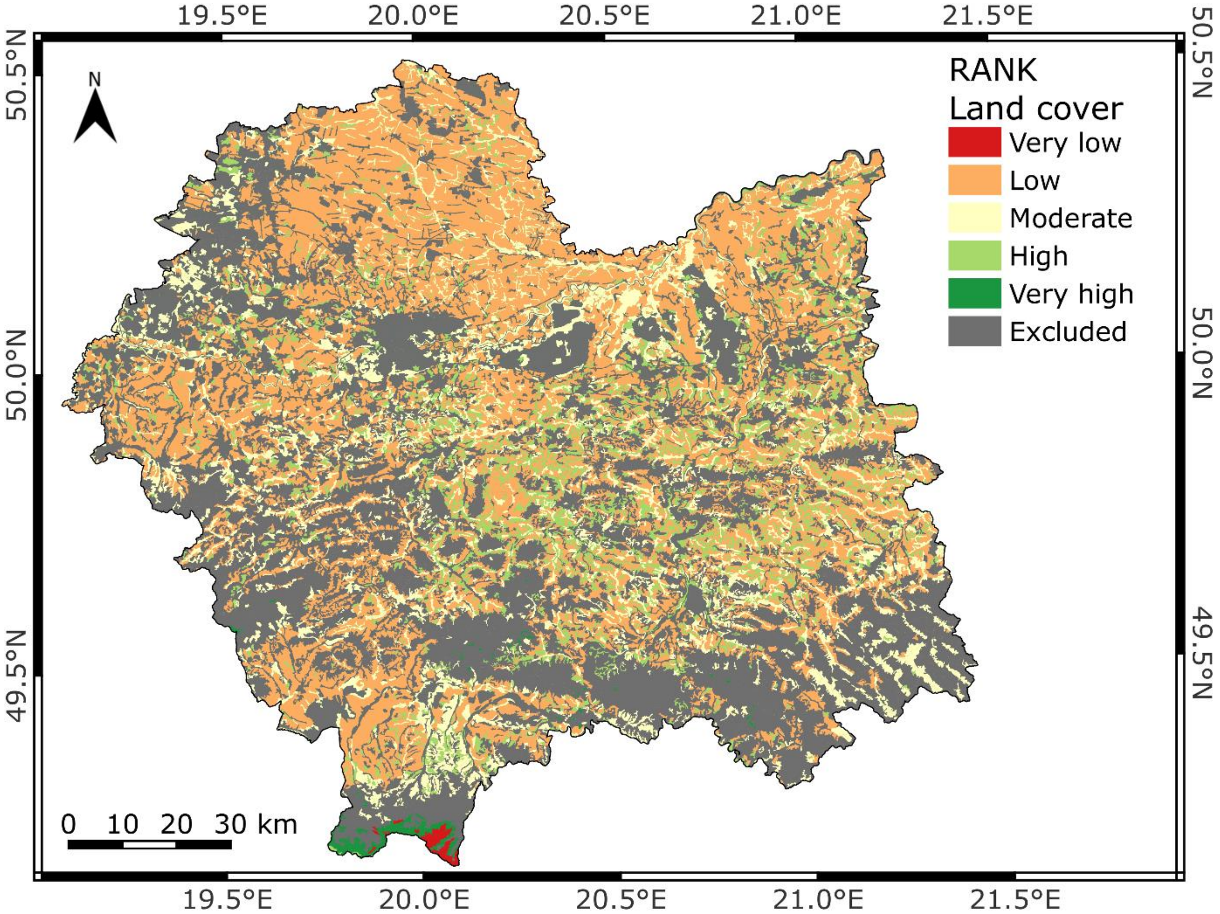


**Figure 3.8** Land cover classification map
*Source: own elaboration*

- Distance from roads

Transportation costs also play a large role in PV investment. Economic factors determine that locations away from roads are unsuitable. Therefore, the following classification in terms of distance from roads was adopted: very low (>1000 m), low (750-1000 m), moderate (500-750 m), high (250-500 m), very high (<250 m). These data are shown in the Table 3.10.

**Table 3.10** Distance from roads classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Distance from roads (m) | Very low | >1000 | 1 |
| | Low | 750-1000 | 2 |
| | Moderate | 500-750 | 3 |
| | High | 250-500 | 4 |

| Criteria | Rank | Range | Values |
|---|---|---|---|
| | Very high | <250 | 5 |

*Source: own elaboration*

The vector layer showing roads in Malopolska was downloaded from [27]. In order to visualize the distance classification from roads, the vector processing tool in QGIS program - 'buffer' was used. Linear objects have been surrounded by fields according to the ranges given in the table above. Then, as in other cases, unique colors were assigned according to ranks. The distance from roads classification map is shown in **Figure *3.9*Błąd! Nie można odnaleźć źródła odwołania.**.

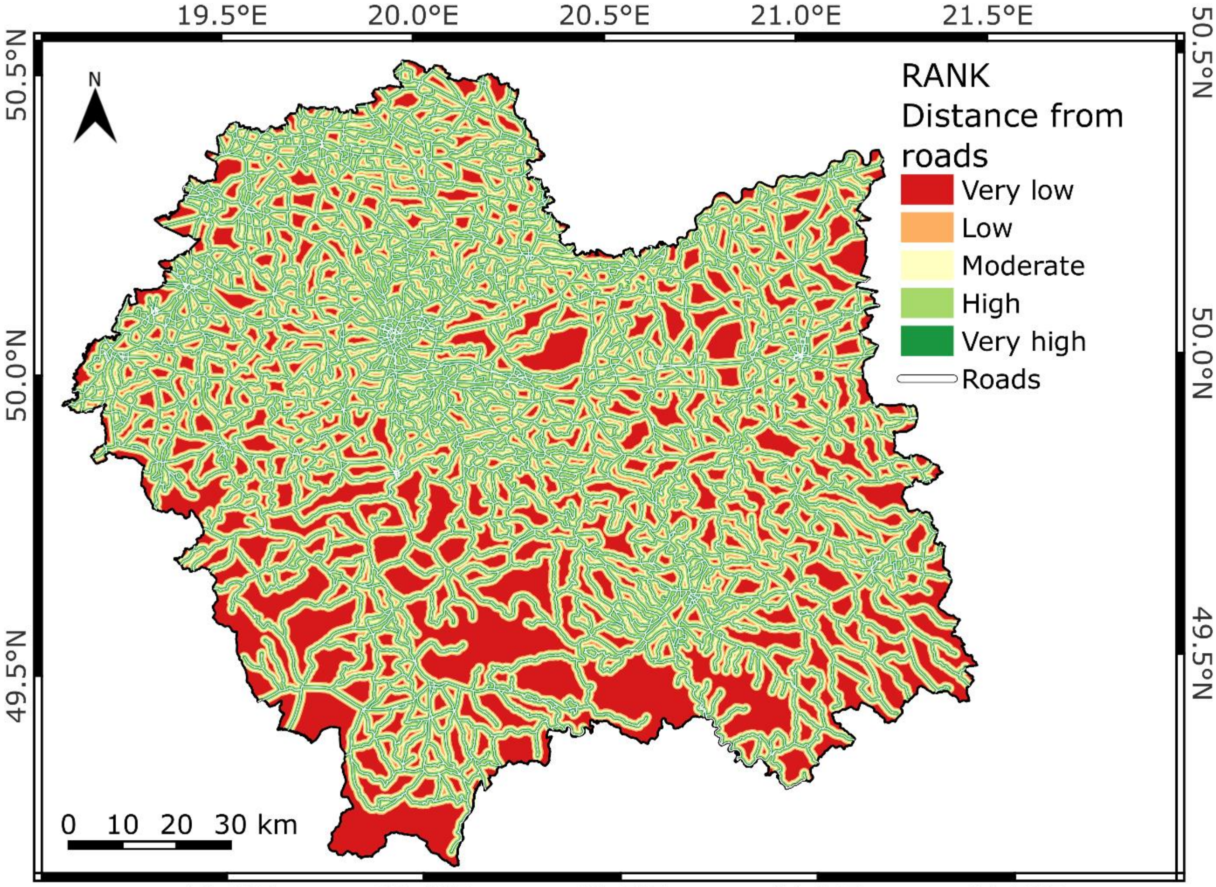


**Figure 3.9** Distance from roads classification map
*Source: own elaboration*

- Distance from cities/residential area

Distance from cities is another important factor in selecting locations for PV farms. Areas close to cities are less attractive due to development plans. Therefore, in this thesis the distance was classified as suitability as follows: very low (<500 m), low (500-1500 m), moderate (1500-3000 m), high (3000-4000 m), very high (>4000 m). The classification is shown in Table 3.11.

**Table 3.11** Distance from residential area classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Distance from cities (m) | Very low | <500 | 1 |
| | Low | 500-1500 | 2 |
| | Moderate | 1500-3000 | 3 |
| | High | 3000-4000 | 4 |
| | Very high | >4000 | 5 |

*Source: own elaboration*

A Corine Land Cover map was used to create a map of the classification in terms of distance to cities and populated areas. Anthropogenic areas were buffered as they were for road classifications. The map is shown in Figure 3.10.

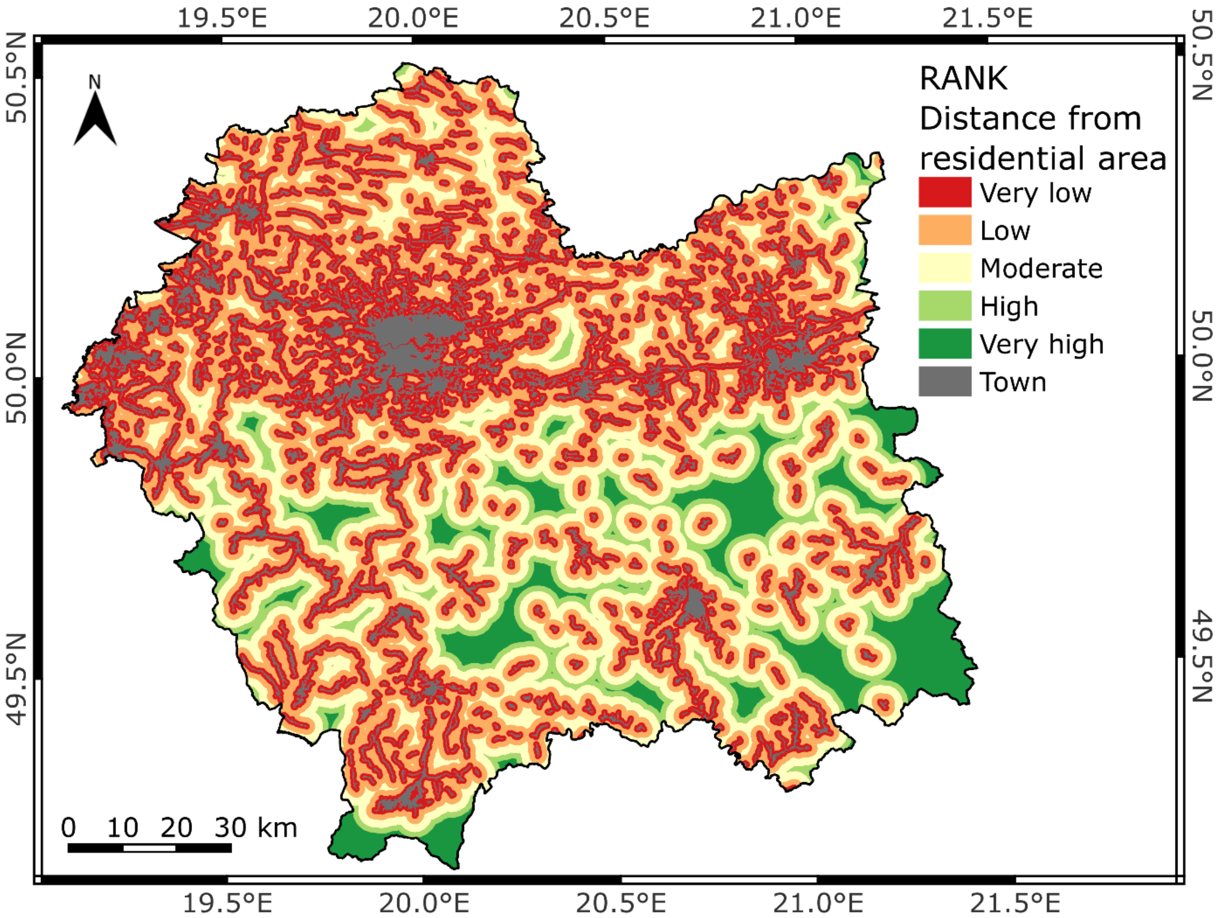


**Figure 3.10** Distance from residential area classification map
*Source: own elaboration*

- Distance from forests

Proximity to a forest can result in shading of PV panels in a solar power plant. Therefore, areas at a certain distance from forests were considered more suitable. The following classification in terms of suitability was adopted: very low (<30 m), low (30-60 m), moderate (60-90 m), high (90-120 m), very high (>120 m). The classification of distances to forests is shown in Table 3.12.

**Table 3.12** Distance from forests classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Distance from forest (m) | Very low | <30 | 1 |
| | Low | 30-60 | 2 |
| | Moderate | 60-90 | 3 |
| | High | 90-120 | 4 |
| | Very high | >120 | 5 |

*Source: own elaboration*

Corine Land Cover map was used to create the forest distance classification map. The processes were repeated in QGIS software. The resulting map is shown in Figure 3.11.

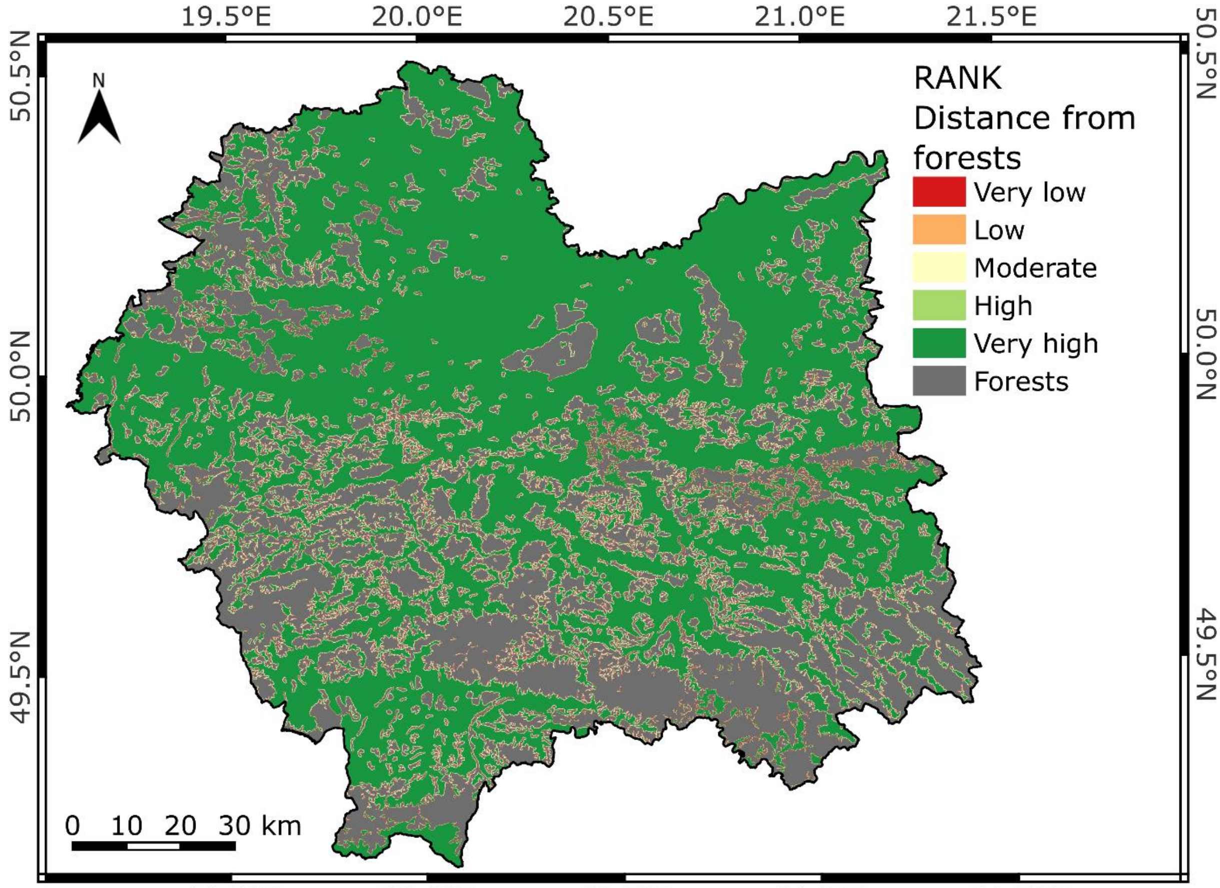


**Figure 3.11** Distance from forests classification map
*Source: own elaboration*

- Distance from stream/waterbodies

Distance from rivers and bodies of water also influences site selection. It was assumed that the more suitable locations are those that are further from water bodies. The following classification was adopted: very low (<500 m), low (500-1000 m), moderate (1000-1500 m), high (1500-2000 m), very high (>2000 m). Distance from water bodies classification is presented in Table 3.13.

**Table 3.13** Distance from water bodies classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Distance from stream (m) | Very low | <500 | 1 |
| | Low | 500-1000 | 2 |
| | Moderate | 1000-1500 | 3 |
| | High | 1500-2000 | 4 |
| | Very high | >2000 | 5 |

*Source: own elaboration*

Corine Land Cover map was used to create distance classification map of waterbodies. Distances were determined through the 'buffer' tool. The map is shown in Figure 3.12.

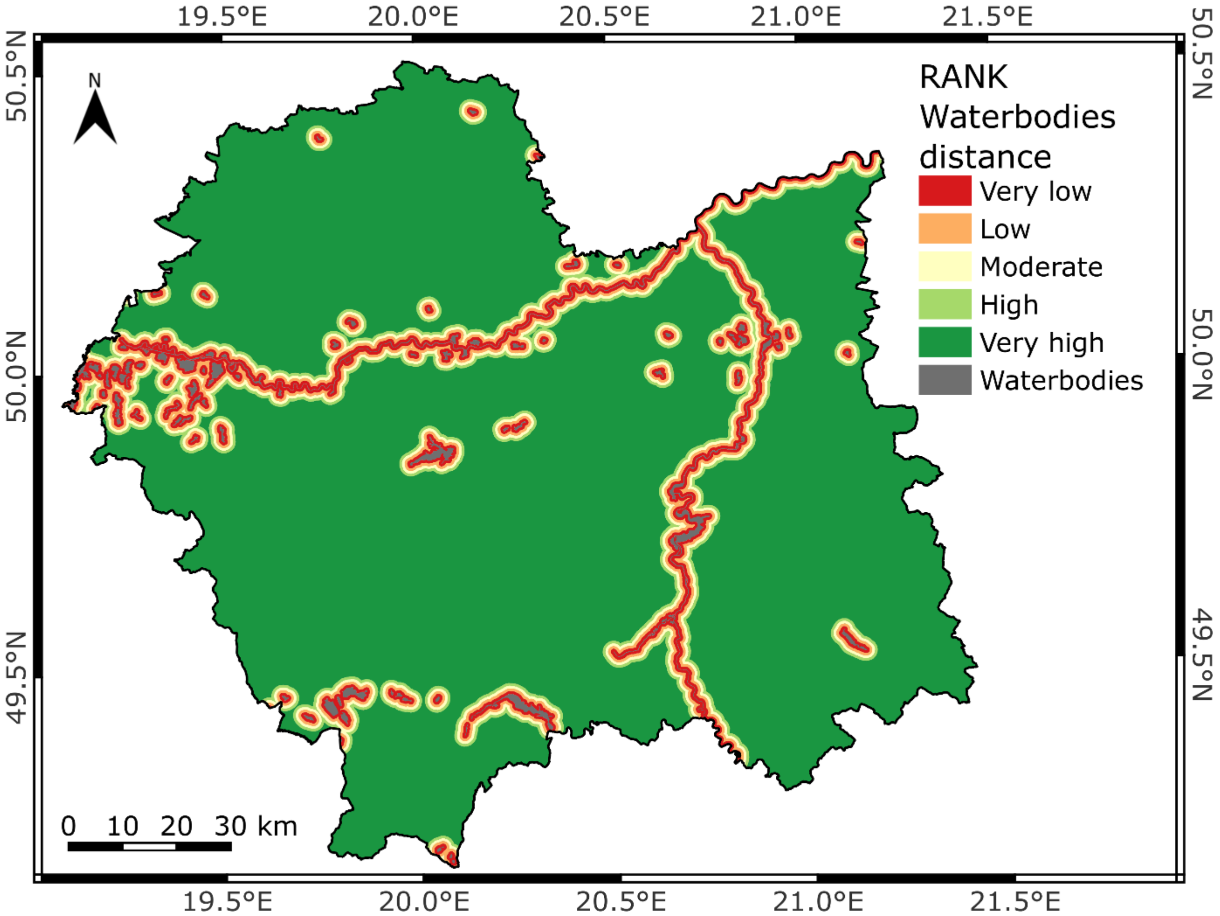


**Figure 3.12** Distance from water bodies classification map
*Source: own elaboration*

- Distance from power lines

Distance from power lines is an important factor due to the cost of investment. The greater the distance, the less suitable the location is for a photovoltaic farm. A classification of suitability in terms of distance was adopted: very low (>1000 m), low (750-1000 m), moderate (500-750 m), high (250-500 m), very high (<250 m). The data is presented in the Table 3.14.

**Table 3.14** Distance from power lines classification

| Criteria | Rank | Range | Values |
|---|---|---|---|
| Distance from power transmission lines (m) | Very low | >1000 | 1 |
| | Low | 750-1000 | 2 |
| | Moderate | 500-750 | 3 |
| | High | 250-500 | 4 |
| | Very high | <250 | 5 |

*Source: own elaboration*

To determine the classification map in terms of distance from power lines, data from [27] were used. Due to grid voltage variations and power losses, medium voltage lines were adopted as the most suitable for PV farms. Then, geoprocessing was done as in the case of distance from roads. The map is illustrated in Figure 3.13.

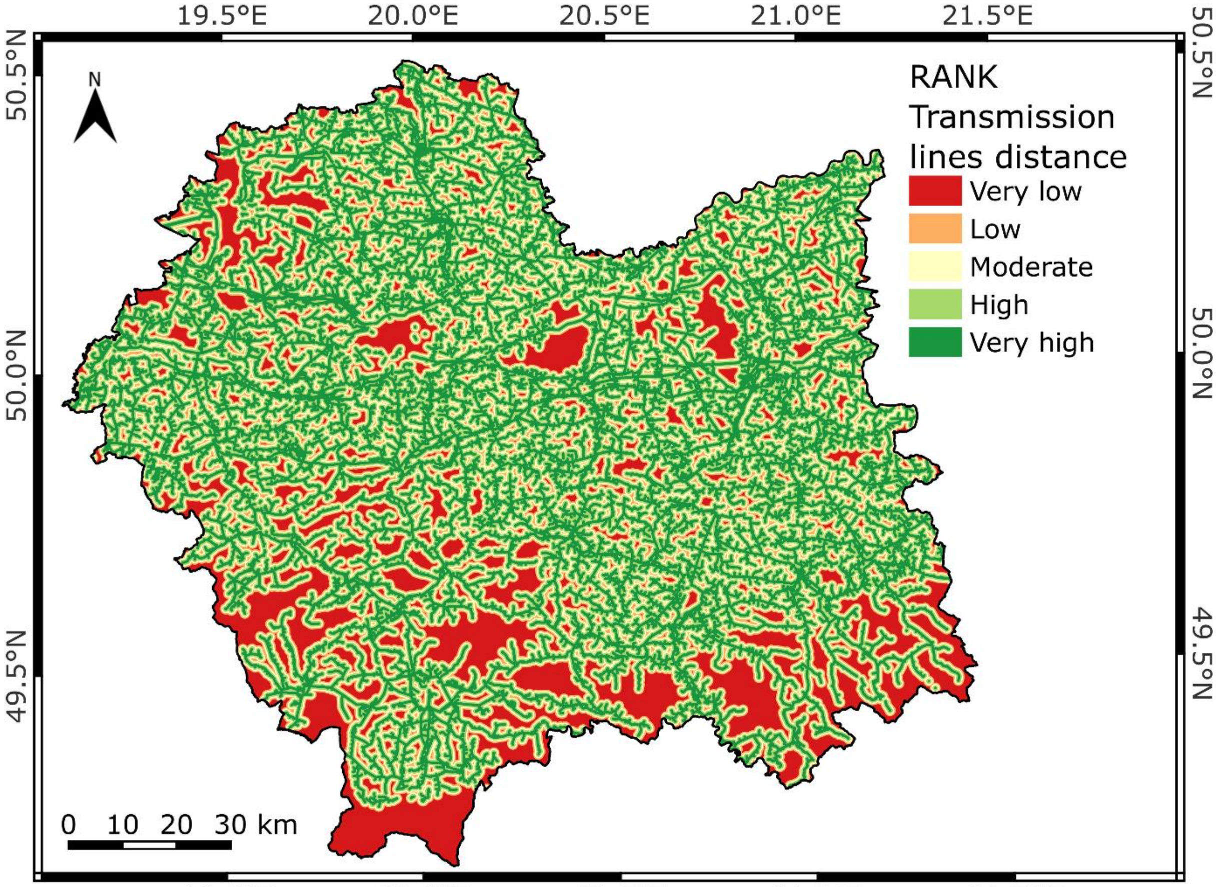


**Figure 3.13** Distance from power transmission lines classification map
*Source: own elaboration*

## 3.6. PV land suitability

In order to create a site suitability map for PV systems, all the criteria maps were combined into one using the aggregate tool. The final $PV_{Rank}$ parameter was then calculated for each polygon of the layer. The calculation took into account the importance of the criteria, the classifications adopted and used the mathematical formula (3.7).

$$PV_{Rank} = \sum_{i} w_i \cdot R_i \tag{3.7}$$

Where, $PV_{Rank}$ is land suitability parameter, $w_i$ refers to weight vector of each criteria, $R_i$ is classification values.

$PV_{Rank}$ scores were obtained in the range of 2.078-4.504. The scores were divided into equal ranges in terms of relevance: very low (<2.563), low (2.563-3.048), moderate (3.048-3.533), high (3.533-4.018), very high (>4.018). In this way, a map of suitability in terms of criteria was obtained.

## 3.7. Levelized cost of energy

The Levelized Cost of Electricity (LCOE) is the average cost of electricity considering the entire life of the system. LCOE is a measure commonly used in the electricity sector to compare different generation technologies. Therefore, this research paper uses LCOE in estimating the cost of energy in selected locations and evaluating the profitability of investment in photovoltaic farms. The lower it is, the more competitive the generation source is. LCOE helps investors to make final decisions about the investment. It speeds up and simplifies the complexity of decision making and helps evaluate different solutions. Although LCOE is valuable in the selection of energy systems, it has its limitations. Due to complexity and uncertainty of assumptions, it can give wrong results and be misinterpreted. For photovoltaic systems, the uncertainty of quantities such as lifetime, degradation, and failures can result in a discrepancy compared to reality.

LCOE is calculated by comparing the total system cost over the life of the plant to the total amount of energy produced by the plant. Two methods are mainly used to calculate LCOE: the net present value (NPV) or the annuity method. The NPV method considers the current cost-related cash outflows discounted over the life of the system and the cash inflows directly related to electricity production. Discounting energy production is important for financial reasons because production directly accounts for sales revenue. Therefore, production that is distant in time reduces the present value of revenue. Annual expenses over the life of the system consist of capital and operating costs. The general formula for LCOE is shown in Equation (3.8).

$$LCOE = \frac{I_o + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \tag{3.8}$$

Where: $LCOE$ is Levelized Cost of Electricity (PLN/kWh), $I_o$ is investment expenditure (PLN), $A_t$ is annual operating cost (PLN/year), $M_{t,el}$ is produced amount of electricity (kWh/year), $i$ is discount rate (%), $n$ is lifetime (years), $t$ is year of lifetime (1, 2, … $n$)

The annual expenditures consist of fixed costs and variable costs that include maintenance, repairs and other expenses related to the operation of the plant. The weighted average cost of capital (WACC) can be calculated based on the capital structure (equity, external financing, debt) and the cost of capital from each source. WACC is expressed in relation to the interest rate (discount factor).

Discounting costs and energy production over the life of the system ensures comparability. In this thesis, LCOE was used to compare selected sites, not to calculate return on investment. By regulation and tax law, and by the fact that LCOE does not take into account energy production per hour, this method is not applicable to calculating the profitability of individual investments. By adding additional influencing data it is possible to assess profitability, but for this purpose each investment should be assessed individually. For this purpose, a financial calculation based on cash flow model should be carried out. Due to the amount of data, such an assessment is beyond the scope of this thesis.

### 3.7.1. Locations

LCOE calculations for selected polygons could be performed using the 'mean coordinates' tool. By calculating the center of gravity of the subsets and giving the resulting points varying input data. However, the results obtained would be distorted by the different shapes and areas of these polygons. It is assumed that for a 1 MWp photovoltaic farm, the minimum plot size must be 2 hectares and the width should be at least 50 m. This is to guarantee the optimal operation of the PV system, by appropriate distances between rows of PV panels. Therefore, in order to compare the locations in terms of LCOE, it was decided to create points evenly distributed in Malopolska. Grid of points at distances equal to 1 km was created in QGIS using the regular points research tools. The grid was cropped over the area of the province. In this way, 15167 location points were obtained. Then points located in excluded areas were removed. In this way 8894 locations were determined to be included in the levelized cost of electricity calculations. A map of the points is shown in Figure 3.14.The coordinate system was changed to WGS 84 to determine the decimal coordinates of these points.

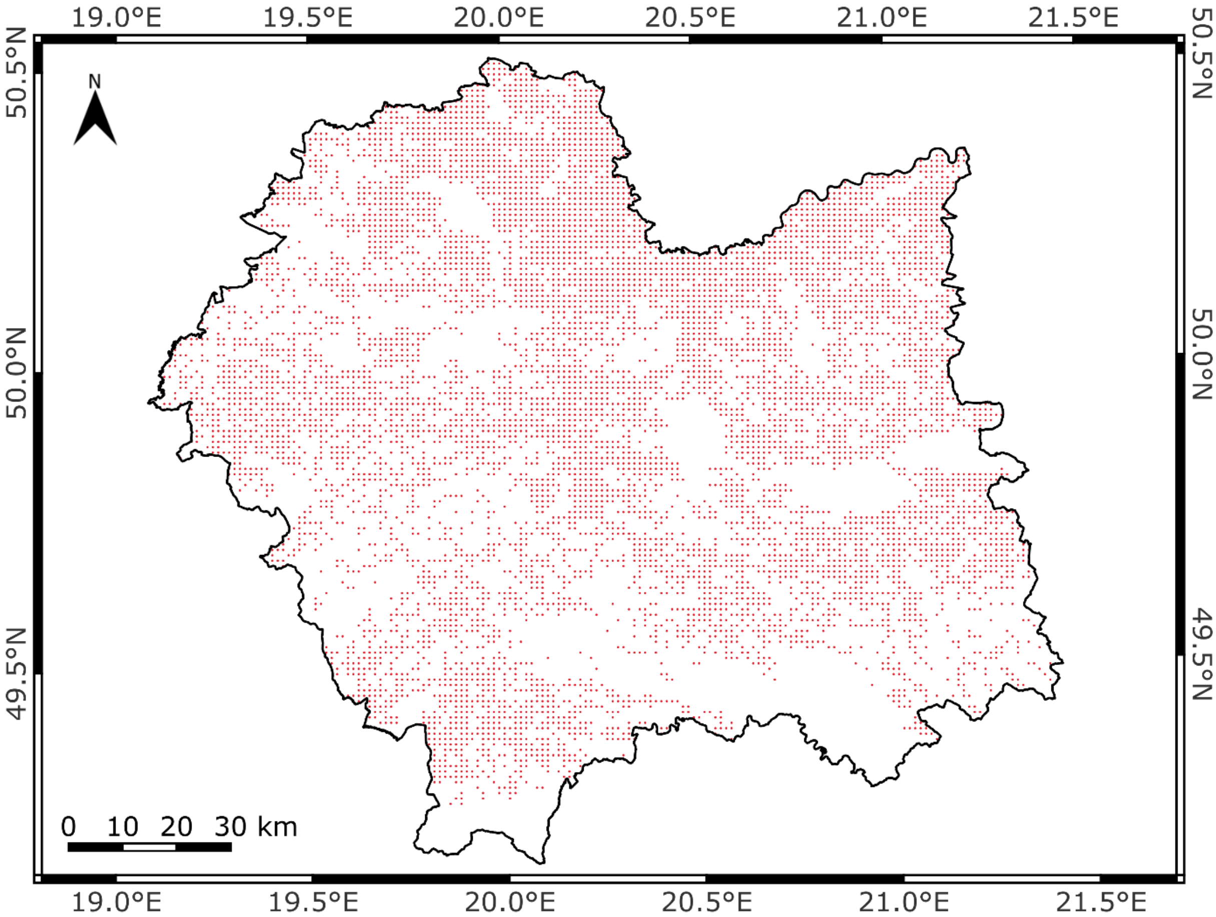


**Figure 3.14** Map of location points
*Source: own elaboration*

### 3.7.2. Assumptions

The profitability of investing in photovoltaic farms depends largely on energy production, but financial data such as investment and operating costs also have an impact. The cost of capital is also important, and depending on the source of financing, the investment may have a higher or lower profitability. Investment costs CAPEX and operating costs OPEX also vary with the size of the solar system. This is due to the so-called economies of scale, in which unit costs (relating to 1kWp installed) decrease as the rated capacity of the system increases. In 2021, for small rooftop installations (10 kWp), the average investment cost was about 5000 PLN/kWp, for larger installations (50 kWp) it was about 3200 PLN/kWp, while for PV farms (1 MWp) the costs were about 2700 PLN/kWp. In this thesis, the costs of electricity production were calculated for each location, assuming an installed capacity of 1 MWp. It was assumed that for the assumed photovoltaic farm the average CAPEX cost is 2.7 million PLN [30]. Due to the size of the photovoltaic system, not only the cost values but also their structure change. In this research study, the investment cost structure was adopted as shown in Table 3.15.

**Table 3.15** Investment cost structure for a PV farm with installed capacity of 1MWp

| PV farm component | Cost share (%) | Cost (PLN thou) |
|---|---|---|
| PV modules | 43 | 1161 |
| Inverters | 7 | 189 |
| Transformer station | 12 | 324 |
| Construction | 22 | 594 |
| Fencing | 0,5 | 13,5 |
| Overvoltage and lightning protection | 1 | 27 |
| Protection | 0,5 | 13,5 |
| DC cabling and connectors | 1 | 27 |
| AC and ZK cabling | 2 | 54 |
| Lighting and monitoring | 0,5 | 13,5 |
| Site organization | 0,5 | 13,5 |
| Additional devices and equipment | 1 | 27 |
| Design work - building permit | 1 | 27 |
| Construction work and measurements | 8 | 216 |

*Source: compiled from [31]*

The following financing parameters were assumed in the LCOE calculation. It should be noted that financing terms vary depending on risk and expected rate of return. In addition, the cost of equity and debt can vary depending on interest rates. In many studies, the investment financing aspect is variable for different projects and technologies. In this study, a constant discount rate was assumed for all locations. It is calculated by the weighted average cost of capital WACC according to Equation (3.9). Photovoltaic farms have a higher WACC parameter due to the higher expectations of investors compared to small installations.

$$WACC = k_e \frac{K_E}{K} + k_d \frac{K_D}{K} \tag{3.9}$$

Where: $WACC$ is weighted average cost of capital (%), $k_e$ is return on equity (%), $K$ is value of invested capital (PLN), $K_E$ is equity value (PLN), $k_d$ is interest rate on foreign capital/debt (%), $K_D$ is value of foreign capital/debt (PLN)

The WACC parameter is calculated as a nominal value, taking into account interest rates. Using real values would involve taking the inflation rate into account. Forecasting inflation over the long term is difficult and often subject to error. Therefore, all costs of capital are considered in nominal terms. This paper takes the cost of foreign capital (debt) as 3%, return on equity as 6.5%. In addition, it was assumed that debt represents 80% of the total capital in the investment, equity represents 20%. The lifetime $n$ of the farm was assumed to be 30 years. Therefore, the WACC was 3.7%. It was assumed that the average CAPEX cost is PLN 2.7 million and the OPEX cost is 1% of the CAPEX cost annually. Due to the deterioration of PV panels each year, the degradation factor was set at 0.25%. The assumed data are presented in Table 3.16.

**Table 3.16** Assumed data for a 1 MWp PV farm

| Ground-based PV system (1 MWp) | |
|---|---|
| Lifetime (years) | 30 |
| Share of debt (%) | 80 |
| Share of equity (%) | 20 |
| Interest rate on debt (%) | 3 |
| Return on equity (%) | 6,5 |
| WACC nominal (%) | 3,7 |
| Annual degradation (%) | 0,25 |
| CAPEX (PLN million) | 2,7 |
| OPEX (% of CAPEX) | 1 |

*Source: compiled from [32]*

### 3.7.3. Input data

Electricity production from PV farms was estimated through the PVGIS portal. The 'Performance of grid-connected PV' tool was selected to calculate the monthly and annual production from the PV system. The estimates include solar radiation, temperature, humidity, wind speed and PV panel technology. The calculations were based on PVGIS-SARAH2 solar database. Crystalline silicon, the most commonly used in PV farms, was selected as the PV panel technology. The system losses were assumed to be 14% and the installation method was free-standing. In addition, panel slope and azimuth optimization were enforced for each location [33]. By the number of locations, it was decided to use Application Programming Interface. The script was written in Python language, which resulted in annual electricity production $pPV$ (kWh/year) from 1 MWp at each point in first year. The source code for the script is shown in Appendix 2.

In the thesis it was assumed that the difference in investment costs between the locations is due to the different distances from the power lines $pDistance$ (m). Processing tool was used to determine the shortest distance of each point to the medium voltage line: shortest path (layer to point) calculation. Based on [34], the cost of a medium voltage cable line is assumed to be 200 PLN/m.

Operating costs, on the other hand, depend on land lease prices and are dependent on land cover. Due to insufficient data on land classes and rental prices, it was assumed on the basis of [35] that the annual unit lease costs $pLeaseUnit$ (PLN/(ha·year)) are 15 thousand PLN for arable land and 12 thousand PLN for wasteland and non-agricultural land. In addition, it was assumed that 2 hectares of land are needed to build 1 MWp PV farm.

### 3.7.4. Calculations

Levelized cost of electricity calculations were performed based on a general formula (Equation (3.8)) including assumptions and input data. The GAMS software was used for the calculation and the code is presented in the Appendix 2. The input data of energy production, distance to power lines, and unit land lease cost were placed in a worksheet named Input_Data of Excel in tabs respectively: PVproduction, Distance, Lease. Total investment expenditure $I_o$ (PLN) was calculated according to the Equation (3.10), adding the average CAPEX cost and cable cost.

$$I_o = CAPEX + pDistance \cdot pCableCost \tag{3.10}$$

Where: $CAPEX$ is average investment cost of 1 MWp of PV farm (2.7 PLN million), $pDistance$ is distance of location to power line (m), $pCableCost$ is unit cost of medium voltage cable (200 PLN/m)

Land lease costs $pLeaseCost$ (PLN/year) were calculated based on the following Equation (3.11).

$$pLeaseCost = pLeaseUnit \cdot pArea \tag{3.11}$$

Where $pLeaseUnit$ is the annual unit lease costs (12000 PLN/(ha·year) for arable land and 15000 PLN/(ha·year) for wasteland and non-agricultural land), $pArea$ is land area needed for 1MWp PV farm (2 ha).

Operating costs $A_t$ (PLN/year) were calculated using the Equation (3.12), summing average operational expenses and the cost of land lease $pLeaseCost$ (PLN/year).

$$A_t = 1\% \cdot I_o + pLeaseCost \tag{3.12}$$

Electricity production $M_{t,el}$ (kWh/year) in a given year was calculated from Equations (3.13) and (3.14), assuming production in the first year consistent with PVGIS estimates $pPV$ (kWh/year), and panel degradation of 0.25% in subsequent years.

$$M_{1,el} = pPV \tag{3.13}$$

$$M_{t+1,el} = M_{t,el} \cdot 99.75\% \tag{3.14}$$

The discount rate $i$ (%) was assumed to be equal to the nominal weighted average cost of capital $WACC$ (3.7%) (Equation xxx).

$$i = pWACC \tag{3.15}$$

# 4. Results

This paper focuses on the Malopolska province area in southern Poland as an example of finding suitable locations for solar power plants. Due to the diversity of the terrain GIS and MCDA based modeling is useful for this type of research. This type of work can support regional scale renewable energy development plans. The open sourced program QGIS was used as the tool used for spatial analysis. It offers functionalities necessary for geographic analysis such as geodata management, editing and storage, geoprocessing, visualization and many others. Ease of use, large packages library and constantly developed program code makes this tool very useful for this type of work. The main result of the applied GIS and AHP research methodology is a map of optimal locations for photovoltaic farms. The identification of favorable sites is a very important factor especially for investors who want to reduce costs and increase efficiency of the system. The final maps divides the site into five categories of suitability (very low, low, moderate, high, very high) and excluded sites. In the next step, an economic analysis of the location was carried out. The levelized cost of electricity parameter was used to determine the more economically reasonable regions. For this purpose, GAMS software was used and the results were converted into a map in QGIS.

The following subsections discuss the major findings of the study. The results of the work in the first section are about finding and visualizing areas of suitability for PV systems. The analysis was performed using raster and vector data defined in subsections 3.3. The results were classified in vector data. The final PV suitability map was created based on subsection 3.6. The second section presents the results of the LCOE calculation. The calculations were performed according to subsection 3.7.

## 4.1. PV land suitability

The development of maps of the suitability of areas for photovoltaic systems was mainly based on the steps of geographic data collection and processing, criteria classification and weighting, and vector layers processing. Maps were developed based on exclusion criteria and decision options. The datasets were overlaid and by considering the weighting of the given criteria, a final map of the suitability of areas for PV farm construction was developed (Figure 4.1).

As can be seen from Figure 4.1 most of the land in the study region has high suitability for PV farm construction. The final results show that the most optimal areas are located in the central, eastern and southern parts of the Malopolska province. Excluding excluded areas, in these parts the distance from cities and the non-use of land for agricultural purposes result in favorable conditions. High suitability dominates the study area. It can be seen mainly in most of the northern areas due to high solar radiation and flat land surface. On the other hand, areas with low and very low suitability are few and scattered in the province. They include areas close to cities and mountainous areas where the ground slope is higher.

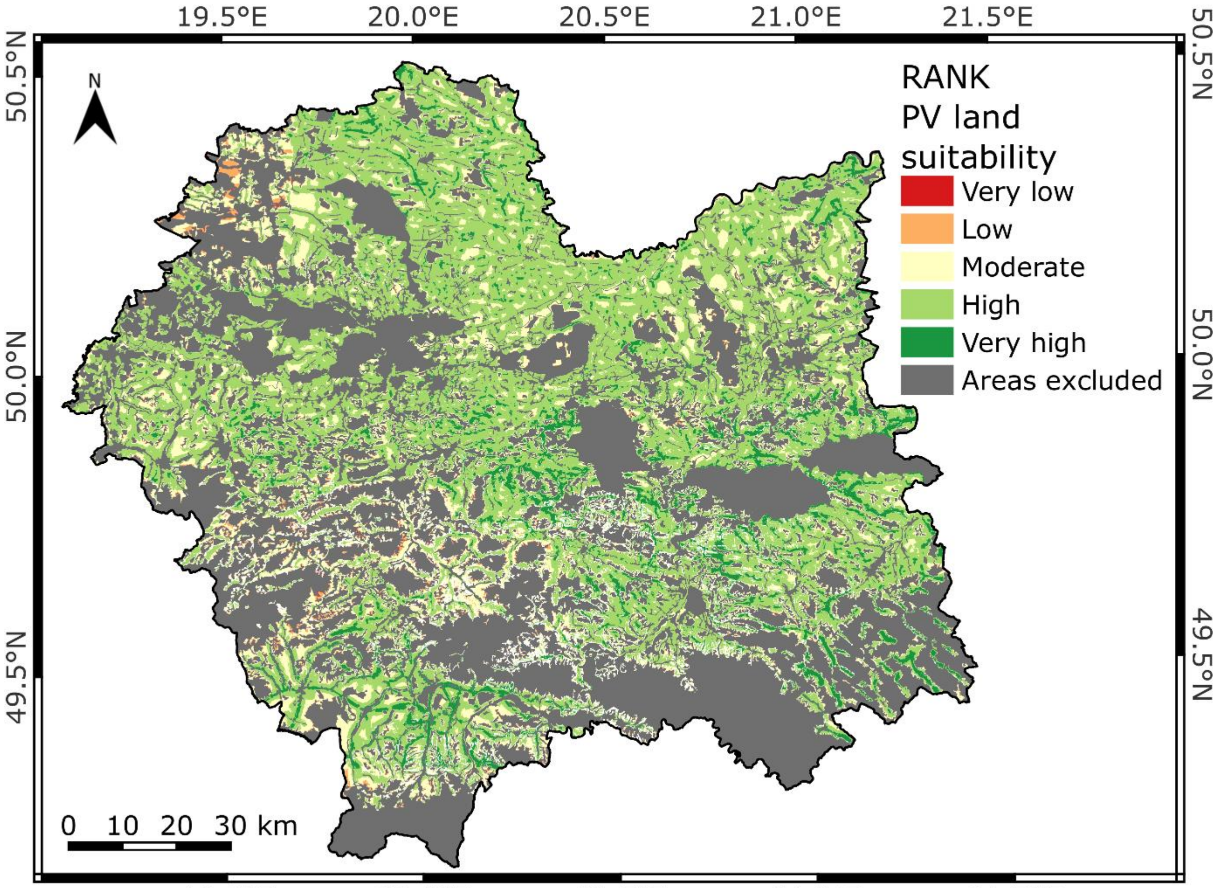


**Figure 4.1** PV land suitability map
*Source: own elaboration*

The land area fields by classification and proportion are shown in Table 4.1 and Figure 4.2. In summary, the results of the analysis showed that 7389.21 km2 is excluded from the possibility of PV farms, which is 48.6% of the total land area. The remaining results divide the suitability into: very low (approximate area equal to 8.92 km2 and share of 0.1%), low (approximate area equal to 198 km2 and share of 1.3%), moderate (approximate area equal to 1587 km2 and share of 10.5%), high (approximate area equal to 5253 km2 and share of 34.6%) and very high (approximate area equal to 752 km2 and share of 5%).

**Table 4.1** Area and land share by ranking

| Rank | Area (km2) | Share (%) |
|---|---|---|
| Excluded | 7389 | 48.6 |
| Very low | 8,92 | 0.1 |
| Low | 198 | 1.3 |
| Moderate | 1587 | 10.5 |
| High | 5253 | 34.6 |
| Very high | 752 | 5.0 |

*Source: own elaboration*

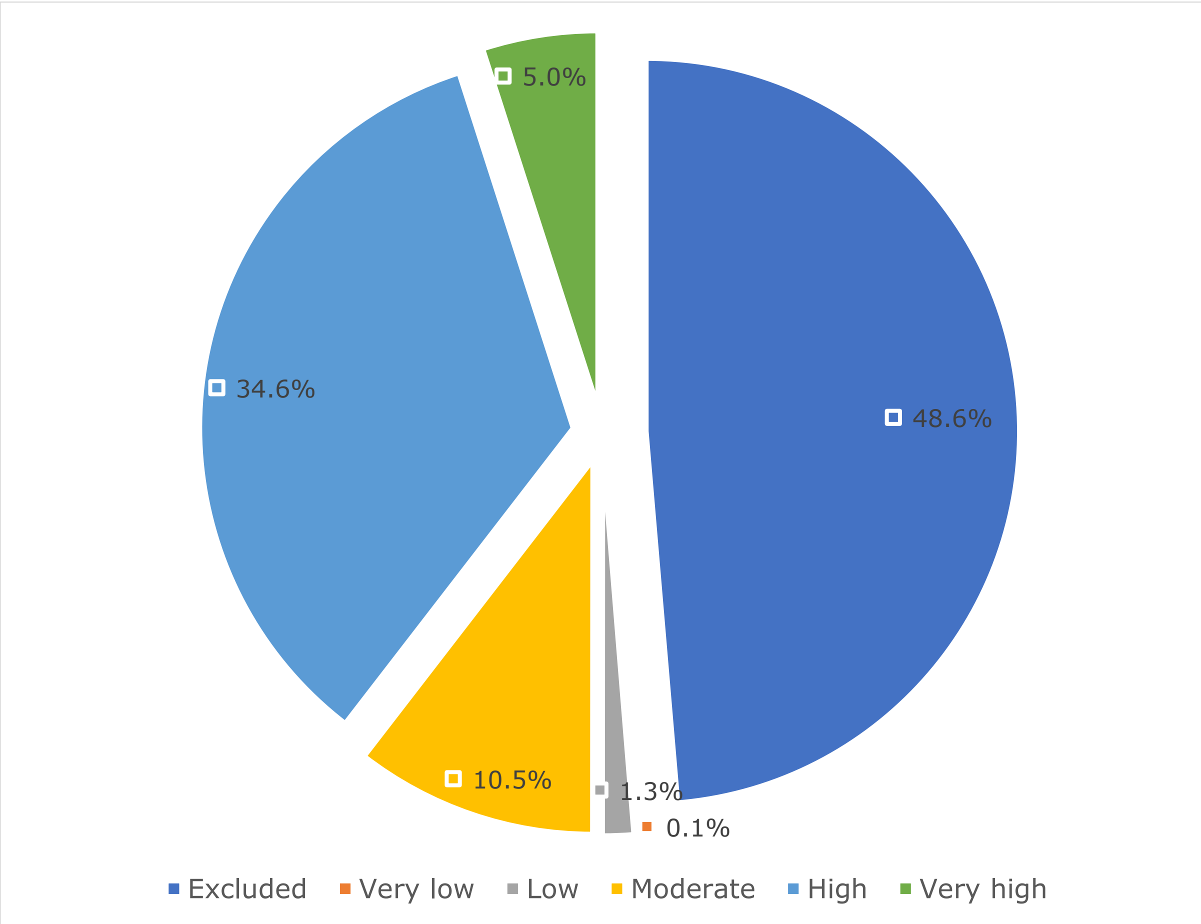


**Figure 4.2** PV suitability share of land
*Source: own elaboration*

## 4.2. Economic potential

This subsection determines the LCOE of solar farm technologies for the locations shown in Figure 3.14 to compare regions economically. This was done using the financial and cost data (subsection 3.7.2), the electricity production simulation performed in PVGIS, and the equations presented in 3.7.4. The simulation results in PVGIS showed that the annual electricity production from a 1 MWp PV farm ranges from 614411 kWh to 1096445 kWh. Lower production was observed in the southern part of the province, while higher production was observed in the north. The calculated levelized cost of electricity ranged from 0.187 PLN/kWh to 0.368 PLN/kWh depending on electricity production and costs. The average LCOE for all locations was 0.2 PLN/kWh and the median was 0.199 PLN/kWh. The calculated values are plausible and consistent with the literature [32].Figure 4.3 presents a summary of LCOE results in the form of a histogram. It illustrates the number of LCOE results broken down into ranges that differ by 0.001 PLN/kWh. By analyzing the histogram, it can be seen that most of the values are in the range of 0.191-0.203 PLN/kWh. The highest number of results was obtained for the range of 0.195-0.196 PLN/kWh.

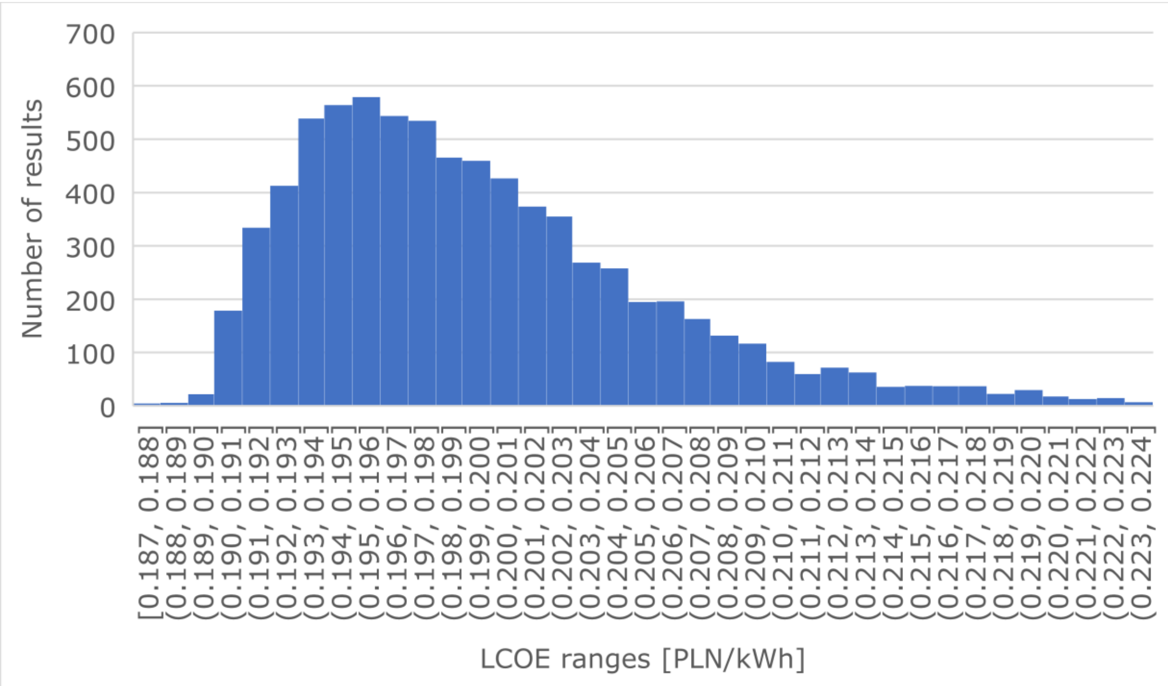


**Figure 4.3** Histogram of LCOE results
*Source: own elaboration*

In order to analyze the impact of the input parameters on the LCOE result, a sensitivity analysis was performed for the average value. The parameters that have been considered are distance to power lines, land lease cost, weighted average cost of capital and electricity production. The results of the analysis are shown in Figure 4.4. It shows the percentage changes of LCOE in relation to the percentage changes of each parameter. From the graph, we can see that the biggest impact on LCOE changes is the change in energy production. The other parameters have a linear effect on LCOE.

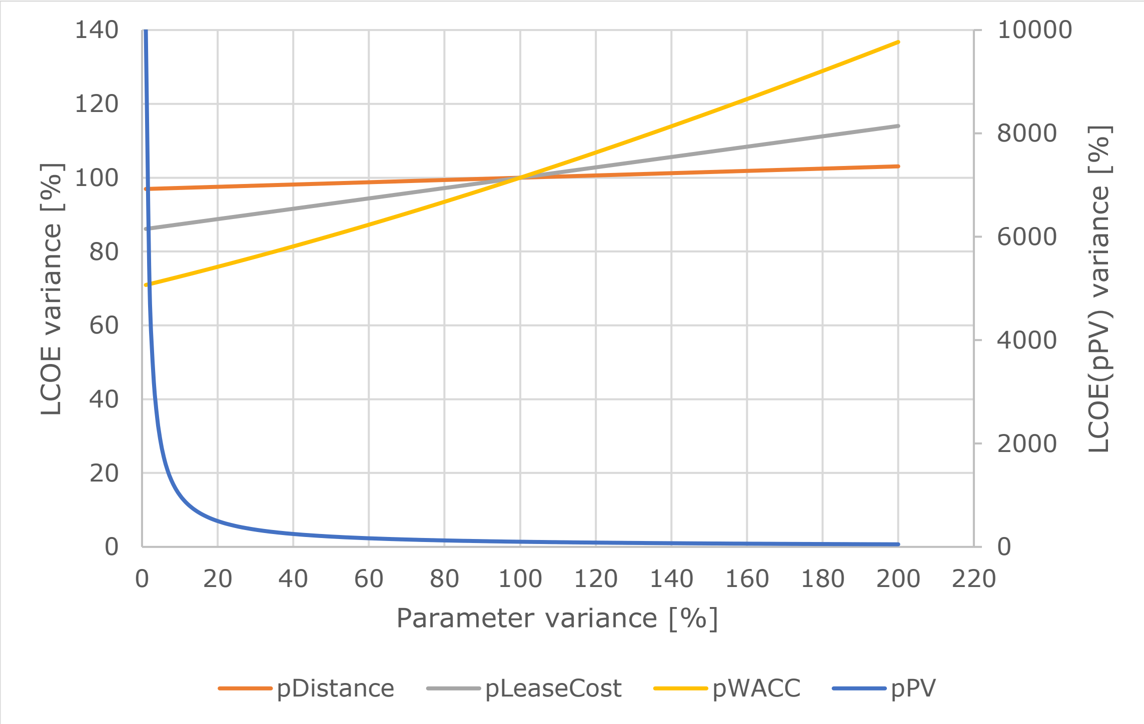


**Figure 4.4** Sensitivity analysis of LCOE
*Source: own elaboration*

To create the LCOE utility map, the values were divided into five ranges and given classifications, similar to PV suitability: very low, low, moderate, high, very high (Table 4.2).

**Table 4.2** LCOE classification

| | Rank | Range | Values |
|---|---|---|---|
| LCOE (PLN/kWh) | Very low | >21 | 1 |
| | Low | 0.205-0.21 | 2 |
| | Moderate | 0.2-0.205 | 3 |
| | High | 0.195-0.2 | 4 |
| | Very high | <0.195 | 5 |

*Source: own elaboration*

A map of land suitability in terms of LCOE is shown in Figure 4.5. Each pixel on the map corresponds to a land area of 1 $km^2$. It can be seen that the most economically viable areas for investment in solar farms are in the northern and north-eastern part of Malopolska. This is largely due to increased energy production, compared to other regions. This area also has a developed network of power lines. In contrast, the southern, southeastern, and part of the northwestern areas are not suitable for ground-mounted PV systems due to lower power production, as well as greater distances to medium voltage lines.

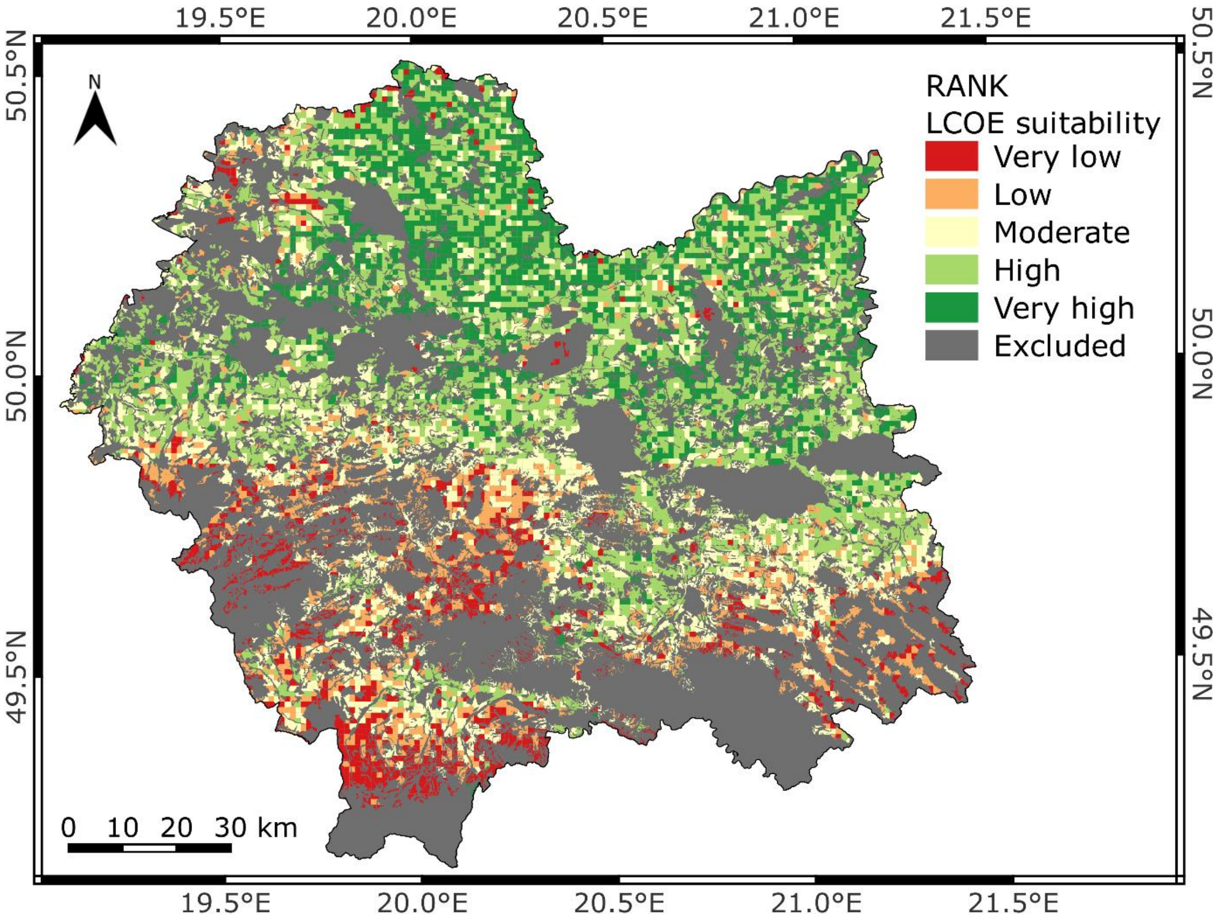


**Figure 4.5** LCOE suitability map
*Source: own elaboration*

## 4.3. PV development

The results of the PV land and LCOE suitability analysis were aggregated into a single map. For this purpose, the average of the component rankings was determined. The map shown in Figure 4.6 represents the result of the calculation of areas suitable for PV farm development. A classification of the potential of these lands was made as in previous cases into: very low, low, moderate, high, very high. The areas with the highest potential were also proposed.

The map and proposed areas may be considered for potential investment. The results of this work may contribute to faster development of PV farms in the

Małopolska province. They can be taken into account in land use plans and contribute to the improvement of development strategies. This improvement can be implemented by considering technical, economic and social factors, taking into account the potential of energy production from solar renewable energy.

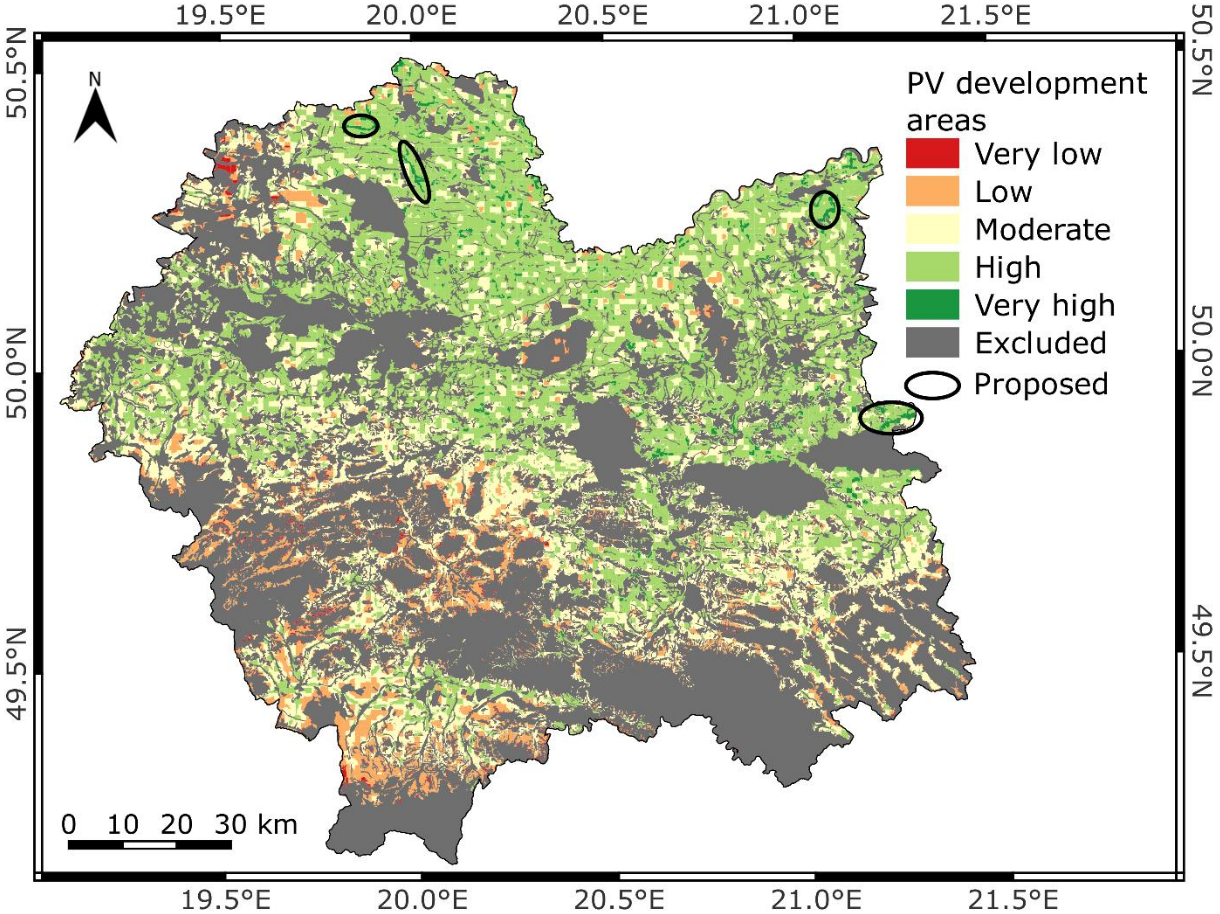


**Figure 4.6** Map of land suitable for PV development
*Source: own elaboration*

## 4.4. Future work

Due to the availability of geographic data, several limitations were adopted in the research paper. Publicly available data are not high resolution, and scales vary due to data sources. Additionally, the criteria are subject to uncertainty, although they were assumed based on expert opinion and other studies. Therefore, the process of weighing the criteria is also uncertain and depends on the internal preferences of the investor. In the case of land in Poland, its class plays a key role. It is very difficult to install photovoltaic systems on land with class III and higher. Unfortunately, due to lack of data, all arable lands are classified the same. Legal aspects have been largely omitted as they are beyond the scope of this thesis. The map of land suitability for PV farms can be used as a preliminary guide before a detailed analysis of individual areas. Special attention should be paid to research, legal aspects and field investigation before investing. The mapping results should be reviewed in the final decision-making process from an environmental and legal perspective. Land cover should be verified by field surveys or accurate satellite imagery. In addition, the distance from power lines was assumed without taking into account, by the unavailability of information, the capacity and without studying the impact of the solar power plant on the power grid. Furthermore, PV farms must not be located in flood-prone areas, which should be considered in further studies. The shape of the plots was also ignored. A plot of land for a 1 MWp PV system must have an area of about 2 ha and should be about 50 m wide. It is also important to keep in mind the social aspects, which have been omitted in this paper. Potential locations must also be checked to ensure that they do not contain tourist sites. While the LCOE parameters are valuable for making investment decisions in power generation, it has its limitations. Therefore, decisions should also be based on other economic indicators. The levelized cost of electricity calculations should be supplemented with a thorough financial analysis of the investment. Simplified data was used in the assumptions to compare locations, not to calculate profitability. Due to lack of information about land classes, an accurate analysis of operating costs was not possible. The maps and locations presented should be considered in terms of the "probability" of success of a solar renewable energy investment in a given region.

# 5. Summary and conclusions

Due to the negative ecological impact of conventional power plants using fossil fuels in electricity production, it is crucial to develop renewable energy, including photovoltaic plants, in Poland. Compared to thermal power plants, PV systems have a negligible impact on the environment and do not generate greenhouse gases and pollutants. In addition, rising fossil fuel prices positively affect the economic aspect of PV power plants, in contrast to traditional power plants. Among other things, through European Union regulations, photovoltaics has become the preferred branch of renewable energy in Poland in the energy transformation. In recent years, a dynamic increase in the capacity of PV installations in Poland can be observed, which leads to the conclusion that they are currently preferred by investors. The aim of this study was to show the methodology for selecting optimal locations for the construction of photovoltaic farms on the example of Malopolska province. Geographic Information System and MCDM decision-making process were used to determine areas that are economically justified and allow efficient PV system operation. Environmental and economic aspects were taken into account and a spatial analysis was performed. A review of the literature and scientific articles allowed the selection of criteria for determining the optimal location of solar farms. The criteria were divided into three categories: meteorological, environmental, locational. A total of 15183 km2 of land area in the region was analyzed. Areas protected by law and technically and economically unsuitable for large-scale PV farms were excluded from the study. The AHP method allowed assigning weights to criteria, and tools available in QGIS program allowed creating maps of proper locations in Malopolska. The resulting maps allow us to assess the potential of the study area for the development of photovoltaic farms, which can be important information when compared with land use plans. The results obtained indicate a great potential for the development and use of solar energy systems especially in the north of the province.

The second part identifies the most economically optimal sites. The levelized cost of electricity parameter was applied for this purpose. The estimation of electricity production from PVGIS program was used and differences in investment and operational costs were taken into account. It was assumed that the difference results mainly from the distance to the power lines and the cost of land rent.

Finally, a land suitability map in terms of LCOE was determined. The results show that the northern and northeastern regions are economically appropriate.

Given the results of both studies, a final map of land suitability for ground-mounted photovoltaic systems was determined. The area was divided into six categories. The resulting map shows that the northern and northeastern areas of Malopolska are more optimal than the southern areas. This is because the solar irradiance in these areas is higher and they are flat lands. The results show that the development of land use plans can be supported by GIS-based spatial analysis. In addition, decision-making processes coupled with GIS can serve for a better, sustainable expansion of large-scale PV farms.

In the end, research gaps have been shown that should be filled in order to better develop solar renewable energy in Poland. Additional land mapping by soil class is needed for PV farms to be successful. Technical data and economic models for solar energy should also be developed. Additional research in this area could lead to a revision of Poland's energy plan and a faster transition towards renewable energy sources. Investigating the impact of PV farms on the stability of the power grid is also an important need. Regional development plans should take into account local electricity demand and investment opportunities in the region. Finally, a more company-friendly system for solar energy development should be created.

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# Appendix 1

## Corine land cover classes

**1. Artificial surfaces**

**1.1 Urban fabric**
- 1.1.1. Continuous urban fabric
- 1.1.2. Discontinuous urban fabric

**1.2 Industrial, commercial and transport units**
- 1.2.1. Industrial or commercial units
- 1.2.2. Road and rail networks and associated land
- 1.2.3. Port areas
- 1.2.4. Airports

**1.3 Mine, dump and construction sites**
- 1.3.1. Mineral extraction sites
- 1.3.2. Dump sites
- 1.3.3. Construction sites

**1.4 Artificial, non-agricultural vegetated areas**
- 1.4.1. Green urban areas
- 1.4.2. Sport and leisure facilities

**2. Agricultural areas**

**2.1 Arable land**
- 2.1.1. Non-irrigated arable land
- 2.1.2. Permanently irrigated land
- 2.1.3. Rice fields

**2.2 Permanent crops**
- 2.2.1. Vineyards
- 2.2.2. Fruit trees and berry plantations
- 2.2.3. Olive groves

**2.3 Pastures**
- 2.3.1. Pastures

**2.4 Heterogeneous agricultural areas**
- 2.4.1. Annual crops associated with permanent crops
- 2.4.2. Complex cultivation patterns
- 2.4.3. Land principally occupied by agriculture
- 2.4.4. Agro-forestry areas

**3. Forest and seminatural areas**

**3.1 Forests**
- 3.1.1. Broad-leaved forest
- 3.1.2. Coniferous forest
- 3.1.3. Mixed forest

**3.2 Shrub and/or herbaceous vegetation associations**
- 3.2.1. Natural grassland
- 3.2.2. Moors and heathland
- 3.2.3. Sclerophyllous vegetation
- 3.2.4. Transitional woodland shrub

**3.3 Open spaces with little or no vegetation**
- 3.3.1. Beaches, dunes, and sand plains
- 3.3.2. Bare rock
- 3.3.3. Sparsely vegetated areas
- 3.3.4. Burnt areas
- 3.3.5. Glaciers and perpetual snow

**4. Wetlands**

**4.1 Inland wetlands**
- 4.1.1. Inland marshes
- 4.1.2. Peat bogs

**4.2 Coastal wetlands**
- 4.2.1. Salt marshes
- 4.2.2. Salines
- 4.2.3. Intertidal flats

**5. Water bodies**

**5.1 Inland waters**
- 5.1.1. Water courses
- 5.1.2. Water bodies

**5.2 Marine waters**
- 5.2.1. Coastal lagoons
- 5.2.2. Estuaries
- 5.2.3. Sea and ocean

*Source:* [28]

# Appendix 2

```
path = r"C:\Users\Maciek\Desktop\AGH\Thesis\QGIS\GeoPortal\malopolskie\warstwy_wektorowe\economy\siatka.txt"

file = open(path, "r")

lines = file.readlines()

file.close()

newTable = []

for i in lines:

    temp = i.strip()

    newTable.append(temp.split(" "))

#print(newTable)

import webbrowser

#webbrowser.open('https://re.jrc.ec.europa.eu/api/v5_2/PVcalc?lat=49.200&lon=19.300&peakpower=1000&loss=14&pvtechchoice=crystSi&mountingplace=free&optimalangles=1&outputformat=basic&browser=1')

import time

elem = 0

for row in newTable:

    #print(row)

    #print(newTable [elem][0])

    #print(newTable [elem][1])


webbrowser.open('https://re.jrc.ec.europa.eu/api/v5_2/PVcalc?lat='+newTable[elem][1]+'&lon='+newTable[elem][0]+'&peakpower=1000&loss=14&pvtechchoice=crystSi&mountingplace=free&optimalangles=1&outputformat=basic&browser=1')

    elem = elem + 1

    time.sleep(0.2)
```

# Appendix 3

```
$Title 'LCOE'

$setglobal ID C:\Users\Maciek\Desktop\AGH\Thesis\GAMS

sets

l 'location point' /p1*p8894/

t 'year' /t1*t30/;

$call gdxxrw.exe input=%ID%\Input_Data.xlsx output=%ID%\Input_Data.gdx
par=PV rng=PVproduction!A2:B8895 rdim=1

parameter  pPV(l)  ‘Elektricity annual production (kWh)’

$GDXIN %ID%\Input_Data.gdx

$LOAD pPV

$GDXIN

$call gdxxrw.exe input=%ID%\Input_Data.xlsx output=%ID%\Input_Data.gdx
par=Distance rng=Distance!A2:B8895 rdim=1

parameter  pDistance(l)  ‘Distance to power lines (m)’

$GDXIN %ID%\Input_Data.gdx

$LOAD pDistance

$GDXIN

$call gdxxrw.exe input=%ID%\Input_Data.xlsx output=%ID%\Input_Data.gdx
par=LeaseUnit rng=Lease!A2:B8895 rdim=1

parameter  pLeaseUnit(l)  ‘Annual cost of land leasing (PLN)’

$GDXIN %ID%\Input_Data.gdx

$LOAD pLeaseUnit

$GDXIN

parameter pT(t);

pT('t1')=1;

loop(t, pT(t+1) = pT(t)+1);

parameter Mt(l,t);

Mt(l,'t1')=pPV(l);

loop(t, Mt(l,t+1) = Mt(l,t)*0.9975);
```

```
parameter pWACC 'Weighted average cost of capital (%)';

pWACC = 3.7;

parameter i 'Discount rate (%)';

i = pWACC;

parameter pCableCost 'Unit cable cost (PLN/m)';

pCable = 200;

parameter pArea 'Land area (2 ha)';

parameter pLeaseCost(l) 'Land lease cost (PLN/year)';

pLeaseCost(l) = pLeaseUnit(l)*pArea;

parameter pCAPEX 'Average investment cost (PLN)';

pCAPEX = 2700000;

parameter Io(l) 'General investment cost (PLN)';

Io(l) = pCAPEX + pDistance(l)*pCableCost;

parameter At(l) 'Annual operating cost (PLN/year)';

At(l) = 0.01*Io(l) + pLeaseCost(l);

parameter pLCOE(l) 'Levelized cost of electricity (PLN/kWh)';

pLCOE(l) = (Io(l) + sum(t, At(l)/vcPower((1+i/100),pT(t))))/sum(t,
Mt(l,t)/vcPower((1+i/100),pT(t)));

execute_unload '%ID%\pLCOE.gdx'

execute 'gdxxrw.exe input=%ID%\pLCOE.gdx output=%ID%\pLCOE.xlsx
par=pLCOE rng=pLCOE!A1'

display pLCOE;
```