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## AHP-based site suitability for agrivoltaics in Lublin Voivodeship, Poland

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Ocena przydatności terenów dla agrowoltaiki w województwie lubelskim  
z wykorzystaniem metody AHP

**Abstract.** In Poland, as in the global energy market, the popularity of renewable energy sources, whose main advantage over fossil fuels is climate neutrality, is growing. An alternative to dedicating land exclusively to renewable energy is agrivoltaics, which involves dual use of land: for agricultural production and for photovoltaic installations that convert solar energy into usable energy simultaneously. The study's main purpose was to answer two questions: to what extent are the agricultural lands of eastern Poland suitable for the development of agrivoltaics, and how does the selection of criteria affect the final result of the analysis in light of the Analytic Hierarchy Process. The study area was the Lublin Voivodeship, whose potential was evaluated based on 8 orography and land use criteria. The study focuses on spatial conditions, whereas legal and economic conditions have not been considered. The analysis showed that implementing agrivoltaics is theoretically feasible on 79% of the Voivodeship's total agricultural land, of which 9,961 km<sup>2</sup> can be considered at least moderately highly suitable. Additionally, two alternative scenarios were analysed: in the first, only orography criteria were assessed, and in the second, only land use. The comparative analysis revealed that the choice of criteria significantly impacts the results. The highest area suitability was obtained in the assessment considering land use only, and the lowest for orography.

**Keywords:** agrivoltaics, renewable energy, photovoltaics, Poland, land suitability

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## INTRODUCTION

The progressive exploitation of fossil fuels, leading to the gradual depletion of their resources, and the lack of climate neutrality are the two main problems associated with obtaining energy via non-renewable sources from the point of view of the global energy market. The counterweight to fossil fuels is renewable energy, characterised by its recoverability and lack of negative impact on climate change. In recent years, a successive increase in the importance of renewable energy sources in the global energy market has been observed, manifesting in both an increase in generating capacity and energy consumption [IEA et al. 2023, IEA 2024]. The main contributor to the development of renewable energy globally is Europe, where the share of renewable energy in the total generation potential in 2022 was 35%, which was 10% greater than that in the global market [IEA 2023]. In Poland, the renewable energy market is developing very rapidly. As indicated by the Energy 2023 report published by the Polish Central Statistical Office [Statistics Poland 2023a], in 2021, Poland was in 4th place in the European Union in terms of the amount of energy produced from renewable sources.

The problem of meeting the constantly growing energy needs of societies that care for the environment is often considered by researchers not as a separate problem but holistically as part of a larger entity, the food–water–energy nexus [Campana and Lawford 2022]. The main threats to the elements of this system from a global perspective are the growing demand for resources and climate change, which makes it necessary to make efforts for better use of available assets [Cansino-Loeza et al. 2022]. In the European region, the drive to more efficiently use these resources to meet society's needs is compounded by rising prices for both food and energy, resulting from the market recession caused by the Ukraine war [Mbah and Wasum 2022]. One of the aspects that can be improved in this regard is the better use of available land resources for certain forms of development demanded. In this context, one solution of interest to researchers in recent years is agrivoltaics (AV), which involves the dual use of the same land resources: agricultural land and solar photovoltaic farms [Mamun et al. 2022]. One of the advantages of this concept is the coexistence of two utility functions in the same area that are not competitive with each other [Weselek et al. 2019]. As studies have shown, AV systems not only allow better utilisation of available land resources but can also significantly improve the efficiency of agricultural production. Studies have shown that such systems can contribute to stabilizing agricultural production by reducing the volume of production in years with favourable climatic conditions but contribute to reducing losses in drier periods, to which land without irrigation systems is particularly exposed [Amaducci et al. 2018, Weselek et al. 2021]. In addition to the positive impact on agricultural production itself, AV systems can increase the profitability of agricultural activities by generating additional income from energy production [Malu et al. 2017] and (in the case of off-grid systems) lead to greater energy independence in rural areas [Harinarayana and Vasavi 2014].

One of the key issues in the context of the development of AV is the identification of an appropriate location for investment. The quality and usefulness of the results of the evaluation are directly influenced by the criteria (their selection and relevance) and methodology used in the assessment itself. Analysis of the suitability of specific sites for the location of solar farms has been the subject of many studies in recent years [Almasad et al. 2023]. An approach often used in evaluating areas for solar farms has been to use the geographic

information system (GIS) environment and various multi-criteria analysis methods, such as analytic hierarchy process (AHP) [Ruiz et al. 2020, Prieto-Amparán et al. 2021], weighted overlay (WO), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), simple additive weighting (SAW) [Shehab et al. 2024] are often used to evaluate the suitability of areas for solar farms. Vrinceanu et al. [2022] used a GIS weighted overlay approach to analyse the Romanian area, taking into account 10 different factors (including orography and climatic and anthropogenic conditions), and the results revealed that nearly 30% of the entire country's land area has relatively high potential for siting photovoltaic (PV) farms. An example of a study on a smaller scale is the work of Yousefi et al. [2018], who used a combination of GIS and Boolean fuzzy logic on the terrain fit of an area of approximately 30,000 km<sup>2</sup> in Iran for PV. The authors, based on an analysis of 9 different criteria, determined matching areas that were mostly near two urban centres.

For AV systems, the selection of criteria is a more complex process than monoculture land development for PV farms. The increase in the level of complexity of the issue, compared with that of ordinary PV systems, is caused by the necessity of considering the evaluation of the agricultural aspect and the criteria directly arising from it. Factors such as climatic conditions, land use, and orography are crucial from the perspective of economic viability and the effective coexistence of PV systems with agricultural land use. The literature analysis, in which selected items from 2018–2023 were collected [Alami Merrouni et al. 2018, Doorga et al. 2019, Colak et al. 2020, Ruiz et al. 2020, Albraheem and Alabdulkarim 2021, Günen 2021, Munkhbat and Choi 2021, Ouchani et al. 2021, Prieto-Amparán et al. 2021, Rios and Duarte 2021, Settou et al. 2021, Sun et al. 2021, Elboshy et al. 2022, Rekik and El Alimi 2023, Raza et al. 2023], revealed that different sets of criteria were used to determine optimal locations for PV systems, among which we can distinguish climatic criteria, orography, and criteria related to land use (fig. 1).

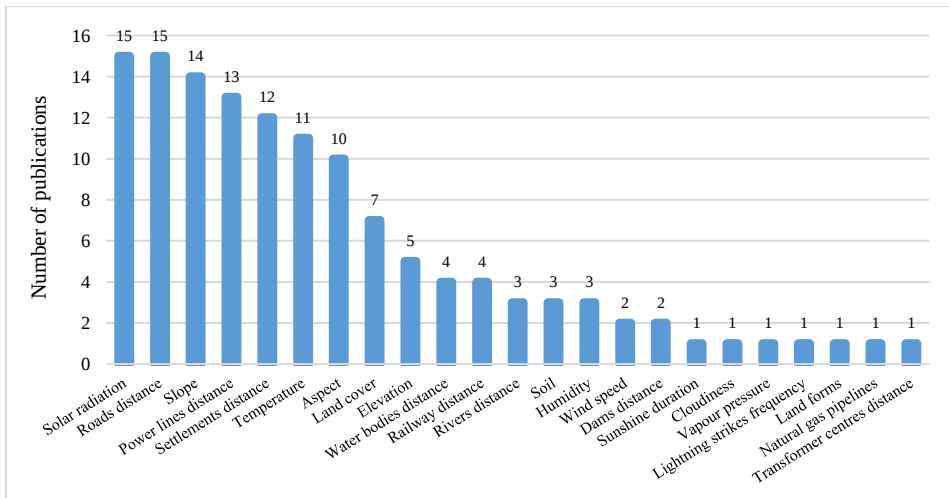


Fig. 1. Criteria used in the selected literature for PV farm location assessment

Although some of the criteria are mentioned in almost every literature item discussed (solar radiation, distance from roads, slope), some criteria are less frequently considered by authors (such as elevation or humidity). In addition to discrepancies in the selection of

criteria, the subjectivity of the assessment can be influenced by the choice of weights for individual criteria. In practice, the relevance of individual criteria is commonly determined by the judgement of experts (e.g. from the solar power sector, scientists), and the subjectivity factor can be minimised by formulating final weightings based on a synthesis of judgements from a group of specialists originating from different sectors.

This study attempts to estimate the suitability of the eastern Polish region for AV installations. An additional objective of this work is to supplement existing knowledge on the use of the AHP method in assessing the suitability of areas for AV by evaluating the impact of criteria selection on the results. The dependency of the analysis results on the selection of criteria is obvious in the multi-criteria analysis (MCA) methods. This paper attempts to assess the scale of this dependence in a complex spatial environment when assessing the suitability of an area for a specific type of investment, such as solar farms located on agricultural land. To the best of the authors' knowledge, this issue has not yet been considered in determining optimal AV areas. The structure of this paper is as follows: 2 – characteristics of the research area, 3 – materials and methods, 4 – results, 5 – conclusion and discussion.

## STUDY AREA

Lublin Voivodeship is an administrative unit of Poland with an area of 25,122 km<sup>2</sup> (fig. 2) located in the eastern part of the country (36), which is also a separate region in the NUTS-2 classification with evidence code PL31. The capital and largest city of Voivodeship is Lublin. In addition, there are 50 smaller cities, among which the largest in terms of population is Zamość (58,942 citizens), and the smallest is Józefów on the Vistula River (817 citizens) [Statistical Office in Lublin 2023a].

According to the Köppen-Geiger classification [Kottek et al. 2006], the study area is located in a continental climate zone characterised by a lack of a dry season and with a warm summer. The growing season in Lublin Voivodeship (which is a period with an average daily temperature above 5°C) lasts an average of 220–230 days, whereas the average for Poland is 224 days [Tomczyk and Bednorz 2022]. High variability in weather conditions in the Polish region translates into high variability in PV module operating temperatures, which can vary between –20°C and +70°C [Matuszczyk et al. 2015]. The study area is characterised by very good insolation conditions on a country-wide scale. According to the Global Solar Atlas (based on average values for the period 1994–2018), the average annual sum of global horizontal irradiance (GHI) in the Lublin Voivodeship area is 1122 kWh m<sup>-2</sup>, whereas the average for Poland is 1086 kWh m<sup>-2</sup>. At the point with the lowest recorded value, radiation amounted to 1086 kWh m<sup>-2</sup>, which can still be considered suitable solar conditions for the deployment of solar energy systems [Klugmann-Radziemska 2014, Pedrero et al. 2019]. The digital elevation model (DEM) analysis revealed that Lublin Voivodeship is quite differentiated in terms of terrain elevation. The altitude of the land in the study area ranges from 101 to 388 meters above sea level. The relief of the Lublin Voivodeship is quite diverse and consists of the Central Poland Lowlands, Lublin-Lviv Upland, Polesie, Volhyn-Podole Upland, and Northern Subcarpathians [Solon et al. 2018]. There are numerous territories of high natural value within the study area,

including 2 national parks (Roztoczański and Poleski), 17 landscape parks, and numerous protected landscape areas and nature reserves.

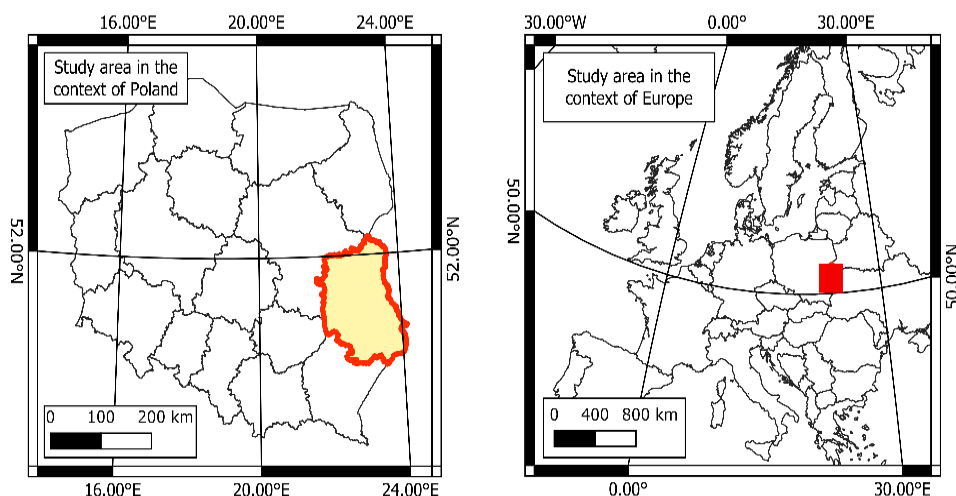


Fig. 2. Study area location in the context of Poland and Europe

At the country level, Lublin Voivodeship is an important hub of plant agricultural production. According to the Polish Central Statistical Office report for 2022 [Statistical Office in Lublin 2023b], Lublin Voivodeship is among the leaders in the country in terms of global agricultural production (crop and livestock), with a share of 8.5% of total domestic production in the analysed period. The report indicates that cereals (28.9%), fruits (25.5%), industrial (14.3%), and vegetables (13.8%) accounted for the largest share of total crop production in 2021. In the overall crop structure of the study area, it is possible to distinguish plants which, based on empirical analyses, show good performance (understood as higher overall land productivity) in AV cultivation: wheat (3,298 km<sup>2</sup> of arable land in 2022), corn (765 km<sup>2</sup>) and potatoes (99 km<sup>2</sup>) [Trommsdorff et al. 2021, Jo et al. 2022]. Agricultural land makes up the vast majority of the total land cover within the study area. In this work, the following manifestations of agricultural land use are distinguished: arable land, grassland vegetation, and permanent crops such as orchard plantations and plant nurseries. The region's problem is the relatively high fragmentation of agricultural farms. According to the 2020 Agricultural Census, in the year of the survey, almost 37% of all farms had areas of 2–5 ha, and the average area of a single farm was 8.6 ha, which was smaller than the average for Poland (11.4 ha) [Statistics Poland 2023b].

Land with various forms of agricultural use is the main form of land use in the study area, and according to data from the CLC database, it covers an area of 16,939 km<sup>2</sup>, accounting for more than 67% of the total area (fig. 3).

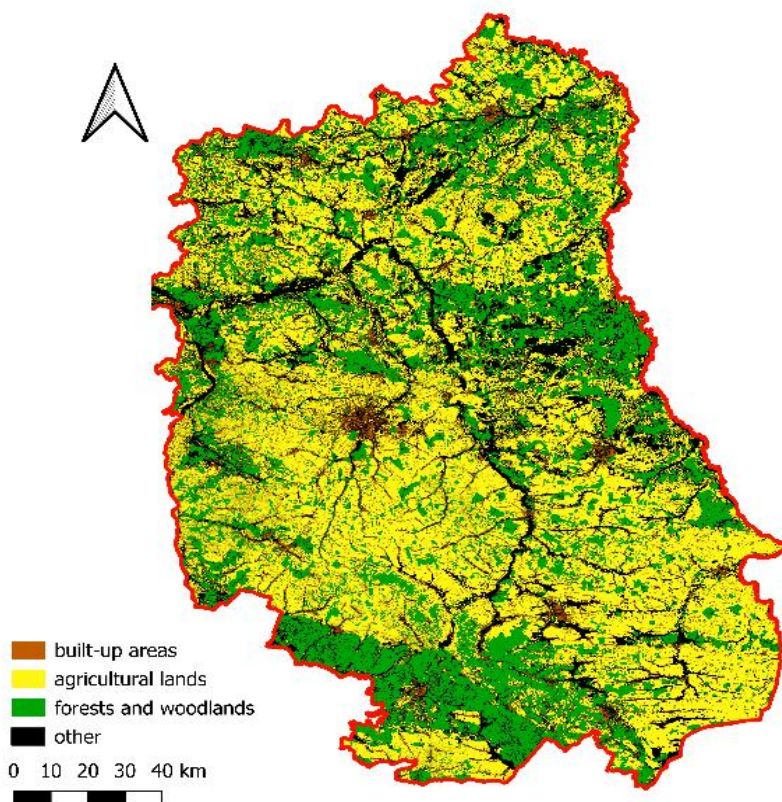


Fig. 3. Forms of land use in Lublin Voivodeship [own elaboration based on CLC data]

The area's agricultural land structure includes 72% non-irrigated arable land, 17% pasture, meadow, and other permanent grasslands used for agriculture, 5% complex cropping patterns, 5% land occupied mainly by agriculture, with significant areas of natural vegetation, and 1% fruit tree and berry plantations.

#### MATERIAL AND METHODS

According to the adopted methodology, the starting point was to set evaluation and exclusion criteria for the study area (fig. 4). The evaluation criteria were analysed via the AHP method to establish weighting values. In the next stage, the spatial data was collected and processed in QGIS software. The processing resulted in 3 suitability maps of the area for the established alternatives.

This study used spatial and numerical statistical data as research material. The main analytical material was spatial data in the form of digital elaborations. Details of the spatial layers used are shown in table 1.

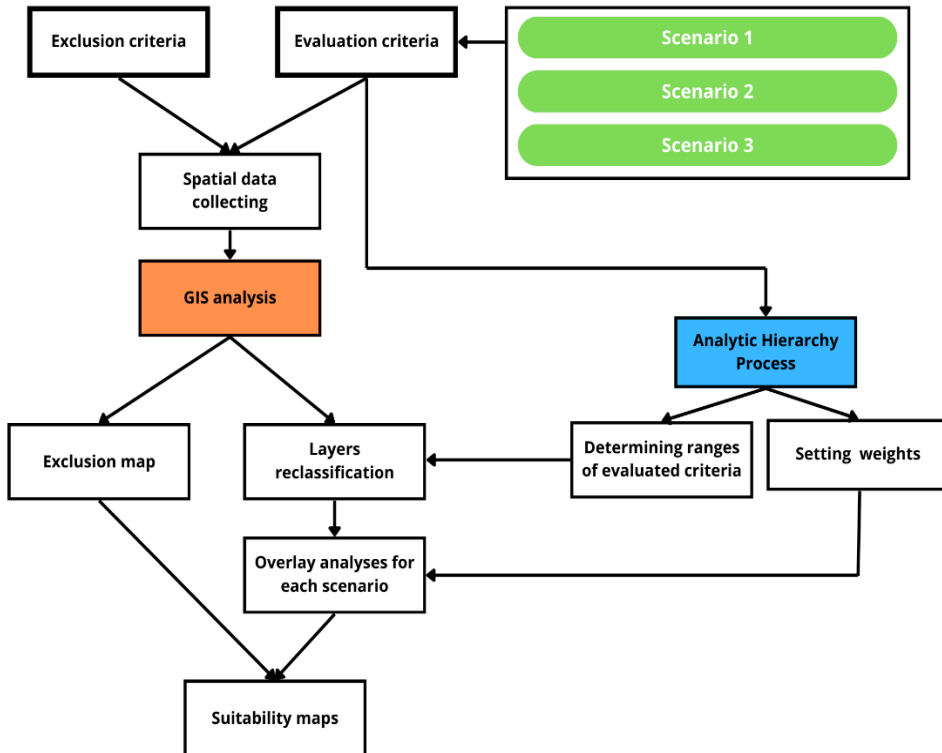


Fig. 4. Flowchart of the work

One of the limitations of the work is not taking into account climatic conditions (insolation, temperature). Although they significantly affect module performance in practice [Zondag 2008, Chikate and Sadawarte 2015], their variability due to the scale of the study adopted is small. Based on Global Solar Atlas data, the variation in annual GHI totals between points in the area is a maximum of  $61 \text{ kWh m}^{-2}$ , and in 95% of the area, the differences are no more than  $40 \text{ kWh}$  ( $1100\text{--}1140 \text{ kWh}$ ). In the case of the average annual temperature, the difference between the lowest and highest values was  $1^\circ\text{C}$ , which theoretically could translate into a difference in panel efficiency of around 0.3% [Nájera-Ruiz et al. 2018]. Limitations of the work also include the lack of assessment of the soil quality, the reason for which was the lack of adequate quality spatial data. According to Kurowska et al. [2022], under Polish conditions, the use class of the soil translates directly into the

legal conditions of the area. In the case of soils of classes I–III the development of AV can be associated with certain restrictions (planning permission), which makes the legal procedure more complicated and expensive. In addition, the lack of detailed analysis of the different types of crops found in the area in terms of their predispositions can be considered a limitation.

Table 1. Spatial data used in the study

| Data                                             | Aim of use      | Type/format | Spatial resolution | Year      | Source                                                                                                                                                                         |
|--------------------------------------------------|-----------------|-------------|--------------------|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Polish database of topographic objects (BDOT10k) | land cover      | vector/shp  | –                  | 2023      | Polish Central Office of Geodesy and Cartography ( <a href="https://www.geoportal.gov.pl/">https://www.geoportal.gov.pl/</a> )                                                 |
| CLC                                              | land cover      | vector/shp  | –                  | 2018      | Copernicus Land Monitoring Service ( <a href="https://doi.org/10.2909/cd534ebf-f553-42f0-9ac1-62c1dc36d32c">https://doi.org/10.2909/cd534ebf-f553-42f0-9ac1-62c1dc36d32c</a> ) |
| DEM                                              | orography       | raster/tiff | 1 arc-second       | 2014      | U.S. Geological Survey ( <a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> )                                                                       |
| GHI                                              | Solar resources | raster/tiff | 9 arcseconds       | 1994–2018 | Global Solar Atlas ( <a href="https://globalsolaratlas.info/">https://globalsolaratlas.info/</a> )                                                                             |

### Evaluation criteria

For the analysis of fit, 8 criteria most frequently repeated in the problem literature were extracted (fig. 1). Among these proximity to roads (100%), slope (93%), proximity to power lines (87%), proximity to settlements (80%), temperature (73%), aspect (67%), land use (47%), altitude (33%) and proximity to railway lines (27%). For the selected criteria, 5 ranges of values were determined, which were then assigned to five classes of fit: low, moderately low, medium, moderately high, and high. The designated scores were assigned to fit classes from 1 to 5, with class 1 indicating high suitability of the area, class 5 indicating low suitability, and values 2–4 represented the respective intermediate assessments (tab. 2).

Based on the classes assigned to each range for each criterion, maps of the suitability of each criterion were developed (fig. 5).

The cells were assigned values from a scale of 1–5, after which overlay analysis was carried out on the basis of the values assigned to each cell. The following subsections provide a detailed description of the individual criteria selected as comparison factors and their role in the overall fit analysis.

Table 2. Selected criteria

| Criterion type | Criterion                                    | Units    | Adopted ranges of values   | Values after reclassification |
|----------------|----------------------------------------------|----------|----------------------------|-------------------------------|
| Orography      | slope                                        | degrees  | 15–20                      | 5                             |
|                |                                              |          | 10–15                      | 4                             |
|                |                                              |          | 6–10                       | 3                             |
|                |                                              |          | 3–6                        | 2                             |
|                |                                              |          | 0–3                        | 1                             |
|                | aspect                                       | degrees  | N (330–360/0–30)           | 5                             |
|                |                                              |          | NE (30–60), NW (300–330)   | 4                             |
|                |                                              |          | E (60–120), W (240–300)    | 3                             |
|                |                                              |          | SE (120–150), SW (210–240) | 2                             |
|                |                                              |          | S (150–210), flat          | 1                             |
|                | elevation                                    | m        | 101–196                    | 5                             |
|                |                                              |          | 197–291                    | 3                             |
|                |                                              |          | 292–388                    | 1                             |
| Land use       | roads distance                               | km       | >3                         | 5                             |
|                |                                              |          | 1.51–3                     | 4                             |
|                |                                              |          | 0.81–1.5                   | 3                             |
|                |                                              |          | 0.31–0.8                   | 2                             |
|                |                                              |          | 0–0.3                      | 1                             |
|                | transmission lines distance (medium voltage) | km       | >3                         | 5                             |
|                |                                              |          | 1.51–3                     | 4                             |
|                |                                              |          | 0.81–1.5                   | 3                             |
|                |                                              |          | 0.31–0.8                   | 2                             |
|                |                                              |          | 0–0.3                      | 1                             |
|                | cities distance                              | km       | 25–50                      | 5                             |
|                |                                              |          | 15–25                      | 4                             |
|                |                                              |          | 10–15                      | 3                             |
|                |                                              |          | 5–10                       | 2                             |
|                |                                              |          | 0–5                        | 1                             |
|                | land cover                                   | CLC code | 242, 243                   | 5                             |
|                |                                              |          | 222                        | 3                             |
|                |                                              |          | 211, 231                   | 1                             |
|                | railway distance                             | km       | >3                         | 5                             |
|                |                                              |          | 1.51–3                     | 4                             |
|                |                                              |          | 0.81–1.5                   | 3                             |
|                |                                              |          | 0.31–0.8                   | 2                             |
|                |                                              |          | 0–0.3                      | 1                             |

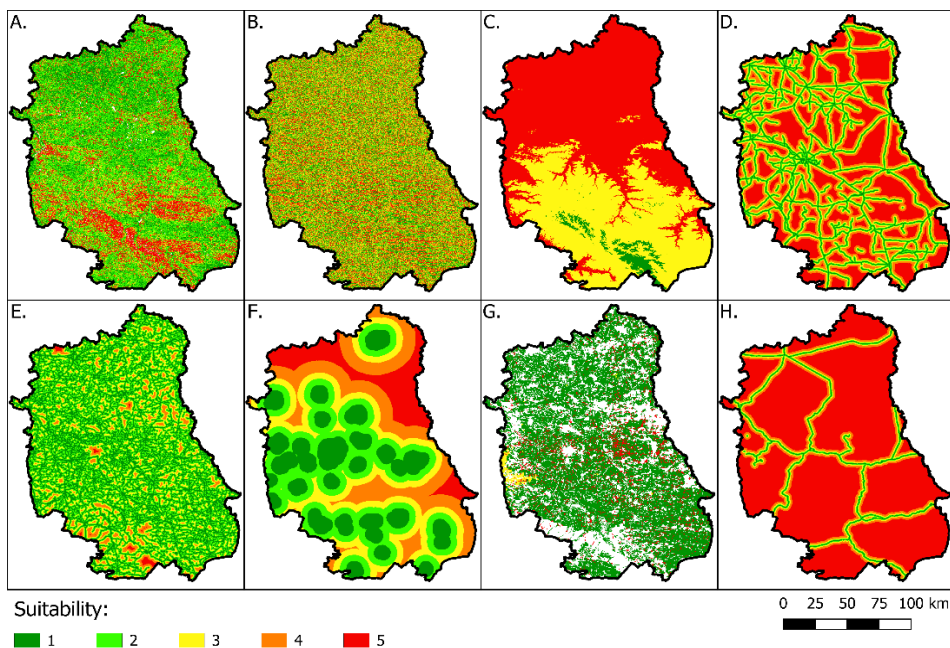


Fig. 5. Study area land suitability according to each criterion: A – slope, B – aspect, C – elevation, D – distance from major roads, E – distance from power lines, F – distance from cities, G – land use (agricultural land only), H – distance from railroads

## Orography

The desirable terrain for investment in terms of slope (A) is flat or slightly sloping land. Locating PV farms in such areas allows for significant cost savings, particularly at the construction stage. For the same reason, areas with extremely steep slopes would require high capital expenditures, making them financially unviable. The ranges of values for slope were formulated based on Yang et al. [2019], who recommended 20 degrees as the upper limit of slope for the location of solar farms.

The aspect (B) is a factor that can help or hinder the optimal positioning of panels in relation to direct incident solar radiation. The optimal tilt direction of panels with a constant orientation results from the geometric relationship between the sun and the Earth and, in practice, depends primarily on latitude. In the case of northern latitudes, it is suggested that the panels slope in a southerly direction, so the best direction of sloping land for investment is characterised by land tilted in a southerly direction or flat. In this study, the aspect representation was an azimuth.

An increase in altitude can lead to better insolation (greater atmospheric transparency) [Redi et al. 2010] and decrease in temperature, which can translate into better performance of PV panels [Barbón et al. 2023]. An ambiguous issue is the effect of height on costs at the construction stage. On the one hand, regions with higher altitudes may be less expensive, making them more accessible for potential investors [Barbón et al. 2023]; on the other hand, the cost of bringing the necessary infrastructure and connection to the network

may be greater in these regions [Adjiski and Serafimovski 2024]. This study assumes that higher altitudes are better for locating solar installations, and according to this approach, three classes of suitability were adopted.

### **Land use**

Roads proximity (D) translates into better accessibility of the land, which is important at the construction stage and helps reduce investment costs; however, at the operation stage and related inspection as well as maintenance works, transportation accessibility can be economically advantageous. This study assumes that areas more than 3 km from such infrastructure have the lowest rating (5) for suitability.

Proximity to the electrical transmission network (E) at the construction phase translates into lower costs of connecting the installation to the grid, whereas during the operating period, this results in lower energy losses during transmission. In this study, the accessibility of medium-voltage transmission lines was evaluated, and the distance ranges for infrastructure were taken over the same range as those for road infrastructure.

Settlement proximity (F) is an important component of economic viability. The vicinity of groups of electricity consumers leads to lower transmission losses and sometimes also a reduction in costs for the construction and maintenance of the power grid. In the detailed assessment of matching areas, the classification proposed by Raza et al. [2023] was adopted, according to which the best areas for investment are those located no further than 5 km from cities.

Based on the CLC classification, 5 types of agricultural land use forms (G) occurring within the study area were distinguished: non-irrigated arable lands (211 CLC code), fruit trees and berry plantations (222), pastures (231), complex cultivation patterns (242) and lands principally occupied by agriculture, with significant areas of natural vegetation (243), which were then classified into 3 groups of suitability.

The criterion of railway line proximity (H) can facilitate the integration of the installation with the power grid by utilising the existing railway electrical infrastructure, which can translate into reduction of connection costs and lowering of energy transmission losses, improving the overall efficiency of the system. The construction of PV installations in the proximity of railway infrastructure may facilitate integration with the grid by utilising the railway's spare connection capacities, which may translate into lower investment costs and allow for better use of the existing infrastructure [Shen et al. 2020, Binduhewa 2021]. The rating ranges for this criterion were adopted in the same way as those for distance from the road and energy infrastructure.

### **Exclusion criteria**

The following areas were considered unsuitable for AV systems: territories under legal protection (Natura 2000, national and landscape parks, and nature reserves), sites located closer than 300 m from flowing waters (due to the risk of flooding), and urban areas. In addition, areas that were not agricultural land were excluded from the evaluation. Based on the above criteria, excluded zones were designated (fig. 6).

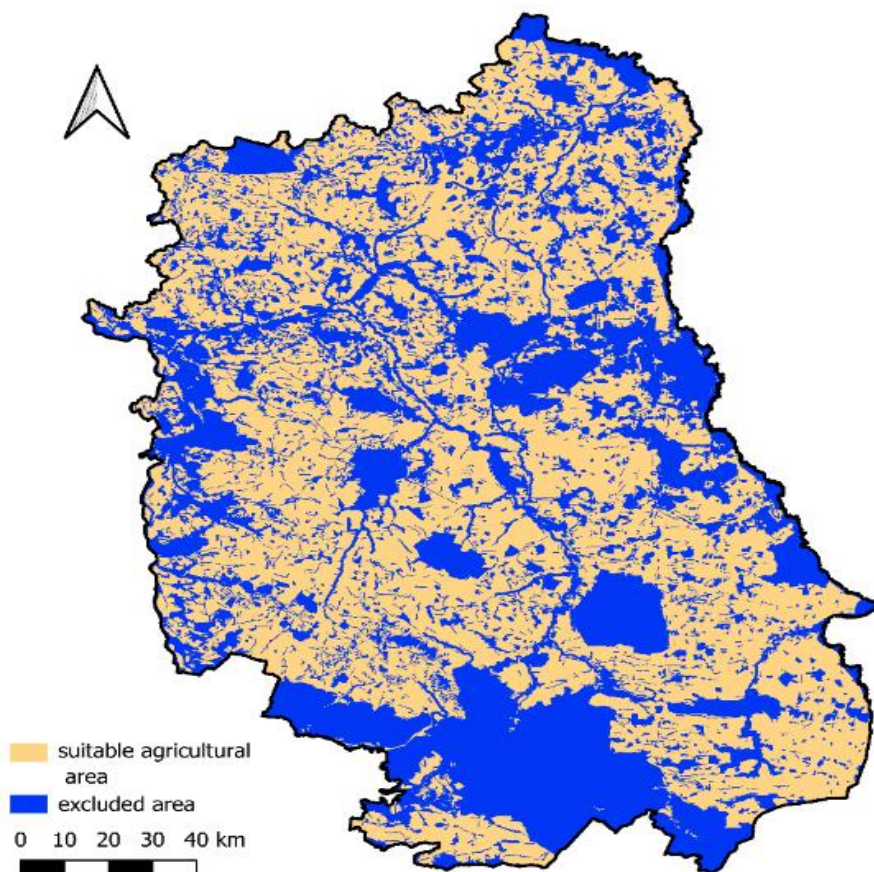


Fig. 6. Excluded areas based on the adopted criteria

Based on adopted criteria, suitable land occupy a total of 14,230 km<sup>2</sup> of the study area. This area also accounted for 84% of all agricultural land and nearly 57% of the Voivodeship area.

### Analysis of alternatives

In the analysis of alternatives, results were compared across the group of all criteria in Scenario 1 (S1) to Scenario 2 (S2) including only orography criteria and Scenario 3 (S3) land use. The criteria were evaluated and compared according to the principles of the AHP, which is one of the multi-criteria decision-making (MCDM) methods introduced by T.L. Saaty [Saaty 1987]. The first step was the creation of a preference matrix in which comparison was made between the criteria included in the pairwise analysis with adopted scale 1–9 (tab. 3). The comparative values were determined according to Rios and Duarte [2021].

Table 3. Pairwise comparison of criteria

| Factor | A     | B    | C     | D    | E    | F     | G     | H     |
|--------|-------|------|-------|------|------|-------|-------|-------|
| A      | 1     | 1/3  | 9     | 1/3  | 1/7  | 1     | 1/2   | 9     |
| B      | 3     | 1    | 9     | 1    | 1/4  | 3     | 2     | 9     |
| C      | 1/9   | 1/9  | 1     | 1/9  | 1/9  | 1/9   | 1/9   | 1     |
| D      | 3     | 1    | 9     | 1    | 1/4  | 2     | 1     | 9     |
| E      | 7     | 4    | 9     | 4    | 1    | 7     | 5     | 9     |
| F      | 1     | 1/3  | 9     | 1/2  | 1/7  | 1     | 1/2   | 9     |
| G      | 2     | 1/2  | 9     | 1    | 1/5  | 2     | 1     | 9     |
| H      | 1/9   | 1/9  | 1     | 1/9  | 1/9  | 1/9   | 1/9   | 1     |
| Sum    | 17.22 | 7.39 | 56.00 | 8.06 | 2.20 | 16.22 | 10.22 | 56.00 |

where 1 indicates equal importance of both criteria, and 9 indicates extreme preference for a given criterion over the reference criterion. A characteristic feature of the comparison matrix is the reciprocal relationship between pairs of criteria, which can be expressed as:

$$X_{ij} = \frac{1}{X_{ji}} \quad (1)$$

S1 involved the entire matrix, whereas in S2 and S3 only criteria corresponding to them were taken into account and the weights for every scenario have been determined (tab. 4).

Table 4. Scenarios criteria and weights

| Criterion | Scenario 1 | Scenario 2 | Scenario 3 |
|-----------|------------|------------|------------|
| A         | 0.08       | 0.32       | 0.00       |
| B         | 0.16       | 0.63       | 0.00       |
| C         | 0.02       | 0.05       | 0.00       |
| D         | 0.14       | 0.00       | 0.17       |
| E         | 0.39       | 0.00       | 0.53       |
| F         | 0.08       | 0.00       | 0.11       |
| G         | 0.12       | 0.00       | 0.16       |
| H         | 0.02       | 0.00       | 0.03       |

To validate results, the consistency of the matrix for each scenario was checked. For this purpose, the Consistency Index was determined according to the equation [Saaty 1987]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

where  $\lambda_{max}$  represents the maximum eigenvalue of the matrix and  $n$  represents the number of criteria. Based on the values of  $CI$ , the Consistency Ratio was calculated as follows:

$$CR = \frac{CI}{RCI} \quad (3)$$

where the values of the Random Consistency Index ( $RCI$ ) dependent on the number of elements compared in each set were used as the  $RCI$  values [Golden and Wang 1989].

Based on the weights determined overlay analyses were carried out in the QGIS software for each scenario. The reclassified evaluation values of each criterion were multiplied by the weighting factors and then summed for the criteria in each set, resulting in three alternative maps of the suitability of the area for AV.

## RESULTS

As a result of the exclusion criteria, of the 16,939 km<sup>2</sup> of total agricultural land in agricultural use, 3,630 km<sup>2</sup> were excluded. This approach was applied in an unchanged form for each of the analysed scenarios.

Based on the adopted ranges of values for individual criteria and the weights that were assigned to them, areas predisposed for AV development were determined (fig. 7). For the scenario considering all 8 criteria, the percentage of highly suitable areas is extremely small and the smallest of all 3 scenarios, while the vast majority of land evaluated is classified as moderately highly suitable.

Generally, based on this assessment, the spatial conditions of Lublin Voivodeship create fairly good predispositions for the development of AV, to which both the high availability of agricultural land (and favourable forms of its use), well-developed infrastructure, and orographic conditions contribute. Highly suitable areas accounted for 163.2 km<sup>2</sup> and this corresponds to 1.2% of all suitable agricultural lands. The rest of the agricultural land was classified as follows: moderately high suitable – 9,798.6 km<sup>2</sup>, moderately suitable – 4233.6 km<sup>2</sup>, and moderately low suitable – 34.2 km<sup>2</sup>. In this scenario, areas with a moderately high suitability had the relatively largest share, and the smallest number of areas were found to have a high fit compared with S2 and S3 (fig. 8).

In S2, in which only the orography of the site was evaluated, the results of the analysis were the most balanced compared the other two approaches, and no class of fit could be considered dominant within the study area. The largest share (36%) was held by areas categorised as moderately highly suitable, and slightly fewer (30%) were categorised as medium. This analysis showed the highest share of highly suitable areas, accounting for 13% of the total. The dominant level of suitability in S3 was moderately high (67%), and 10% of the area was classified as highly suitable. No low-fit areas were observed in any of the analysed cases.

The discrepancies in the results for the individual scenarios can be considered both at the level of the raw result layers (fig. 9) and after their reclassification, which involves assigning specific ranges of result values to the corresponding suitability classes. Analysis of the raw data layers revealed that when all criteria were included, the mean value of the derived suitability was the highest in S2 analysis (2.67) and the lowest in S3 analysis

(1.80), which indicates that the conditions of the area assessed in S3 are relatively the most favourable. The spread of values for which the standard deviation was taken as the indicator ranged from 0.41 (all criteria) to 0.97 (orography).

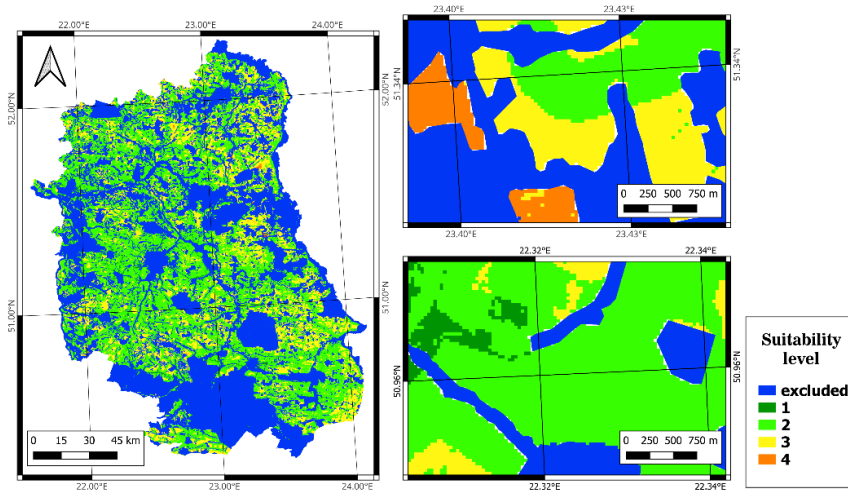


Fig. 7. Suitability of the area based on all criteria evaluation

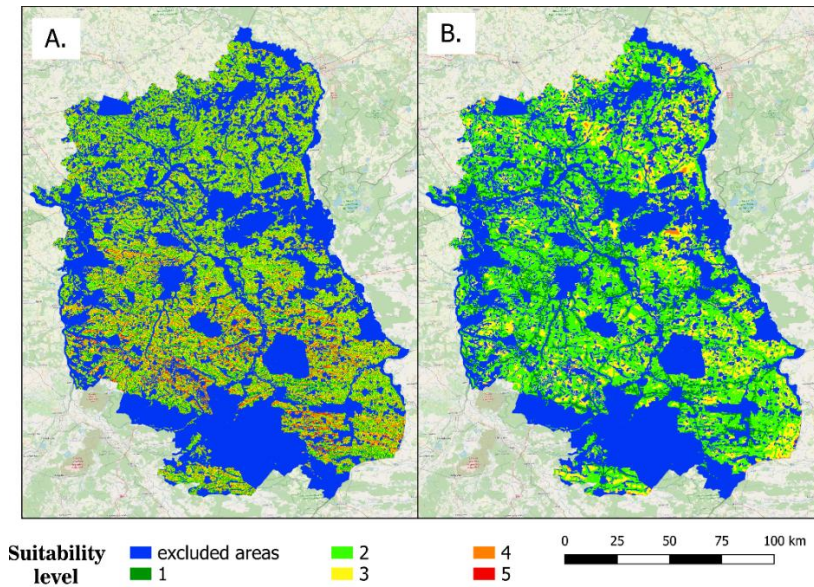


Fig. 8. Comparison of suitability alternatives: A – orography, B – land use

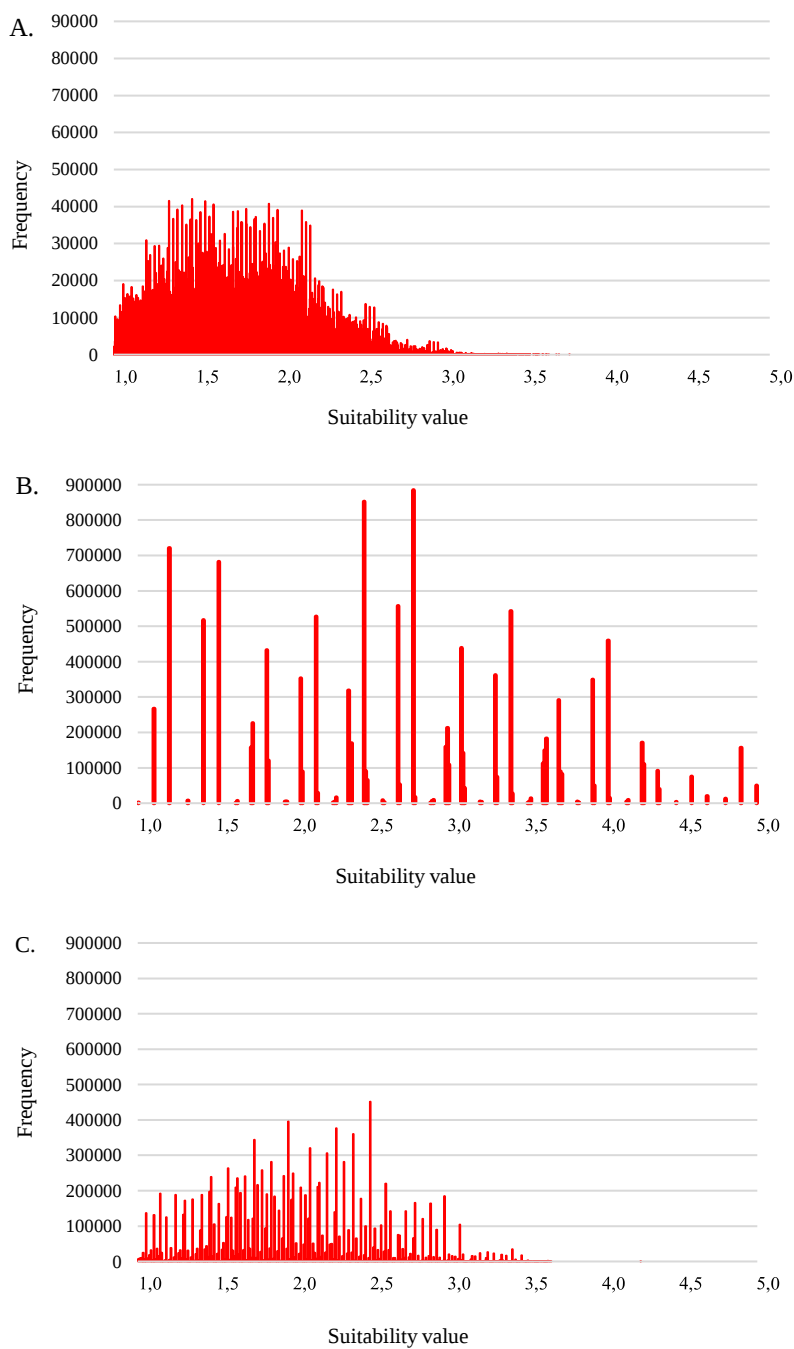


Fig. 9. Histograms of suitability values before reclassification: A – all criteria, B – orography, C – land use

The sensitivity analysis compares the suitability map derived from orography and land use to two alternative criteria selection scenarios: orography only and land use only (Fig. 10).

In both cases, the differences between the maps were at most two classes. More consistency with the S1 analysis was maintained by S3 analysis. In this case, as many as 89% of the sites overlapped, and a difference of one class was observed in 11% of the total area assessed. The analysis of orography differed significantly more from the overall analysis, and agreement between the studies was observed in 71% of the area, whereas the rest of the area showed a difference of one class

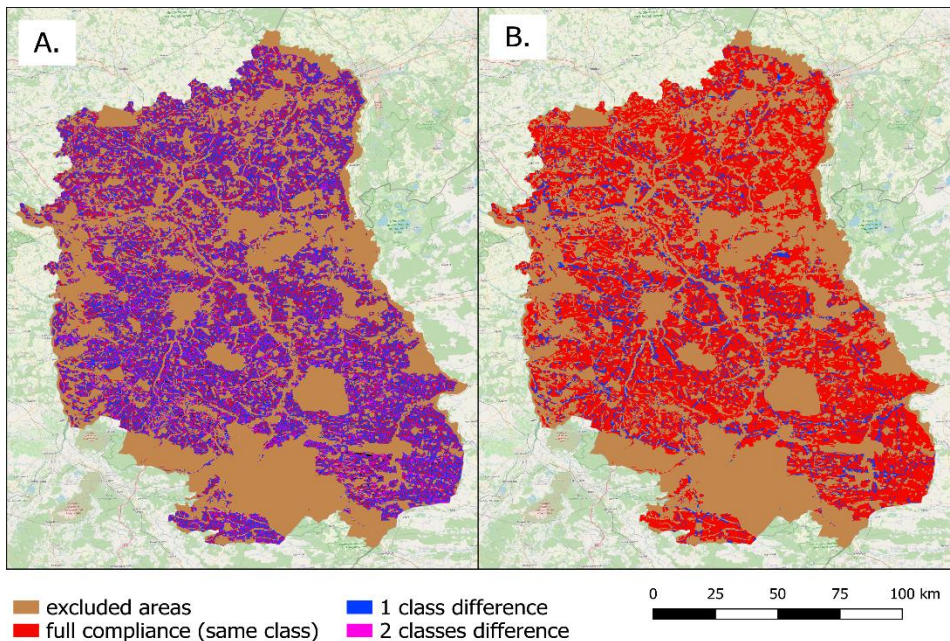


Fig. 10. Comparison of differences between scenarios: A – all criteria vs orography, B – all criteria vs land use

## CONCLUSION AND DISCUSSION

This paper addresses the evaluation of the spatial conditions of the Lublin Voivodeship for the development of AV in light of MCDM. Using the GIS environment and AHP method, a comprehensive assessment of the area was carried out in which a total of 8 criteria. In addition to the analysis of the entire set of criteria, two additional analyses were carried out in parallel: the first assessed only orography, and the second assessed land use.

An analysis of the sensitivity of the AHP assessment to the selection of criteria revealed that in a complex spatial environment, the number of factors under evaluation is not always crucial. When comparing the scenario with the full set of criteria evaluated to the two alternatives in which the number of criteria was truncated, a relatively high convergence of results was observed in comparison of S1 and S3. In S2, significantly greater

inconsistency was observed, reaching a maximum of 2 classes. For both S1 and S2, the key influence of proximity to the transmission network (the dominant criterion) on the results can be observed. The most suitable areas at 97.4% in S1 and 98.1% in S2 were within 300 m distance of a medium voltage power lines. In the analysis of the orography, land orientation was the dominant criterion, and it can be observed from the analysis that the areas least suitable for AV development (classes 4 and 5) are predominantly located in the southern part of the study area, where the relief is more varied and slopes as well as altitudes are relatively higher.

In addition to the selection of evaluation elements themselves, a problematic issue is the evaluation of their importance to each other, which, in the case of MCA, is always influenced by the subjective point of view of the person making the evaluation. An effective way to reduce uncertainty is to determine the importance of criteria based on consultations with expert groups and to synthesise the resulting assessments in a comparative matrix. The selection of appropriate evaluation factors for the determination of suitable sites for AV as well as PV farms in general is a complex problem and should be carried out based on the purpose of the specific analysis. Future research in this area should focus on developing models and methods for the selection of criteria and their evaluation, which are less sensitive to the subjectivity of evaluation and are more based on universal factors.

Potential directions for future research that could significantly deepen the analysis carried out should also include extending the spatial scale (e.g. to the national level), with consideration of the variability of climatic conditions, including solar radiation in particular. An aspect that requires additional analysis is also the economic viability of the investment, which in the case of AVs would require many additional aspects to be taken into account, including: investment costs (during the construction phase) which are higher than for PV; an assessment of different types of agricultural crops and the impact of partial shading on their yield; as well as local electricity and crop prices. A future extension of the analysis could also include soil conditions and the resulting legal prerequisites that realistically determine AV development opportunities. However, the analysis of the legal conditions may be problematic on Polish grounds, as the very concept of ‘agrivoltaics’ does not exist in the country’s legal system and therefore AVs are often treated like typical PV farms, with the same limitations applied to them (e.g. significantly restricted use of soil in class III and better). However, it is important to consider that the lack of a clear definition of this concept leaves a lot of space for subjective interpretation of the law, which generates additional problems in unambiguously assessing the legal potential.

In an assessment taking into account all criteria, over 98% of all suitable areas were classified as “moderately suitable” and “moderately highly suitable”. The percentage of land that could be considered ideal (high suitability) is relatively small, but there is a large base of land that could be used by investors for AV with the appropriate technological and design approach. It can also be expected that sites identified as less suitable for AV may be relatively cheaper to purchase due to relatively poorer infrastructure accessibility, greater distance from cities, or less favourable terrain, which may partially compensate for unfavourable conditions. An important tool in spatial policy that could contribute to improving the profitability of investments on less suitable sites could be the implementation of subsidies and financial support programmes for investment projects. Furthermore, from the perspective of local governments, agrivoltaics can be a form of land use that supports the local economy and contributes to increased energy security. However, the real possibilities for

the development of this type of installations would require adjusting spatial policy both at the national level and in local development plans as a new form of agricultural land use.

Notably, the results of this study are related to a specific area with specific spatial conditions. Changing the area of analysis can also significantly affect the final result, in addition to the selection of criteria and the weights assigned to them. The use of GIS tools in cooperation with MCDM to select suitable sites for agribusiness investment has advantages such as virtually unlimited possibilities for selecting assessment aspects and supporting the decision-making process based on the individual preferences of specific users. On the other hand, problematic aspects include the high sensitivity of the analysis to the human factor. The spatial aspect of evaluation can pose additional challenges in making a decision that is as close to optimal as possible, alongside the careful selection of evaluation elements and their mutual relationships. Criteria that are crucial in one area may have a marginal impact on the outcome in another due to small variability.

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