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Using geodetic data to optimize the distribution of solar and wind energy installations

Abstract. This study was aimed at identifying the optimal locations for solar and wind power plants in the Republic of Kosovo using geodetic parameters and evaluation criteria. The study used global publicly available data, including an elevation model, geographic coordinates, a land cover database, and information on solar radiation and wind characteristics, which were processed in GRASS GIS software. The analytic hierarchy process was used to calculate the weights of the criteria, which provided an integrated assessment of the suitability of the territories. The study found that 61.8% of the territory of the Republic of Kosovo is suitable for utilizing sunlight, indicating the country's significant potential for solar energy production. However, in the case of wind energy installations, the study found that only 32.5% of the territory could be considered optimal for solar power plants. This difference in percentages demonstrates the importance of considering many factors in the planning and construction of energy installations to ensure their stable and efficient operation. The study also confirmed that the F1 model, which uses all the criteria with their respective weights, provides the most reliable results for determining the optimal locations for energy installations. Sensitivity analysis showed that this model was the most effective in classifying suitable locations compared to other rasters such as F2 and F3. This confirms the importance of taking into account various parameters and their impact on the selection of optimal locations for power plants. The results open up possibilities for optimizing the use of solar and wind potential in the Republic of Kosovo, confirming the possibility of using geodetic data and geoinformation data to identify optimal locations for energy installations

Keywords: alternative energy; renewable resources; geographical information systems; hierarchy model; weighting coefficients

INTRODUCTION

The global spectrum of climate change and growing demands for sustainable development pose an urgent challenge to societies to develop and implement alternative energy sources. Solar and wind energy are among the most promising sources of renewable energy, but their optimal distribution requires comprehensive approach and accurate analytics. The use of geodetic data can be a key tool in solving this problem, allowing to effectively identify the most favourable locations for solar and wind power plants. Due to population growth and industrialization, society may face increasing energy needs, which threatens the stability of energy supply and natural ecosystems.

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Therefore, the problem of finding efficient energy sources that not only meet the needs of the present, but also ensure sustainability and environmental values is becoming extremely relevant. The use of solar and wind power plants in this regard is one of the most promising areas. It should be noted that the issue of practical use of geodetic data to ensure the optimal distribution of solar and wind energy installations is still open. Accurately identifying the locations with the greatest potential for their installation, as well as analysing the impact of various factors on their efficiency, requires the integration of geodetic data with information on climatic conditions and local topography (Shtohryn *et al*., 2023). A thorough study of these aspects can help to optimize the use of renewable energy sources and ensure the sustainability of energy supply in the future.

The potential of using alternative energy sources depends on various parameters and criteria that can be taken into account when applying geographic information systems (GIS). A study by S. Lajqi *et al.* (2020) investigated the use of renewable energy potential in the energy sector of the Republic of Kosovo using GIS, which confirmed the effectiveness and accuracy of geographic information systems in this area. The work of Y. An *et al.* (2023) also studied in detail the impact of wind flows on the efficiency of wind farm installation, using GIS to analyse geographic data, also confirming the potential of geographic information systems. The study by S. Izeiroski & B. Idrizi (2023) focused on analysing the impact of geographical features on the efficiency of renewable energy sources, which became the basis for developing strategies to optimize the distribution of energy installations. Thus, the integration of geographical information systems in research has led to significant conclusions and recommendations for the further use of alternative energy sources.

The global horizontal irradiance (GHI), which measures the intensity of solar radiation on the Earth's surface, can be used to determine solar radiation (Komisova *et al*., 2023) The study by D. Kumar (2020) on the distribution of solar radiation to determine the potential for solar energy use confirmed the effectiveness and versatility of this indicator. The study by O.K. Overen & E.L. Meyer (2022), in turn, was aimed at investigating the impact of terrain on the distribution of solar radiation, in particular, how altitude and other parameters affect the intensity of solar insolation. W. Liu *et al.* (2021) also analysed the impact of soil cover and other conditions on solar radiation potential, partly focusing on the use of geodetic data. At the same time, it is important to take into account the interaction of many factors to accurately determine the solar and wind potential of an area, which will allow for more efficient use of alternative energy sources in general.

The parameters of wind speed, direction and seasonal variations can be used to assess the potential for wind energy installations. In the work of C. Jung & D. Schindler (2022), the authors examined the influence of topography on local wind conditions, in particular how mountain ranges and valleys can affect wind speed and direction. The study by A. Rezaeiha *et al.* (2020) also focused on the research of seasonal variations in wind speed and their changes throughout the year in different regions. Meanwhile, S. Deep *et al.* (2020) analysed the impact of wind conditions on electricity generation and its variability depending on seasonal changes in wind speed. However, to fully understand the potential of wind energy use, it is necessary to take into account the complex impact of various factors on the distribution of renewable energy and the efficiency of such power plants.

The purpose of this study is to assess the potential for solar and wind energy use in the territory of the Republic of Kosovo, using geodetic data and geographic information systems. The main objective of the study is to determine the optimal locations for solar and wind power plants, taking into account various conditions. The second objective is to analyse the sensitivity of the models to various parameters and weighting factors to better understand the impact of various factors on the suitability of the territory for the installation of energy facilities.

MATERIALS AND METHODS

The study area is the territory of the Republic of Kosovo, located on the Balkan Peninsula (Fig. 1). The country covers an area of approximately 10,908 km². Kosovo is noted for its unique geographical location and climate, which creates favourable conditions for the use of renewable energy sources.

Figure 1. Location of the study
Source: compiled by the authors

To determine the basic parameters, this study used a variety of geodetic data sources, the vast majority of which are global and publicly available. To establish the basic parameters, we used the Global Digital Elevation Model (GDEM) from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of approximately 50 m (1 arc-second) from 2020. The Harmonized World Soil Database (HWSD) (Food and Agriculture Organization..., 2008) was used to determine the land cover, including its main characteristics. The digital classification sample (DCS) was created using remote sensing classification methods based on optical satellite images and covers a minimum mapping area of 30 ha. Additionally, the averaged global horizontal irradiance (GHI) data with a resolution of 50×50 m were calculated using the risen module.

The accuracy of the GHI was verified using data from weather stations and compared with commercial solar radiation data obtained from the PVGIS web portal. In this study, the average daily GHI value for the period from 2018 to 2020 was used. The three-year period was chosen to exclude the influence of extreme atmospheric conditions, as well as to ensure better data quality and reliability. All raster data were resampled to a spatial resolution of 50×50 m, as SRTM GDEM and GHI data have the same spatial resolution. Information on wind gusts, wind speed, and seasonal variations was obtained from the Global Wind Atlas database, which provides detailed data on wind resources with a spatial resolution of 1 km. These data were adapted to the local conditions of the Republic of Kosovo by using data from regional meteorological stations, which ensured their accuracy and relevance to real conditions.

In order to determine the optimal location of solar power plants and wind turbines, this study selected the analytic hierarchy process (AHP) as the most adapted and effective method to take into account all important factors and solve complex energy planning problems. This included a hierarchy creation process where the problem was broken down into objective, criteria, sub-criteria and alternatives, which allowed structuring the problem and clarifying all its aspects. One of the key steps in the AHP method was a pairwise comparison of the elements at each level of the hierarchy based on their importance. For this purpose, the Saaty comparative scale was used (Table 1), which allowed us to assess the importance of each element in comparison with other elements at the same level of the hierarchy.

Table 1. Comparison of importance indicators

Intensity of importance	Value of the indicator
1 (equal importance)	Both types of activity contribute equally to the achievement of the goal
3 (moderate importance)	Experience gives a certain advantage to one type of activity over another
5 (highly important)	A big advantage of one type of activity over another
7 (very highly important)	Experience gives a very strong preference to one type of activity over another
9 (extremely important)	Evidence that favours one type of activity over another has the highest level of weight
2, 4, 6, 8 (intermediate values)	In the reverse comparison between elements, the inverse intensity values are given importance

Source: compiled by the authors based on Y.E. Coruhlu *et al.* (2022)

When comparing individual pairs of alternatives at the appropriate level of the hierarchy, local weights of criteria and sub-criteria were determined. These weights were expressed in integers and recorded in matrix (1), where the values of the elements are inversely related. In other words, each value in the matrix reflects the degree of importance of one element compared to another, opposite to the intensity. This approach allowed us to systematically evaluate and rank the alternatives, taking into account their relationships at different levels of the hierarchy:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}. \quad (1)$$

Each alternative in this context is denoted by A_i where i varies from 1 to n, which corresponds to the total number of alternatives. The weights between pairs of alternatives are given in each element of the matrix A, denoted as a_{ij} and expressed as follows (2):

$$a_{ij} = \frac{w_i}{w_j}, \quad (2)$$

where i and j correspond to specific alternatives; w_i and w_j are the weights of the respective alternatives A_i and A_j.

Each value a_{ij} represents how much more important one alternative is compared to the other, and these values have reciprocal inverse correspondences in the matrix, i.e., $a_{ji} = \frac{1}{a_{ij}}$, which made it possible to systematically analyse the relative importance of each alternative in the context of multi-criteria decision-making.

GRASS GIS software was used to visually demonstrate the optimal locations for solar and wind power plants, providing powerful tools for detailed analysis and mapping. In particular, version 7.8.5 was chosen for its ability to process large amounts of data with high accuracy. The analysis also included normalization of the data, where pixel values ranged from 0 to 1, indicating the suitability of the area for power plants. Pixels with a value of 1 indicated the best locations for construction, while pixels with a value of 0 were unsuitable.

RESULTS

The peculiarities of energy planning, which often involves numerous conflicting goals and constraints, encourage the use of hybrid methods of multi-criteria decision-making. In this context, the AHP method is particularly effective, as it allows taking into account a variety of factors and criteria, and provides a qualitative and quantitative assessment of alternatives (Witt & Klumpp, 2021; Zayat *et al.*, 2023).

To determine the optimal locations for the construction of solar and wind power plants in the Republic of Kosovo, it is first necessary to determine the exact parameters required. These parameters have been classified into two groups: those that are critical for accurate siting, and those that improve the quality of the final result. Thus, the following categories of parameters were identified for energy planning:

- critical parameters include solar radiation levels, the number of sunny days per year, wind gusts, wind direction, seasonal variations in wind speed, average annual temperature and other data that affect the efficiency of solar panels and wind farms;
- additional parameters that enhance the quality of the result include terrain topography, altitude, slope, and orientation of the surface, and geographic coordinates. These parameters are also important for the optimal location and performance of power plants.

Critical parameters were analysed to determine the optimal locations for solar and wind power plants due to their direct impact on the efficiency and sustainability of energy production. The level of solar radiation is a key indicator for assessing the potential of solar power plants. High solar radiation and a significant number of sunny days ensure maximum productivity of solar panels, contributing to their efficient operation (Bhowmik *et al.*, 2020). For wind power plants, it is critical to analyse the average wind speed and seasonal variations. High and stable wind speeds allow wind turbines to operate at full capacity, while knowledge of seasonal variations helps to optimize maintenance and operation schedules (Prema *et al.*, 2021).

In turn, the analysis of additional parameters that improve the quality of the result also plays an important role in determining the optimal locations for power plants. Topography, altitude, slope, and orientation of the surface determine not only the technical feasibility of installing equipment, but also its efficiency. For example, solar panels located on southern slopes receive more sunlight during the day, which increases their productivity (Altintas & Utlu, 2021). For wind turbines, altitude, and open spaces without significant obstacles, such as mountains or forests, provide the best conditions for capturing wind energy. Latitude and longitude allow us to determine the exact location of the site on the Earth's surface, which is necessary for analysing solar radiation, the length of the sunny day, and wind characteristics (Ojeda Avila *et al.*, 2021). The main parameters used in this study are detailed in Table 2.

Table 2. Main research parameters

Parameter name	Parameter type	Requirements for the parameter
GHI	Critical	0-1
Wind gust speed	Critical	0-1
Wind direction	Critical	0-1
Seasonal variations in wind	Critical	0-1
Geographical coordinates	Additional	Latitude=0-1 Length=0-1
Tilt level	Additional	No more than 30% of the total
Orientation (azimuth)	Additional	North, south=0-1 West, east=0-1
Height above sea level	Additional	No more than 300 m 100-500 m

Source: compiled by the authors

Various parameters were taken into account in the study, but the GHI and wind characteristics proved to have the greatest impact on decision-making regarding solar and wind power plants. It is worth noting that the level of distribution of wind resources and solar radiation is uneven throughout the Republic of Kosovo, and this is important when considering the use of such alternative energy. The GHI parameter was chosen because of its critical impact on the assessment of the solar potential of a particular area, as it measures the total amount of solar energy incident on a unit area of horizontal surface. This value includes both direct solar radiation and diffuse radiation, which is important for a full understanding of the solar energy potential of a particular location. GHI data is available at high temporal (annual, monthly, daily values) and spatial resolution (up to 1 km or less), which allows for detailed modelling of the energy potential in different areas and under different conditions. The use of GHI allows creating accurate models for predicting the energy productivity of solar installations throughout the year, taking into account seasonal and climatic changes, which is especially important for countries with variable weather, such as Kosovo (Mohammadpour *et al.*, 2022).

The parameters of wind gust speed, wind direction and seasonal wind variations have been selected for several technical reasons that are crucial for optimizing the siting of wind turbines. Wind gust speed is a key parameter as it affects the efficiency and stability of wind turbines. High wind gust speeds can provide a higher level of electricity generation, but also create significant loads on turbine structures (Akçaba & Eminer, 2022). This requires consideration of maximum wind speeds in the design and siting of turbines to ensure their durability and reliability. Wind direction is another critical parameter, as it determines the optimal orientation of wind turbines to maximize energy capture. Understanding the dominant wind directions in a given area allows the turbines to be positioned correctly so that they can efficiently utilize the available wind resource, which is particularly important in difficult terrain where wind flows can vary depending on the topography. Seasonal variations in wind, in turn, are taken into account to understand changes in the wind resource throughout the year. This allows forecasting electricity production in different seasons, which is important for ensuring a stable energy supply (Wang *et al.*, 2020). In some regions of Kosovo, there can be significant changes in wind speed and direction throughout the year, which requires additional attention when assessing the performance of wind turbines. Taking into account seasonal variations helps to plan the distribution of energy resources and determine the most appropriate periods for maintenance and optimization of turbine performance.

Orientation (azimuth) also has a significant impact on the efficiency of alternative energy sources, especially in the context of generating electricity from solar panels. The technical aspects of orientation can be illustrated by the example of azimuth, which is measured in degrees from north (0°) in a clockwise direction. For solar panels, the most efficient orientation depends on the geographical latitude and climatic conditions (Selvakumar *et al.*, 2024). In the Northern Hemisphere, the optimal orientation is usually south (180°), as this maximizes the solar energy capture during the day. In contrast, in the Southern Hemisphere, the optimal orientation is north (0°). When solar panels are oriented to the south (180°), their efficiency is highest in the Northern Hemisphere. In this case, solar radiation reaches its maximum during the day, providing the maximum amount of captured energy. The performance factor in this orientation is 1, which means 100% optimal performance. On the other hand, the north orientation (0° azimuth) is the best for the Southern Hemisphere, as it also allows for maximum solar radiation during the day with a productivity factor of 1. Orientation to the east (90°) and west (270°) is less efficient compared to the southern azimuth. East-facing solar panels capture the maximum amount of solar radiation in the morning, while west-facing panels capture it in the evening. The performance factor for the east and west azimuth is approximately 0.8-0.9, which corresponds to 80-90% of the optimal performance.

For wind turbines, orientation is also important, but more so in relation to the direction of the prevailing winds. The orientation of the turbine should ensure maximum wind energy capture throughout the year. If the dominant winds are from the north (0°), the efficiency of the turbine will be high because the maximum amount of wind energy is captured. Similarly, orientation to the south (180°), east (90°) or west (270°) will be effective if the dominant winds are from the respective directions. The efficiency factor for wind turbines varies depending on local conditions and the prevailing wind directions. The study also selected requirements for the altitude parameter, with a limit of no more than 300 m. This ensured the selection of areas that do not exceed critical altitudes that could have a negative impact on the efficiency of solar and wind energy. Altitudes above 300 m may be less attractive in terms of accessibility, technical complexity and efficiency in terms of energy collection and transportation. At the same time, the range from 100 to 500 m takes into account a variety of geographical conditions and energy use potential. Altitudes in this range provide optimal conditions for collecting energy from the sun and wind, taking into account both minimum and maximum altitude requirements for the efficient operation of solar and wind power plant (von Krauland & Jacobson, 2024).

Analysing geographical coordinates such as latitude and longitude helps in determining the optimal location of solar panels and assessing wind resources. Latitude has a significant impact on the angle of incidence of the sun's rays and the length of a sunny day, as in areas closer to the equator, the sun's rays fall more directly, which increases the intensity of solar radiation. Longitude, in turn, affects local time and, accordingly, the timeframe of maximum solar activity. In addition, the analysis of geographical coordinates helps to identify areas with the best wind conditions, where the wind frequency and speed are optimal for the installation of wind turbines. The slope requirements, which are set at 30%, are also important for the efficiency of power plants. The slope of the site affects the angle of incidence of the sun's rays, as well as the wind speed and direction, which affects the efficiency of solar panels and wind turbines (Stoliarov, 2024). Setting a requirement of 30% slope can ensure an optimal relationship between the angle of solar radiation and the surface of solar panels. In addition, the slope of the land affects the distribution of wind. Rises and slopes can contribute to the formation of turbulence, which increases the efficiency of wind turbines. A slope requirement at a certain level can provide optimal conditions for collecting wind energy and maximizing its production (Nazir *et al.*, 2020).

The terrain analysis in the study was performed using a raster model with normalized pixel values. Each pixel was assigned a value indicating its suitability for construction, taking into account slope and orientation. A value of "1" was assigned to areas with a perfect zero slope, making them the best for construction, while a value of "0" indicated areas with a slope greater than 30%, making them less suitable. Using the parameter analysis described above, a hierarchy model was developed (Fig. 2).

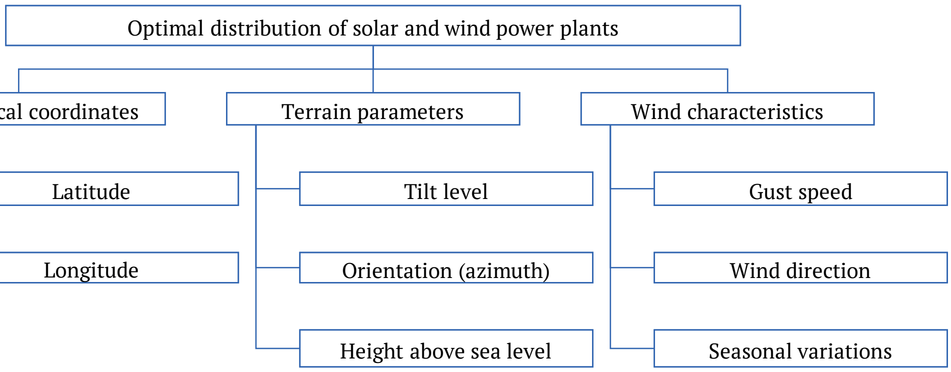

Figure 2. Hierarchy model

Source: compiled by the authors

This model is based on criteria and sub-criteria based on a detailed analysis of the various aspects that influence the selection of optimal power plant locations. Each criterion and sub-criterion have been carefully defined based on its contribution to the decision-making process and its importance for achieving the objective. This approach allows creating a more accurate and informed model that takes into account all relevant factors in determining the optimal locations for solar and wind power plants. The importance of the main parameters (Tables 3 and 4) was assessed using the method of pairwise comparisons, with the use of the Saaty scale for each pair of parameters. Then, local weights were calculated for these key parameters using the of AHP, which allowed taking into account the individual contribution of each parameter to the selection of optimal locations for solar and wind power plants, providing a more objective assessment and a better understanding of their role in the decision-making process.

Table 3. Indicators of importance of the main parameters (for solar panels)

Indicator	GHI	Geographical coordinates	Terrain parameters	Weight indicators
GHI	1	2	3	0.478
Geographical coordinates	0.3	1	2	0.213
Terrain parameters	2	0.5	1	0.309
$\lambda = 5.162$; $CI = 0.058$; $CR = 0.065$				

Source: developed by the authors

Table 4. Importance of key parameters (for wind turbines)

Indicator	Wind performance	Geographical coordinates	Terrain parameters	Weight indicators
Wind performance	1	2	3	0.443
Geographical coordinates	0.25	1	0.5	0.185
Terrain parameters	0.5	2	1	0.372
$\lambda = 5.504$; $CI = 0.033$; $CR = 0.047$				

Source: compiled by the authors

Using the AHP, calculations were performed, and weighting factors were assigned to the rasters. The total sum of all these raster data creates a final raster indicating the optimal locations for the construction of solar and wind energy installations in the Republic of Kosovo. To calculate this final raster, a mathematical expression was used, which in the case of solar power plants had the form (3):

$$F1 = 0.478 * R_1 + 0.213 * R_2 + 0.309 * R_3, \qquad (3)$$

where R_1 is the value of the GHI weighting factor; R_2 – geographical coordinates; R_3 – terrain parameters.

At the same time, in the case of wind power plants, this expression looks like (4):

$$F1 = 0.443 * R_1 + 0.185 * R_2 + 0.372 * R_3, \qquad (4)$$

where R_1 is the value of the weighting factor of wind characteristics; R_2 – geographical coordinates; R_3 – terrain parameters.

In order to verify the accuracy and objectivity of the results obtained through multi-criteria analysis in the context of determining the optimal locations for solar and wind power plants, the study conducted a sensitivity analysis. This analysis includes consideration of the impact of changing the weights of the criteria in three scenarios. The first scenario (F1) uses the criteria and weights described in the study. In the second scenario (F2), all criteria have the same weighting. The third scenario (F3) examines the impact of changing the weighting, where less weight is given to certain criteria, such as geographical parameters. This analysis allows assessing how sensitive the results are to changes in the weighting factors and helps to understand the impact of different weightings on the final decisions on the optimal locations for solar and wind power plants. The sensitivity assessment helps to identify the most important criteria and their weighting in decision-making, and provides a more objective assessment of the analysis results. To analyse in detail the results of the three scenarios with locations suitable for both solar and wind power plants, histograms were created for each of the final rasters (F1, F2 and F3), as shown in Figure 3. They allow visualizing the distribution of suitable locations in different scenarios, as well as understanding how changing the weighting factors affects the number and quality of potential locations.

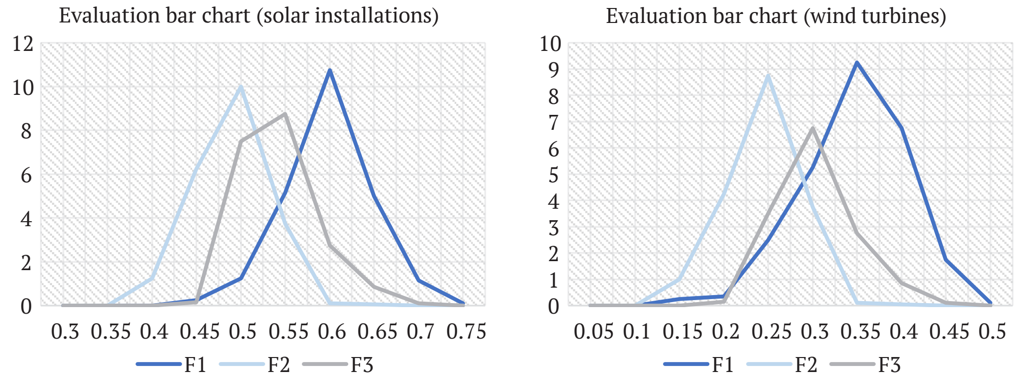

Figure 3. Evaluation histograms for optimal placement of power plants
Source: compiled by the authors

In addition, for each of the three scenarios, the relevant statistical indicators were calculated and presented in Table 5. For wind power plants, the calculation was carried out similarly (Table 6). This allowed for a comprehensive assessment of the impact of changes in the weighting factors on the distribution of optimal locations for both solar and wind power plants.

Table 5. Statistical indicators for optimal placement of energy installations (solar panels)

Indicator	F1 result	F2 result	F3 result
Pixels in total	42,906,590	42,906,590	42,906,590
Correct pixels	37,474,062	37,474,062	37,474,062
Incorrect pixels	5,432,528	5,432,528	5,432,528
The lowest value, %	0.4105	0.4018	0.3750
The largest value, %	0.8253	0.7933	0.7535
Arithmetic mean value, %	0.6179	0.5975	0.5642
Standard deviation, %	0.0475	0.0422	0.0418

Source: compiled by the authors

Table 6. Statistical indicators for the optimal location of energy installations (wind turbines)

Indicator	F1 result	F2 result	F3 result
Pixels in total	42,906,590	42,906,590	42,906,590
Correct pixels	37,474,062	37,474,062	37,474,062
Incorrect pixels	5,432,528	5,432,528	5,432,528
The lowest value, %	0.2366	0.2105	0.2120
Highest value, %	0.4123	0.3992	0.3713
Arithmetic mean value, %	0.3244	0.3048	0.2916
Standard deviation, %	0.0525	0.0479	0.0467

Source: compiled by the authors

A detailed analysis of the scenarios for the location of solar and wind power plants represented by rasters F1, F2 and F3 showed that in both cases, raster F1 contains the largest number of suitable locations for the construction of energy facilities. The histogram in Figure 3 shows that raster F2 has the smallest spread of values and lower mean values, indicating that the multi-criteria decision-making method applied to F2 provides more accurate results than the equal weighting scenario. Raster F1 has a wider range of values and a higher percentage of the most suitable locations for the construction of solar power plants than F3, which makes it more optimal. The statistical indicators presented in Tables 5 and 6 confirm these conclusions: in both cases, the F3 raster showed the worst results among all three scenarios. The maximum and average values for the F1 raster were higher, indicating a better classification of suitable locations for solar and wind power plants. Thus, the results of the analysis clearly demonstrate that the F1 raster provides the most accurate and reliable results for power plant locations, outperforming both the equal weighted raster (F2) and the raster with less weighting of geographic coordinates (F3). This conclusion is supported by visual analysis of the histograms as well as statistical data indicating that the F1 raster is more efficient and accurate in identifying optimal locations for power plants. Based on the results of the calculations and the analysis of solar and wind potential, the optimal locations for solar and wind power plants were identified (Fig. 4, 5). All analyses were performed in GRASS GIS software version 7.8.5 with a spatial resolution of 50×50 m in the official coordinate system of the Republic of Kosovo, which ensures the reliability and adequacy of the results.

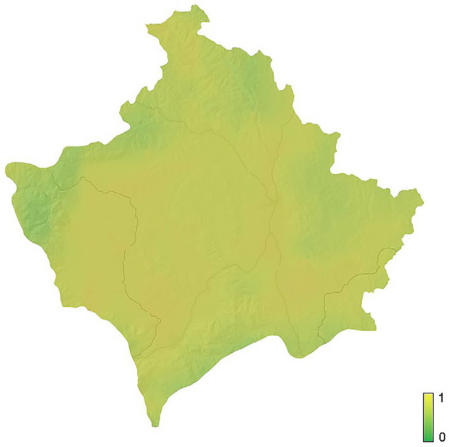

Figure 4. Map of the optimal location of solar energy installations in the Republic of Kosovo
Source: compiled by the authors

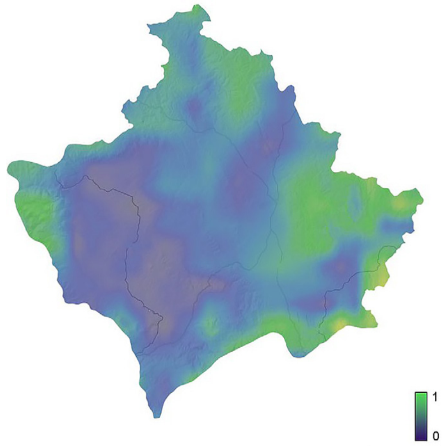

Figure 5. Map of the optimal location of wind power plants in the Republic of Kosovo
Source: compiled by the authors

The analysis of the data obtained allows concluding that, based on numerous parameters and criteria, 61.8% of the surface of the territory of the Republic of Kosovo is suitable for the use of solar potential. At the same time, this figure is about 32.5% for the placement of solar power plants. Thus, the approach considered in this study shows that although a significant part of the territory has the potential for solar energy generation, the actual suitability for the installation of solar power plants is significantly lower due to various additional requirements and limitations. The obtained results confirm the prospects of using geodetic data to analyse and determine the potential of renewable energy sources, in particular solar and wind energy. This allows effectively determining the optimal locations for the installation of solar and wind power plants, as well as taking into account various factors affecting their operation.

DISCUSSION

Exploring the potential for using alternative forms of energy, such as solar and wind, is becoming increasingly important in the search for sustainable and environmentally friendly sources. Growing global demand for energy and increasing environmental challenges have led to the need to study and use renewable energy sources, which contributes to the development of modern technologies and research in this area. Such research is becoming critically important for developing effective strategies for energy security, reducing dependence on traditional energy sources and reducing greenhouse gas emissions. The integration of alternative energy sources into the energy system contributes to the stability, diversification, and sustainability of energy production, which are critical elements of modern energy planning (Rubino *et al.*, 2017). In addition, the efficient use of alternative energy can contribute to the development of innovative technologies and increase the country's competitiveness in the international market. The development of effective methods for assessing and using alternative energy sources can stimulate industrial development, create new jobs and contribute to economic growth. Such research is an important step towards creating a sustainable and environmentally friendly future.

In this study, a multi-attribute decision-making methodology (MADM) was applied to systematize and evaluate the various criteria and alternatives that influence the choice in the context of optimizing the distribution of solar and wind power plants. The use of this methodology allowed for a comprehensive analysis of various aspects, including parameters for assessing solar resources as well as wind resources, which is an important factor for making informed decisions. This approach helps not only to identify optimal solutions, but also to take into account potential consequences and risks, which helps to ensure a more sustainable and efficient distribution of energy resources. The study by R. Rathi *et al.* (2020) also analysed the impact of changing decision-making criteria on the final results, which allowed for a better understanding of the importance of each criterion and its impact on the selected alternatives. The work of M.L. Kamari *et al.* (2020), which focused on the development of a model for predicting the energy potential of solar installations, allowed for future forecasts and more accurate planning of energy infrastructure development. In addition, the study by M. Şahin (2021) examined the impact of various solar and wind energy development strategies on economic, environmental and social aspects, which is important for developing effective policies and strategies in the field of alternative energy sources. The results of the above-mentioned works complement the findings of this study, providing additional support for the development of strategies and policies aimed at balancing the use of solar and wind energy, taking into account various parameters and factors.

The use of the AHP in this study proved to be extremely useful for systematizing and evaluating the various criteria that influence decision-making in optimizing the distribution of solar and wind energy installations. This method allowed taking into account various aspects such as altitude, slope, orientation and establishing their relative importance. The hierarchical structure of the AHP method allowed for the ranking of criteria and alternatives based on their hierarchical interconnectedness, which helped to conduct an objective analysis and select the best solutions. Additionally, the AHP provided a convenient and clear tool for taking into account the weight of each criterion, which contributed to informed and balanced decision-making. The use of this method can contribute to a more efficient use of energy resources, as well as to the achievement of the set objectives in the context of sustainable development. The work of J.A. Romero-Ramos *et al.* (2023), which focused on analysing the impact of geodetic and geographical conditions on the distribution of solar power plants, allowed a detailed assessment of the solar energy potential depending on various factors. The results of the work of L. Albraheem & L. Alabdulkarim (2021), which focused on the impact of climatic conditions on the efficiency of solar power plants, also provided important conclusions regarding the optimal placement of such plants. However, in comparison with the results of the above studies, it was found that the consideration of various criteria and alternatives, the use of a hierarchical approach and the sound analysis conducted in this study make it completer and more relevant for making effective decisions in the field of energy technologies.

An important part of this work was also the use of three different rasters (F1, F2 and F3) to assess the suitability of the territories of the Republic of Kosovo for solar and wind energy installations. The F1 raster took into account all the criteria with appropriate weights, which allowed for the most accurate and reliable results. The analysis showed that F1 demonstrates the highest efficiency in classifying suitable locations, with maximum accuracy in showing the optimal areas for the placement of installations. The histograms and statistical indicators obtained in the course of the work confirmed that F1 has the largest number of pixels with high suitability values, which indicates its superiority over other rasters. Raster F2, which used the same weights for all criteria, turned out to be less accurate and showed a much smaller spread of values. This indicates that an equal distribution of weights does not take into account the actual importance of each criterion, which leads to less accurate results. At the same time, raster F3, where the weights for certain criteria were reduced, showed the worst results among the three, confirming that underestimating the importance of certain criteria negatively affects the overall assessment of the suitability of territories. The study by S.A. Memon *et al.* (2021) examined the impact of various criteria on the selection of locations for wind and solar power plants, which confirmed the importance of accurately setting the weighting coefficients for each parameter. In turn, S. Rekik & S. El Alimi (2023) focused on the impact of climatic and environmental factors on the selection of optimal locations for solar and wind power plants, which also emphasized the importance of an integrated approach in multicriteria analysis. Thus, the results of this study, in conjunction with the above-mentioned works, demonstrate that the correct consideration of weighting factors is critical to accurately determine the optimal locations for energy installations. This confirms the need for a systematic approach and the use of reliable analysis methods to make informed decisions in the renewable energy sector.

The results of the study showed that 61.8% of the territory of the Republic of Kosovo is suitable for the use of solar potential, which indicates a significant potential for the development of solar energy in the country. However, when additional requirements for the siting of solar energy installations are taken into account, the suitability of the territory decreases to 32.5%. This decline indicates that there are numerous technical, climatic and other constraints that need to be taken into account when planning the placement of solar panels. This means that although the country has significant potential for solar energy generation, its effective use requires detailed planning and the removal of obstacles such as the lack of necessary infrastructure, difficult terrain or environmental restrictions (Rubino *et al.*, 2023). These findings highlight the importance of conducting detailed analyses and preparing strategies to maximize the use of the available potential, which can significantly increase the region's energy independence and stability. The study by M.R. Elkadeem *et al.* (2022) focused on analysing the technical barriers and opportunities for integrating solar energy systems into existing infrastructure, which helped to identify the main obstacles and ways to overcome them. At the same time, the work of Z. Ullah *et al.* (2021) considered the possibility of using and optimal strategies for combining several sources of alternative energy when placing solar and wind installations. However, in comparison with the results of this study, the above-mentioned works did not cover such a wide range of criteria and parameters that allow a more comprehensive assessment of the suitability of territories for the placement of solar panels and wind turbines in the Republic of Kosovo, which makes this study unique and more comprehensive.

Thus, research in this area is extremely important for the sustainable development of the energy sector in different regions of the world. They help to determine the optimal locations for solar and wind power plants, taking into account various factors. Such studies help support the transition to renewable energy sources, contributing to increased energy independence and reduced environmental impact, which are key factors for sustainable development and improved quality of life.

CONCLUSIONS

As a result of the study, a comprehensive approach was developed that included the use of geodetic data to determine the optimal locations for solar and wind power plants in the Republic of Kosovo. Using a multi-criteria analysis based on hierarchy analysis and GRASS GIS software, the study identified sites with the highest potential for efficient use of renewable energy sources. The study included the analysis of numerous parameters, such as critical parameters (solar radiation intensity and wind characteristics), as well as additional parameters (altitude, slope, orientation, geographical coordinates). The use of the SRTM global digital elevation model (GDEM) with a spatial resolution of 50×50 m and data from other open and publicly available sources ensured high accuracy of the analysis and quality of the results.

A detailed analysis of the obtained indicators led to the conclusion that 61.8% of Kosovo's territory is suitable for the use of solar potential. At the same time, in the case of wind energy installations, only 32.5% of the territory was optimally suitable for the installation of solar power plants. This difference indicates the need to consider many factors to ensure the stable and efficient operation of energy facilities. The sensitivity analysis showed that the F1 model, which takes into account all the criteria with appropriate weights, provides the most reliable results. The histograms and statistical indicators demonstrated that the F1 raster was the most effective in classifying suitable locations for energy installations compared to other rasters, such as F2 (with the same weights) and F3 (with less weight for the geographical coordinates' indicator). It is worth noting that the global models and databases used in this study, such as GDEM SRTM and HWSD, may not reflect some local features that are important for accurately determining the optimal locations for energy installations. In addition, the AHP involves subjective expert judgements, which may also affect the final results. In addition, this study considered a limited number of parameters and criteria, which may not provide a complete picture of the suitability of the areas.

Further research in this area could focus on the use of more parameters and factors, which would allow for a more qualitative and comprehensive assessment of the suitability of areas for energy installations. Another important area for research could be to expand the study area to other regions, which would allow for comparisons and adaptation of the methodology to different geographical and climatic conditions.

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CONFLICT OF INTEREST

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REFERENCES

[1] Akçaba, S., & Eminer, F. (2022). Sustainable energy planning for the aspiration to transition from fossil energy to renewable energy in Northern Cyprus. *Heliyon*, 8(6), article number e09813. doi: 10.1016/j.heliyon.2022.e09813.

[2] Albraheem, L., & Alabdulkarim, L. (2021). Geospatial analysis of solar energy in Riyadh using a GIS-AHP-based technique. *ISPRS International Journal of Geo-Information*, 10(5), article number 291. doi: 10.3390/ijgi10050291.

[3] Altintas, E., & Utlu, Z. (2021). Planning energy usage in electricity production sector considering environmental impacts with fuzzy TOPSIS method & game theory. *Cleaner Engineering and Technology*, 5, article number 100283. doi: 10.1016/j.clet.2021.100283.

[4] An, Y., Chen, T., Shi, L., Heng, C.K., & Fan, J. (2023). Solar energy potential using GIS-based urban residential environmental data: A case study of Shenzhen, China. *Sustainable Cities and Society*, 93, article number 104547. doi: 10.1016/j.scs.2023.104547.

[5] Bhowmik, C., Bhowmik, S., & Ray, A. (2020). Green energy sources selection for sustainable planning: A case study. *IEEE Transactions on Engineering Management*, 69(4), 1322-1334. doi: 10.1109/TEM.2020.2983095.

[6] Coruhlu, Y.E., Solgun, N., Baser, V., & Terzi, F. (2022). Revealing the solar energy potential by integration of GIS and AHP in order to compare land use decisions on environmental plans. *Land Use Policy*, 113, article number 105899. doi: 10.1016/j.landusepol.2021.105899.

[7] Deep, S., Sarkar, A., Ghawat, M., & Rajak, M.K. (2020). Estimation of the wind energy potential for coastal locations in India using the Weibull model. *Renewable Energy*, 161, 319-339. doi: 10.1016/j.renene.2020.07.054.

[8] Elkadeem, M.R., Younes, A., Mazzeo, D., Jurasz, J., Campana, P.E., Sharshir, S.W., & Alaam, M.A. (2022). Geospatial-assisted multi-criteria analysis of solar and wind power geographical-technical-economic potential assessment. *Applied Energy*, 322, article number 119532. doi: 10.1016/j.apenergy.2022.119532.

[9] Food and Agriculture Organization of the United Nations. (2008). *Harmonized World Soil Database v 1.2*. Retrieved from https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

[10] Izeiroski, S., & Idrizi, B. (2023). *GIS supported methodology for screening of optimal locations for exploitation of renewable energy resources*. Retrieved from https://www.researchgate.net/publication/374545018_GIS_supported_methodology_for_screening_of_optimal_locations_for_exploatation_of_renewable_energy_resources.

[11] Jung, C., & Schindler, D. (2022). On the influence of wind speed model resolution on the global technical wind energy potential. *Renewable and Sustainable Energy Reviews*, 156, article number 112001. doi: 10.1016/j.rser.2021.112001.

[12] Kamari, M.L., Isvand, H., & Nazari, M.A. (2020). Applications of multi-criteria decision-making (MCDM) methods in renewable energy development: A review. *Renewable Energy Research and Applications*, 1(1), 47-54. doi: 10.22044/rera.2020.8541.1006.

[13] Komisova, T., Honcharenko, M., & Sliptsova, N. (2023). Main sources of ionizing radiation and its impact on the population. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 3(103), 1-14. doi: 10.31548/dopovidi3(103).2023.002.

[14] Kumar, D. (2020). Satellite-based solar energy potential analysis for southern states of India. *Energy Reports*, 6, 1487-1500. doi: 10.1016/j.egyr.2020.05.028.

[15] Lajqi, S., Đurin, B., Berisha, X., & Plantak, L. (2020). Analysis of the potential for renewable utilization in Kosovo power sector. *Environments*, 7(6), article number 49. doi: 10.3390/environments7060049.

[16] Liu, W., Liu, Y., Zhou, X., Xie, Y., Han, Y., Yoo, S., & Sengupta, M. (2021). Use of physics to improve solar forecast: Physics-informed persistence models for simultaneously predicting GHI, DNI, and DHI. *Solar Energy*, 215, 252-265. doi: 10.1016/j.solener.2020.12.045.

[17] Memon, S.A., Upadhyay, D.S., & Patel, R.N. (2021). Optimal configuration of solar and wind-based hybrid renewable energy system with and without energy storage including environmental and social criteria: A case study. *Journal of Energy Storage*, 44, article number 103446. doi: 10.1016/j.est.2021.103446.

[18] Mohammadpour, M., Houshfar, E., & Ashjaee, M. (2022). Performance evaluation and multi-objective optimisation of an innovative solar-assisted multigeneration energy storage system for freshwater/O_2/H_2 generation. *Sustainable Energy Technologies and Assessments*, 53(D), article number 102755. doi: 10.1016/j.seta.2022.102755.

[19] Nazir, M.S., Ali, N., Bilal, M., & Iqbal, H.M.N. (2020). Potential environmental impacts of wind energy development: A global perspective. *Current Opinion in Environmental Science & Health*, 13, 85-90. doi: 10.1016/j.coesh.2020.01.002.

[20] Ojeda Avila, C., Salamanca Forero, S., & Bueno-López, M. (2021). Methods for the Characterisation of the Variability of Solar and Wind Resource. In *AETA 2019 – Recent Advances in Electrical Engineering and Related Sciences: Theory and Application* (pp. 224-233). Cham: Springer. doi: 10.1007/978-3-030-53021-1_23.

[21] Overen, O.K., & Meyer, E.L. (2022). Solar energy resources and photovoltaic power potential of an underutilised region: A case of Alice, South Africa. *Energies*, 15(13), article number 4646. doi: 10.3390/en15134646.

[22] Prema, V., Bhaskar, M.S., Almakhles, D., Gowtham, N., & Rao, K.U. (2021). A critical review of data, models and performance metrics for wind and solar power forecasting. *IEEE Access*, 10, 667-688. doi: 10.1109/ACCESS.2021.3137419.

[23] Rathi, R., Prakash, C., Singh, S., Krolczyk, G., & Pruncu, C.I. (2020). Measurement and analysis of wind energy potential using fuzzy based hybrid MADM approach. *Energy Reports*, 6, 228-237. doi: 10.1016/j.egyr.2019.12.026.

[24] Rekik, S., & El Alimi, S. (2023). Optimal wind-solar site selection using a GIS-AHP based approach: A case of Tunisia. *Energy Conversion and Management: X*, 18, article number 100355. doi: 10.1016/j.ecmx.2023.100355.

[25] Rezaeiha, A., Montazeri, H., & Blocken, B. (2020). A framework for preliminary large-scale urban wind energy potential assessment: Roof-mounted wind turbines. *Energy Conversion and Management*, 214, article number 112770. doi: 10.1016/j.enconman.2020.112770.

[26] Romero-Ramos, J.A., Gil, J.D., Cardemil, J.M., Escobar, R.A., Arias, I., & Pérez-García, M. (2023). A GIS-AHP approach for determining the potential of solar energy to meet the thermal demand in Southeastern Spanish productive enclaves. *Renewable and Sustainable Energy Reviews*, 176, article number 113205. doi: 10.1016/j.rser.2023.113205.

[27] Rubino, L., Rubino, G., & Esempio, R. (2023). Linear programming-based power management for a multi-feeder ultra-fast DC charging station. *Energies*, 16(3), article number 1213. doi: 10.3390/en16031213.

[28] Rubino, L., Rubino, G., Marino, P., & Di Noia, L.P. (2017). Smart solid state circuit breaker for photo voltaic power plants. *International Review of Electrical Engineering*, 12(5), 409-423. doi: 10.15866/iree.v12i5.13982.

[29] Şahin, M. (2021). A comprehensive analysis of weighting and multicriteria methods in the context of sustainable energy. *International Journal of Environmental Science and Technology*, 18(6), 1591-1616. doi: 10.1007/s13762-020-02922-7.

[30] Selvakumar, R.D., Wu, J., & Alkaabi, A.K. (2024). Electrohydrodynamic acceleration of charging process in a latent heat thermal energy storage module. *Applied Thermal Engineering*, 242, article number 122475. doi: 10.1016/j.applthermaleng.2024.122475.

[31] Shtohryn, L., Kasiyanchuk, D., Baranichenko, V., & Shtohryn, M. (2023). Geo-information analysis of natural factors of landslide formation in the region of the folded Carpathians (in the Transcarpathian region). *Ecological Safety and Balanced Use of Resources*, 14(1), 75-84. doi: 10.31471/2415-3184-2023-1(27)-75-84.
[32] Stoliarov, O. (2024). Efficient electricity generation forecasting from solar power plants using technology: Integration, benefits and prospects. *Bulletin of Cherkasy State Technological University*, 29(1), 73-85. doi: 10.62660/bcstu/1.2024.73.
[33] Ullah, Z., Elkadeem, M.R., Kotb, K.M., Taha, I.B., & Wang, S. (2021). Multi-criteria decision-making model for optimal planning of on/off grid hybrid solar, wind, hydro, biomass clean electricity supply. *Renewable Energy*, 179, 885-910. doi: 10.1016/j.renene.2021.07.063.
[34] von Krauland, A.-K., & Jacobson, M.Z. (2024). India onshore wind energy atlas accounting for altitude and land use restrictions and co-located solar. *Cell Reports Sustainability*, 1(5), article number 100083. doi: 10.1016/j.crsus.2024.100083.
[35] Wang, Y., Xu, L., & Solangi, Y.A. (2020). Strategic renewable energy resources selection for Pakistan: Based on SWOT-Fuzzy AHP approach. *Sustainable Cities and Society*, 52, article number 101861. doi: 10.1016/j.scs.2019.101861.
[36] Witt, T., & Klumpp, M. (2021). Multi-period multi-criteria decision making under uncertainty: A renewable energy transition case from Germany. *Sustainability*, 13(11), article number 6300. doi: 10.3390/su13116300.
[37] Zayat, W., Kilic, H.S., Yalcin, A.S., Zaim, S., & Delen, D. (2023). Application of MADM methods in Industry 4.0: A literature review. *Computers & Industrial Engineering*, 177, article number 109075. doi: 10.1016/j.cie.2023.109075.

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Використання геодезичних даних для оптимізації розміщення сонячних та вітрових електростанцій

Анотація. Це дослідження було спрямоване на визначення оптимальних місць розташування сонячних і вітрових електростанцій у Республіці Косово з використанням геодезичних параметрів і критеріїв оцінки. У дослідженні були використані глобальні загальнодоступні дані, зокрема модель рельєфу, географічні координати, база даних ґрунтового покриву та інформація про сонячну радіацію і характеристики вітру, які були оброблені за допомогою програмного забезпечення GRASS GIS. Для розрахунку вагових коефіцієнтів критеріїв було використано метод аналізу ієрархій, що дало змогу отримати інтегровану оцінку придатності територій для розміщення сонячних і вітрових електростанцій. Дослідження показало, що 61,8 % території Республіки Косово придатні для використання сонячного світла, що свідчить про значний потенціал країни для виробництва сонячної енергії. Однак, при розміщенні вітрових енергетичних установок, дослідження показало, що лише 32,5 % території можна вважати оптимальними для сонячних електростанцій. Така різниця у відсотках демонструє важливість урахування багатьох факторів при плануванні та будівництві енергетичних об'єктів для забезпечення їх стабільної та ефективної роботи. Дослідження також підтвердило, що модель F1, яка використовує всі критерії з відповідними ваговими коефіцієнтами, дає найбільш достовірні результати для визначення оптимальних місць розташування енергетичних установок. Аналіз чутливості показав, що ця модель є найбільш ефективною для класифікації відповідних місць розташування порівняно з іншими растрами, такими як F2 та F3. Це підтверджує важливість врахування різних параметрів та їх впливу на вибір оптимальних місць для розміщення електростанцій. Отримані результати відкривають можливості для оптимізації використання сонячного та вітрового потенціалу в Республіці Косово, підтверджуючи можливість використання геодезичних та геоінформаційних даних для визначення оптимальних місць розташування енергетичних установок

Ключові слова: альтернативна енергетика; відновлювані ресурси; геоінформаційні системи; модель ієрархій; вагові коефіцієнти