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A Hybrid Fuzzy AHP–MULTIMOORA Approach for Solar Energy Development on Rural Brownfield Sites in Serbia

Vladimir Malinić [1,*], Uroš Durlević [1], Ljiljana Brašanac-Bosanac [2], Ivan Novković [1], Marko Joksimović [1], Rajko Golić [1] and Filip Krstić [1]

[1] Faculty of Geography, University of Belgrade, Studentski trg 3/3, 11000 Belgrade, Serbia; uros.durlevic@gef.bg.ac.rs (U.D.); ivan.novkovic@gef.bg.ac.rs (I.N.); marko.joksimovic@gef.bg.ac.rs (M.J.); rajko.golic@gef.bg.ac.rs (R.G.); filip.krstic@gef.bg.ac.rs (F.K.)

[2] Institute of Forestry, Kneza Višeslava 3, 11030 Belgrade, Serbia; brasanlj@yahoo.com

* Correspondence: vladimir.malinic@gef.bg.ac.rs

Abstract

Global energy demand is steadily increasing, accompanied by a growing emphasis on clean and renewable energy sources. Serbia possesses significant solar energy potential, with solar radiation levels among the highest in Europe—about 40% above the European average. Within this context, rural depopulation clusters offer attractive opportunities for solar energy development due to the availability of underutilized land. This study aims to identify optimal locations for solar power installations in Serbia's depopulated areas by applying multi-criteria decision-making methods under uncertainty. A hybrid framework, combining fuzzy Analytic Hierarchy Process (fuzzy AHP) and fuzzy MULTIMOORA, was employed to evaluate potential sites. Fuzzy AHP was used to determine the relative importance of criteria, while fuzzy MULTIMOORA ensured a robust ranking of alternatives by addressing the vagueness in data and expert judgments. The analysis identified several high-potential brownfield locations, with the most suitable land class covering 5.01% (16.94 km^2) of the examined cluster area (311.3 km^2). These areas are typically characterized by flat terrain, high solar irradiation, and minimal environmental constraints, providing favorable conditions for solar farms. Among the assessed sites, location no. 9 consistently ranked highest across all three fuzzy MULTIMOORA variants: FRPA ($z = 0.0588$), FRS ($y = 0.2811$), and FFMF ($p = 1.6748$). The findings confirm that the hybrid fuzzy AHP–MULTIMOORA approach offers valuable support for informed decision-making on solar energy deployment in depopulated rural regions. Moreover, the utilization of rural brownfield sites contributes to the expansion of renewable energy, rural revitalization, and sustainable land management in Serbia.

Keywords: solar energy; depopulation cluster; fuzzy AHP; fuzzy MULTIMOORA; rural brownfield; sustainable development; spatial management; solar power plants; site selection; geographic information system (GIS)

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1. Introduction

The United Nations Sustainable Development Goals, adopted in 2015, represent a universal call to action aimed at eradicating poverty, protecting the planet, and ensuring peace and prosperity for all by 2030. These 17 interrelated goals serve as a global blueprint for a more secure and sustainable future [1]. Within the framework of sustainable development, population, defined as the set of people living and working within a given territory, remains one of the most important factors influencing the overall socio-economic development of a country and its administrative subunits [2]. Alongside population, space is a fundamental resource that must be utilized rationally and strategically. Population distribution is no longer merely a demographic category; it has become a strategic issue in spatial planning and management, as well as a crucial component of balanced regional development policy [3]. In this context, decision-makers, planners, and stakeholders must balance local community expectations, sustainability objectives, and project feasibility when considering the revitalization of depopulated or completely abandoned areas [4]. One of the key spatial categories warranting special attention in this regard is the rural brownfield.

The term brownfield refers to neglected, abandoned, or underutilized areas of land or infrastructure that were previously developed for industrial, commercial, agricultural, or military purposes. These sites often possess reuse potential, but typically require remediation or rehabilitation due to environmental degradation or physical decay. Historically, urban brownfields have received more academic and policy attention than those in rural settings. This is essentially because urban areas can more readily mobilize highly trained experts. In contrast, rural municipalities often lack internal expertise and rely on external actors, who are less available in these regions [5]. Other factors contribute to the underrepresentation of rural brownfields in policy discourse. Urban brownfields are subject to greater public pressure due to high population density and increased demands for new housing, public spaces, or business zones. Their higher market value, linked to proximity to existing infrastructure, also makes them more attractive to investors [6]. Conversely, rural brownfields often suffer from limited investor interest due to low population density, a smaller local labor force, and minimal political or media visibility. Urban brownfield projects, on the other hand, are often showcased as symbols of successful planning and economic revitalization.

Despite these challenges, rural brownfields, particularly in depopulated regions, possess several advantages. Firstly, they often cover larger, contiguous land parcels, allowing for greater development flexibility compared to urban brownfields, which are constrained by dense urban fabric. Secondly, lower land prices in depopulated areas reduce total investment costs. Thirdly, reusing rural brownfields helps preserve untouched natural areas by redirecting development to already-disturbed sites. Fourthly, such areas are well-suited for large-scale renewable energy projects, including solar and wind farms, which align with sustainability and conservation objectives. Ultimately, the revitalization of rural brownfields can stimulate broader regional development, increase land values, enhance employment opportunities, and facilitate the transfer of modern technologies to rural areas [7].

Significant portions of Serbia, mainly rural, mountainous, and border regions, have been continuously and permanently abandoned, posing a severe challenge for local development [8]. The goal of this paper is to explore the potential of one such depopulated cluster in Serbia as a rural brownfield site that could be revitalized through the construction of solar power plants. Serbia possesses considerable solar energy potential, with solar radiation levels among the highest in Europe and annual sunshine durations ranging from 1500 to 2200 h [9]. The Energy Development Strategy of the Republic of Serbia [10] states that the average annual solar radiation is approximately 1200 kWh/m^2, with regional variations reaching 1400 kWh/m^2 in central Serbia and up to 1550 kWh/m^2 in the southeast. On average, solar radiation in Serbia is around 40% higher than the European average [11]. Despite this significant potential, abandoned and depopulated areas in Serbia have not yet been explicitly connected to the development of solar energy. Instead, such areas have primarily been analyzed through the lenses of tourism [12,13] and cultural heritage preservation [14]. The conceptual basis for considering rural brownfields in this context was more recently established [15]. In line with the objectives of this study, several research tasks were defined. A depopulated cluster in Serbia was identified, within which the classes of suitability for solar power plant installation were determined using GIS tools and fuzzy logic. Based on the multi-criteria evaluation, the identified sites were ranked, and the most suitable location for constructing a solar power plant was selected.

This study has a strong application dimension, aligning with Serbia's strategic commitment to promoting and utilizing renewable energy sources. In 2023, Serbia adopted the Integrated Energy and Climate Plan (INECP) [16] together with the Strategic Environmental Impact Assessment, committing to increasing the share of renewable energy from 30% in 2021 to 45% by 2030. These measures are expected to reduce greenhouse gas (GHG) emissions by 13.2% relative to 2010 levels and by 33.3% compared to 1990 levels. By 2020, the total installed capacity of renewable energy sources had reached 514.61 MW, of which 398 MW originated from wind power. Projections for solar energy indicate a substantial increase in the coming decades. Under the "S" (or WAM) scenario, solar power capacity is projected to grow from 0.016 GW in 2020 to 18.5 GW by 2050, while alternative scenarios (WEM and S-N) suggest growth to 1.77 GW and 16.66 GW, respectively [16]. These figures illustrate the immense potential for solar energy development in Serbia. At the same time, the analysis emphasizes the importance of ensuring that renewable energy expansion proceeds in an economically rational and environmentally sustainable manner. By employing GIS in site selection and focusing on a depopulated cluster as the subject of analysis, this study demonstrates how the reuse of underutilized land can simultaneously contribute to national renewable energy goals, reduce CO_2 emissions, and support local ecological responsibility.

2. Literature Review

Rural areas across Europe, and within the European Union in particular, face a range of regional development challenges, among which the presence of neglected and abandoned brownfield sites is particularly notable [17]. The redevelopment of such areas increasingly relies on renewable energy strategies, whereby rural communities often depend on financial support from higher levels of public authorities, including the EU, national, and regional institutions [18].

A substantial body of literature identifies multiple factors that determine the success of brownfield regeneration projects, such as the integration of renewable energy solutions, especially solar power. Key determinants include the availability and quality of infrastructure, proximity to urban centers, and the extent of pollution and environmental degradation [19]. Other studies emphasize the importance of clearly defined ownership structures and the active participation of multiple stakeholders [20]. In Central and Eastern Europe, the issue of agricultural brownfields has been extensively studied, particularly in post-socialist countries such as the Czech Republic, Poland, and Slovakia [21]. Detailed case studies often highlight the long-term benefits of reusing brownfield land for sustainable development purposes, emphasizing its potential contribution to reducing emissions and mitigating global warming. Within this framework, post-mining brownfields have proven especially suitable for re-purposing into solar power plants, with favorable conditions observed in countries such as Turkey, Spain, and Portugal, where solar energy potential is particularly high [22].

Beyond Europe, renewable energy-based brownfield redevelopment has also become a strategic priority in the United States. Federal initiatives are increasingly promoting the replacement of conventional energy sources with renewables, with a particular focus on rural brownfield sites. Although challenges persist (most notably local zoning restrictions and environmental activism), investment figures remain significant.

In Michigan alone, for instance, renewable energy projects are estimated to have generated more than USD 15 billion in investment and 17,500 jobs in both construction and long-term employment [23].

These international examples demonstrate that the regeneration of rural brownfields through renewable energy development is not only a crucial driver of sustainable regional growth but also a vital instrument in addressing global environmental challenges. Against this background, it is imperative to examine how these broader trends resonate within the Serbian context, where brownfield redevelopment and the potential of solar energy have increasingly garnered scholarly attention.

While international experience provides valuable insights into the factors and practices that shape successful brownfield regeneration, the specific socio-economic and spatial context of Serbia requires a more detailed examination. In Serbia, research on rural brownfields, including the identification and assessment of the potential of abandoned spaces, and their integration into various economic and social functions, is relatively rare and mostly recent. So far, the scientific and professional community has mainly focused on analyzing depopulation processes through examining their causes and consequences, with demographic and economic perspectives dominating (agrarian overpopulation, forced migration, property nationalization, youth emigration, unfavorable educational structure, declining birth rate, deagrarianization, land cover changes, etc.) [24–33]. This and other research suggest that abandoned spaces are becoming a resource suitable for valorization, which would benefit society in a broader sense (i.e., a wider area). Not just the fragments of the former local community that remained to live in that space, thus nullifying the argument that abandoned space is not a resource in itself because there is no one for it to be valorized for.

The relatively limited scope of research in Serbia addressing the issue of abandoned spaces can be attributed to the lack of a systematic and coordinated approach by state institutions. Instead of viewing these spaces as potential resources, they are often perceived as a burden on society and the economy. Even in cases where their potential is identified, the lack of synergy between the business sector, state bodies, and scientific and research institutions significantly hinders their effective valorization and integration into sustainable development strategies. Additionally, specific examples demonstrate that recognized potentials in the past were often treated inadequately. One such example is the construction of small hydroelectric power plants, where in coordination with state structures, it was assumed that public resistance would be minimal because the affected areas were depopulated. This approach, however, elicited a strong negative response from the public, underscoring the need for a more thorough consideration of development policies in these areas.

Additionally, in public and professional discourse, there remains some hesitation about accepting the concept that certain areas are structurally unsuitable for achieving sustainable demographic stability. Isolation, a consequence of the period of Ottoman rule, when people, for the sake of security, chose isolated and difficult-to-access locations [26], in the modern era, becomes an obstacle to economic sustainability. This phenomenon is not exclusive to Serbia, but is a global phenomenon present in countries worldwide. However, the fact that some areas are less suitable for life does not mean that they are also unsuitable for the development of certain economic activities or the rational management of natural resources. A recent study [34] presents a theoretical framework for addressing rural brownfield zones, identifying abandoned military posts, infrastructure facilities, and agricultural parcels as potential sites for implementing diverse energy-related projects, while also considering public and environmental concerns.

Examples of converting abandoned buildings into hunting tourism facilities, art colonies, and eco-lodges, as outlined in [8], can inform innovative approaches to integrating solar panels into broader development strategies for depopulated areas. The case of Ečka in northern Serbia [35] compares brownfield regeneration and greenfield investments, highlighting the economic, social, and spatial advantages of the former–findings that can be applied to rural brownfield sites targeted for solar energy development.

Several studies in Serbia have utilized GIS and multi-criteria decision-making methods to determine the optimal locations for constructing solar power plants. One group of researchers [36] applied the AHP method to determine viable sites for solar panel installation in rural parts of eastern Serbia, demonstrating their economic feasibility. Another study [37] defined the northern parts of Serbia (notably the Banat region) as promising for solar energy development, with a clear demarcation between agricultural zones and areas designated for energy use. A recent study [38] focused on a municipality in central Serbia, applied GIS and the Best–Worst Method to reveal that over 25% of the territory has conditions favorable for solar farms. These methodologies and findings are primarily aligned with the "Smart Planning for Sustainable Development–Mapping Solar Potentials in Serbia" project, which identified 100 of the most suitable locations for solar power plants (up to 10 MW) using GIS and multi-criteria analysis that incorporated social, cultural, environmental, and agroecological criteria. All of the studies mentioned above correspond with current global research trends [39–48]. However, it should be emphasized that most domestic studies have primarily focused on analyzing the potential of existing administrative units (municipalities and cities), while the possibilities of utilizing abandoned and depopulated areas—and recognizing abandonment as a comparative advantage in this context—have remained mainly underexplored.

3. Materials and Methods

3.1. Study Area

This study focuses on a selected depopulation cluster in Serbia as the case study area. Depopulation areas and clusters in Serbia have been identified in previous studies [8,49]. The methodological procedure in these studies consisted of several phases. The first phase involved analyzing data from the publication "Age and Gender, Data by Settlement" [50]. In this phase, settlements with 20 or fewer inhabitants were identified, as well as those that were entirely uninhabited. Such settlements were considered economically and demographically unsustainable because their territories possessed the following characteristics:

- Agricultural holdings are not used or are used extensively;
- Cultivated land is increasingly occupied by natural vegetation.

The second phase involved the formation of depopulation clusters. These are groups of at least two neighboring cadastral municipalities that contain depopulation settlements, which makes it easier to observe this phenomenon in space.

The third phase expanded the analysis to the district level. This was necessary because depopulated areas often cross the administrative borders of municipalities.

Based on the above methodology, Joksimović [15] identified the 10 largest depopulation clusters in Serbia (Table 1, Figure 1), each of which occupies an area of more than 100 km^2.

Table 1. Overview of the ten largest depopulation clusters in Serbia, the respective local self-government units (LGU), and area of depopulation clusters.

No.	Cluster	LGU	Area (km^2)
1.	Vidojevičko–radanski	Prokuplje, Kuršumlija, Bojnik, Lebane	311.3
2.	Staroplaninski	Knjaževac	278.6
3.	Visočko–vidlički	Pirot, Dimitrovgrad	232.1
4.	Kuršumlija North	Kuršumlija	219.9
5.	Kuršumlija South	Kuršumlija	149.1
6.	Svrljiški	Pirot, Bela Palanka	145
7.	Crnotravski	Crna Trava, Leskovac, Vlasotince	133.7
8.	Vlasinski	Surdulica	129.3
9.	Rogozna	Novi Pazar	123.6
10.	Burelski	Dimitrovgrad, Pirot	113
	Total Area		1835.6

Source: Authors, adapted from [15].

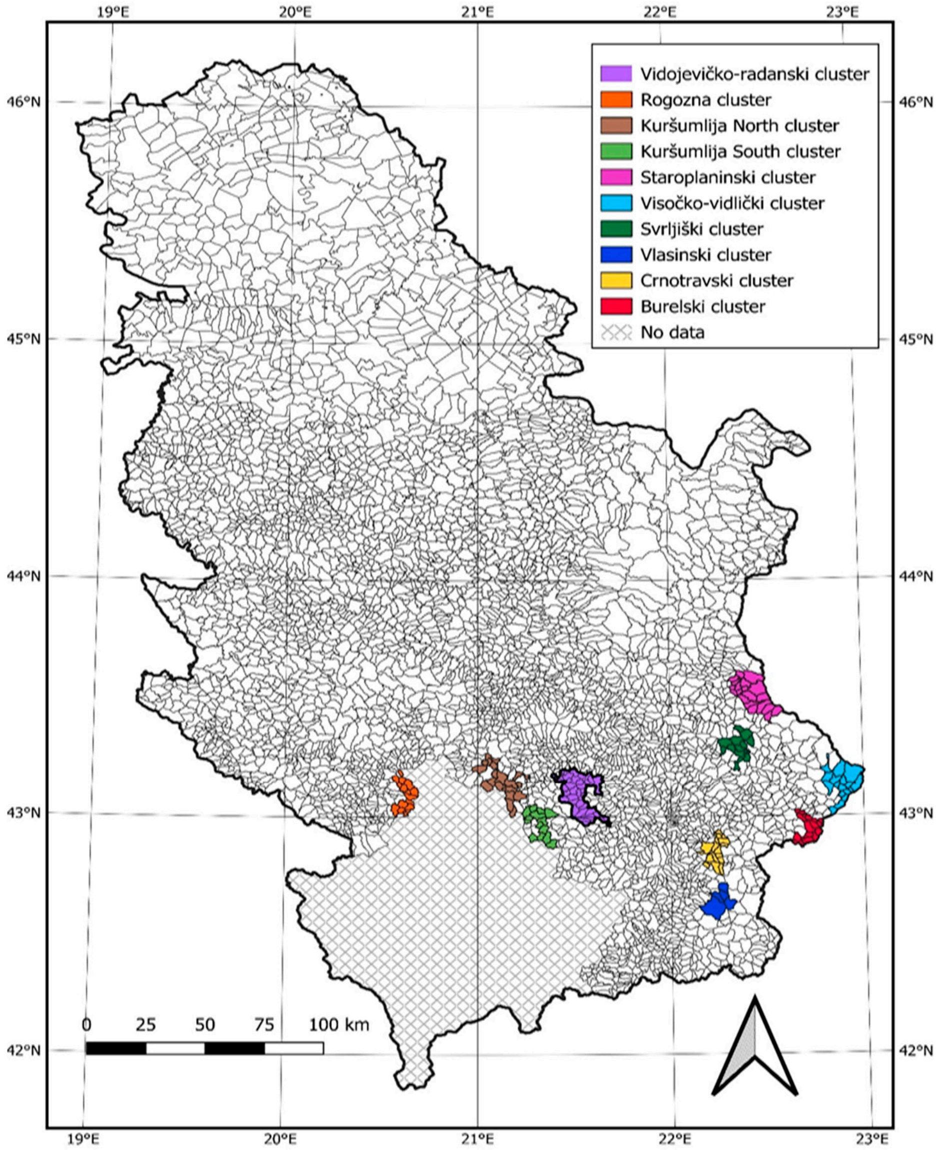


Figure 1. The ten largest depopulation clusters in Serbia. Source: Authors, adapted from [15].

The main limitation of this methodology lies in its reliance on official population census data, which may not accurately reflect the real situation on the ground. This is primarily because the census counts individuals based on their registered address, rather than their actual place of residence. Moreover, the definitions of "abandonment" and "neglect" are partially subjective and may overlook the activities of people who are not formally registered in the area.

To analyze the potential for solar panel installation, the largest depopulation cluster in Serbia—the Vidojevičko–radanski cluster—was selected (Figure 2). This area comprises 42 settlements located across the Vidojevica, Pasjača, and Radan mountains. Between 1991 and 2022, the population in this region declined dramatically from 2751 to 371 inhabitants. The area of arable land in the cluster decreased by 18.2 km^2 from 1990 to 2018, while during the same period, reforestation occurred—deciduous forest cover increased by approximately 7 km^2 [51].

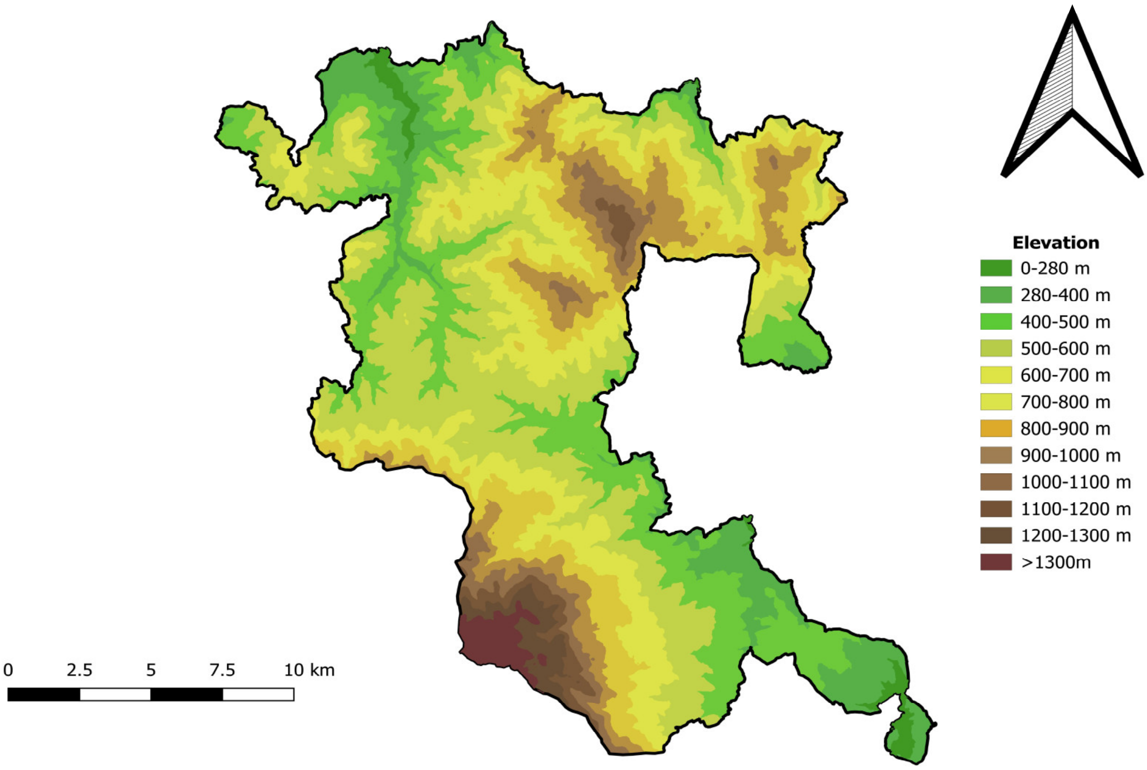


Figure 2. Elevation profile of the Vidojevičko–radanski depopulation cluster.

Forests have played a crucial role in the overall development of human activity and civilization since ancient times, serving as a vital factor in survival and progress. However, overexploitation and the continuous reduction in forested areas contribute to environmental degradation. In this case, given that forests cover 68% of the cluster, the noted changes are not of major significance. Deciduous forests remain the most valuable natural resource in the area. Proper and sustainable forest management is becoming increasingly important, especially in light of the growing prevalence of logging on abandoned plots. In addition to forest resources, the cluster also possesses mineral deposits of copper, lead, and zinc, which belong to the Lece–Halkidik metallogenic unit. To date, no exploitation of metal or non-metal deposits has taken place in this area.

The reasons for selecting this cluster as a potential brownfield location are manifold. First and foremost, it represents a sustainable solution, as it brings into function an area that is otherwise uninhabited and economically inactive, thereby contributing to Serbia's energy system. In addition to increasing the share of renewable energy sources, this approach entails significantly fewer negative environmental consequences compared to the potential exploitation of mineral resources in the Lece–Halkidik metallogenic unit. Another important reason for choosing this cluster is its size. A larger cluster implies a greater extent of available (or underutilized) land, which enables the selection of the most optimal sites within the cluster (relatively flat terrain, favorable solar potential, etc.), as well as the installation of higher-capacity power plants. This, in turn, increases the project's economic viability and facilitates the attraction of potential investors. Furthermore, the availability of a large area makes it possible to minimize potential conflicts with existing land uses and other economic activities in the immediate surroundings.

3.2. Materials

The study employed multiple types of spatial data, which were standardized and processed within a GIS environment (QGIS 3.34.10 LTR) for subsequent application in fuzzy AHP and fuzzy MULTIMOORA analyses, as well as for cartographic outputs. Table 2 summarizes all thematic layers, their sources, and their specific uses. Terrain attributes (slope and aspect) were derived from the EU-DEM digital elevation model. At the same time, layers representing infrastructure, hydrography, and settlements were obtained from publicly accessible datasets or digitized as needed. All vector and raster layers were reprojected to a common coordinate system (UTM Zone 34N, EPSG: 32634) and resampled to a uniform spatial resolution suitable for the analysis.

Table 2. Summary of the spatial datasets utilized.

Layer Name	Data Source	Note
Slope	EU-DEM (EU Copernicus Programme)	Derived from the DTM model
Aspect	EU-DEM (EU Copernicus Programme)	Derived from the DTM model
Protected Areas	Institute for Nature Conservation of Serbia	Most recent database–2024
Road Network	OpenStreetMap (OSM)	Downloaded via QGIS plugin and manually digitized
Watercourses	GeoSrbija	Manually digitized in QGIS
Settlements	GeoSrbija	Manually digitized in QGIS
Land use	Republic Geodetic Authority	Classification of land types and land use purposes

The criteria that were selected correspond to numerous previous studies dealing with solar potential, so that factors that significantly influence the suitability of a location for the application of solar panels were chosen.

3.3. Methods

Solar energy site selection is a complex problem that requires balancing multiple, often conflicting factors, such as topography, solar exposure, land use, accessibility, environmental sensitivity, and socio-economic acceptability. Traditional approaches frequently struggle to address this multidimensionality, particularly under conditions of uncertainty. To overcome these limitations, hybrid fuzzy multi-criteria decision-making (MCDM) methods have emerged as highly relevant for solar energy development, as they integrate technical feasibility with environmental and social considerations in a systematic way [52,53].

Among them, the fuzzy Analytic Hierarchy Process (AHP) provides a robust mechanism for deriving realistic criterion weights under vagueness in expert judgment. In contrast, the fuzzy MULTIMOORA method effectively structures trade-offs between benefit- and cost-oriented criteria. Fuzzy AHP accounts for the imprecision inherent in expert opinions, which are often expressed in linguistic rather than numerical terms. In contrast, MULTIMOORA ensures stable rankings by applying three reference procedures—the ratio system, reference point, and full multiplicative form—thereby reducing the scaling and normalization issues common in other MCDM approaches [54,55].

Applications of similar hybrid models in Turkey, Spain, the United Kingdom, Morocco, Iran, Iraq, Brazil, Saudi Arabia, and other countries and contexts confirm their suitability for renewable energy projects and highlight the transferability of this approach across diverse geographical and institutional settings [37,40,45,47,48,56–64]. Both fuzzy AHP and MULTIMOORA have been widely applied in energy and spatial planning, including solar power plant site selection [65], wind power integration with GIS [66], hybrid renewable energy systems [67], landfill site selection [68], offshore wind farms [69], CO_2 storage sites [70], and renewable energy technology prioritization [71]. By applying the fuzzy AHP–MULTIMOORA framework to rural brownfields in Serbia, this study connects methodological innovation with the urgent need to identify suitable solar sites in marginalized depopulated regions.

Alternative methods were considered but ultimately not selected. Standard AHP, although widely used, relies on exact pairwise comparisons and cannot adequately capture the vagueness inherent in expert assessments. The Analytic Network Process (ANP) is valuable when criteria are strongly interdependent; however, in this study, the selected factors (slope, aspect, land use, distance from roads, rivers, settlements, and protected areas) were intentionally independent, so the added complexity of ANP would not significantly improve the results. VIKOR, designed to identify compromise solutions among conflicting stakeholder preferences, was also deemed unnecessary, since the primary aim here is a straightforward suitability ranking, and its reliance on normalization procedures could introduce additional subjectivity.

3.3.1. Fuzzy AHP

Fuzzy AHP combines the classical AHP method (developed by Saaty [72]) with the concepts of fuzzy logic (fuzzy logic, fuzzy sets, developed by Zadeh [73]) in order to avoid uncertainty and subjectivity in the decision-making process to the greatest extent possible. Most of the basic steps involved in fuzzy AHP are similar to those in the AHP method. This integrated method retains the advantages of AHP and is widely applied [74–84]. The process of building a fuzzy AHP model involves several steps. In the first step, a hierarchical structure is developed with the goal at the top level, attributes/criteria at the second level, and alternatives at the third level:

$$H = (G,\ C,\ A)$$

where

G—the main goal;
C–$\{C_1, C_2, \ldots, C_n\}$—the set of criteria;
A–$\{A_1, A_2, \ldots, A_m\}$—the set of alternatives.

In the second step, a decision matrix or pairwise comparison matrix is constructed, which defines the relative importance of attributes/criteria and alternatives in accordance with the goal. This is achieved using a fuzzy scale of relative importance (Table 3) by comparing each criterion with all other criteria. Unlike the AHP method where estimates are represented by scalar values, in the fuzzy AHP method estimates are expressed by fuzzy numbers. The most commonly used is the triangular fuzzy number (TFN) (Scheme 1):

$$\tilde{a}_{ij} = \left(l_{ij},\ m_{ij},\ u_{ij}\right)$$

where

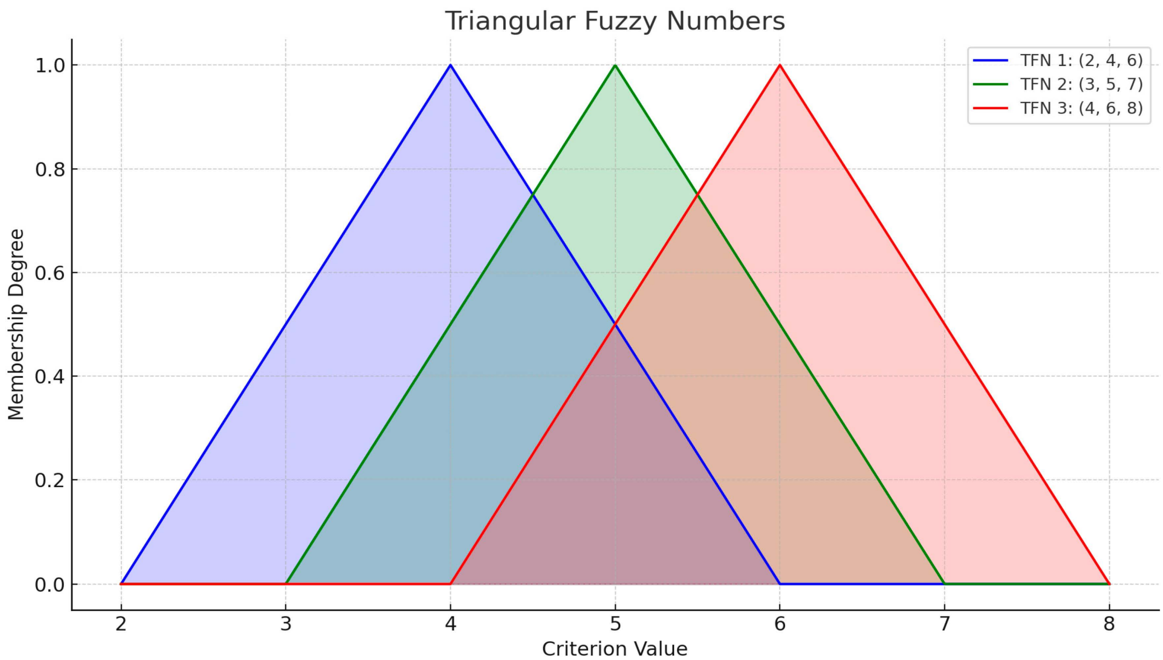
l_{ij}—lower bound;
m_{ij}—most likely value;
u_{ij}—upper bound.

The format of the fuzzy AHP pairwise comparison matrix looks like this:

$$\begin{bmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \tilde{a}_{23} & \cdots & \tilde{a}_{2n} \\ 1/\tilde{a}_{13} & 1/\tilde{a}_{23} & 1 & \cdots & \tilde{a}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & 1/\tilde{a}_{3n} & \cdots & 1 \end{bmatrix}$$

Table 3. Fuzzy AHP scale of relative importance.

Scalar Value (AHP)	Fuzzy Value (Fuzzy AHP)	Inverse Fuzzy Number	Definition
1	1, 1, 1	1, 1, 1	Equal importance
3	2, 3, 4	0.25, 0.33, 0.5	Weak dominance
5	4, 5, 6	0.17, 0.2, 0.25	Strong dominance
7	6, 7, 8	0.125, 0.14, 0.17	Very strong dominance
9	9, 9, 9	0.11, 0.11, 0.11	Absolute dominance
2	1, 2, 3	0.33, 0.5, 1	Intermediate value
4	3, 4, 5	0.2, 0.25, 0.33	Intermediate value
6	5, 6, 7	0.14, 0.17, 0.2	Intermediate value
8	7, 8, 9	0.11, 0.125, 0.14	Intermediate value



Scheme 1. Triangular fuzzy numbers (TFN).

For each triangular fuzzy number, the inverse form is defined as

$$\tilde{a}_{ij} = 1 \ / \ \tilde{a}_{ij}$$

i.e.,

$$\tilde{a} = (\mathrm{l}, \mathrm{m}, \mathrm{u}) = (1/u, 1/m, 1/l)$$

The next step involves calculating the fuzzy geometric mean for each criterion, which is performed as follows:

$$\tilde{r}_i = \tilde{A}1 \otimes \tilde{A}2 \otimes \tilde{A}_n$$

i.e.,

$$\tilde{r}_i = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \otimes (l_n, m_n, u_n)$$

more precisely

$$\tilde{r}_i = (l_1 \cdot l_2 \cdot l_n, m_1 \cdot m_2 \cdot m_n, u_1 \cdot u_2 \cdot u_n)^{\frac{1}{n}}$$

Subsequently, using the obtained fuzzy geometric means for each criterion, the fuzzy weight coefficients are calculated:

$$\widetilde{W}_i = \tilde{r}_i \otimes \left(\sum_{i=1}^{n} \tilde{r}_i\right)^{-1}$$

To transform the fuzzy weight coefficients into scalar values, it is necessary to apply the centroid method, i.e., the following formula:

$$\widetilde{W}_i = \frac{l_i + m_i + u_i}{3}$$

The final step is the normalization of the values obtained in the previous step; that is, the values derived using the centroid method:

$$\frac{W_i}{\sum_{i-1}^{n} \widetilde{W}_i}$$

Although consistency checking is not formally required in the fuzzy AHP methodology, it can be implicitly applied. The very nature of triangular fuzzy numbers reduces the risk of illogical judgments, but it is still advisable to assess the consistency of the system, especially during the initial stage of forming the pairwise comparison matrix. If the Consistency Ratio Index (*CRI*) is less than 0.1, the pairwise comparisons are considered consistent; otherwise, the evaluations should be revised. This test is performed using the following formula:

$$CRI = \frac{CI}{RI}$$

where

CRI—Consistency Ratio Index;

CI—Consistency Index;

RI—Random Index, which depends on the number of criteria n (see the values of this indicator in Table 4).

Table 4. Values of the Random Index.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The Consistency Index (CI) is calculated using the following formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where

$\lambda_{\max}$—the largest eigenvalue of the pairwise comparison matrix;
n—the number of criteria.

The largest eigenvalue of the pairwise comparison matrix is calculated as follows:

$$\lambda_{\max} = \left(\sum_{i=1}^{n} \left(w_i \times \sum_{j=1}^{n} a_{ij}\right)\right) / n$$

3.3.2. Fuzzy MULTIMOORA

After the fuzzy AHP method, the fuzzy MULTIMOORA method was applied. The fuzzy MULTIMOORA method represents an advanced extension of the standard MULTIMOORA approach by incorporating fuzzy numbers to minimize uncertainty and subjectivity in the decision-making process, similar to the principles applied in the fuzzy AHP method. MOORA stands for Multi-Objective Optimization by Ratio Analysis, and it encompasses three analytically distinct components: the Fuzzy Reference Point Approach (FRPA), the fuzzy ratio system (FRS), and the Fuzzy Full Multiplicative Form (FFMF) [85–88]. Each of these sub-methods independently evaluates the set of alternatives, after which the results are synthesized into a final decision output.

Before the fuzzy MULTIMOORA analysis is applied, it is necessary to determine the weight coefficients of the criteria using the fuzzy AHP method. However, a key distinction between fuzzy AHP and fuzzy MULTIMOORA lies in how the criteria are treated; in the latter, each criterion must be defined either as benefit-oriented (positive—where higher values are desirable) or cost-oriented (negative—where lower values are preferable).

In order to integrate the weight coefficients derived from the fuzzy AHP method into the fuzzy MULTIMOORA framework, a normalization procedure must be performed. Without normalization, criteria with larger numerical values could disproportionately influence the final results, leading to analytical bias. The normalization of weights is carried out according to the following formula:

$$\tilde{W}_j^{norm} = \frac{\tilde{W}_j}{\sum_{j=1}^{m} \tilde{W}_j}$$

where

$\tilde{W}_j^{norm}$—normalized weight of criterion j;
$\tilde{W}_j$—original fuzzy weight obtained using the fuzzy AHP method;
m—total number of criteria;
$\sum_{j=1}^{m} \tilde{W}_j$—sum of all fuzzy weights.

This procedure ensures that the sum of all normalized weights is equal to 1, i.e.,

$$\sum_{j=1}^{m} \tilde{W}_j^{norm} = 1$$

The fuzzy ratio system (FRS) represents the first step in the application of the fuzzy MULTIMOORA method. This approach enables the direct comparison of alternatives by computing the difference between the aggregated weighted values of benefit (positive) criteria and the aggregated weighted values of cost (negative) criteria for each alternative. The calculation is based on the following expression:

$$y_i = \sum_{j\in B} \widetilde{W}_j \otimes \widetilde{r}_{ij} - \sum_{j\in C} \widetilde{W}_j \otimes \widetilde{r}_{ij}$$

where

y_i—the final value for alternative i in the fuzzy ratio system (FRS);
$\widetilde{W}_j$—the normalized fuzzy weight of criterion j;
$\widetilde{r}_{ij}$—the normalized fuzzy value of alternative i for criterion j;
B—the set of benefit criteria (where higher values are preferred);
C—the set of cost criteria (where lower values are preferred).

In this way, the total value of each alternative is obtained, where a higher value indicates a better choice:

$$\mathrm{A}^*_{F-RS} = \left\{ A_i \mid \max_i \overline{\mathrm{y}}_i \right\}$$

The second component used for evaluating alternatives is the Fuzzy Reference Point Approach (FRPA). It is based on determining the distance of each alternative from the reference value (the best possible solution). The reference values are determined as follows:

$$r_j = \begin{cases} max_i x_{ij},\ j \in B \\ min_i x_{ij},\ j \in C \end{cases}$$

where

r_j—reference value for criterion j;
x_{ij}—value of alternative iii for criterion j;
B—set of criteria to be maximized (benefit criteria);
C—set of criteria to be minimized (cost criteria).

To measure the distance of each alternative from the ideal solution, the following formula is used:

$$z_i = \max_j d\left[\left(w_j \otimes r_j\right), \left(w_j \otimes x_{ij}\right)\right]$$

where

z_i—the maximum distance of alternative i from the reference point;
d—the distance between two fuzzy numbers;
w_j—weight of criterion j;
r_j—reference value for criterion j;
x_{ij}—value of alternative i for criterion j.

Alternatives are ranked based on the obtained values, where the lowest value is the best because it indicates the smallest distance from the ideal solution:

$$A^*_{F-RP} = \left\{ A_i \middle| \min_i \mathrm{z}_i \right\}$$

The final stage is the application of the Fuzzy Full Multiplicative Form (FFMF) approach, where the ratio of the products of normalized criterion values for benefit and cost criteria is calculated. The key advantage of this approach is that it allows exponential emphasis on the differences between alternatives, which can be useful when criteria have very different value domains. The formula applied is as follows:

$$P_i = \prod_{j \in B} \tilde{x}_{ij} / \prod_{j \in C} \tilde{x}_{ij}$$

where

P_i—result for alternative i;
$\tilde{x}_{ij}$—value of alternative iii for criterion j;
B—set of benefit criteria (where a higher value is more desirable);
C—set of cost criteria (where a lower value is more desirable).

After applying all three components of the fuzzy MULTIMOORA method—FRS, FRPA, and FFMF—the next step is to aggregate the results in order to obtain the final ranking of the alternatives. There are several ways to perform this aggregation, and in this study, average ranking was applied. This approach involves calculating the average position of each alternative across all three methods.

3.4. Evaluation Procedure and Expert Participation

All procedures and approaches used for the purpose of this study are presented in the flow chart given in Figure 3.

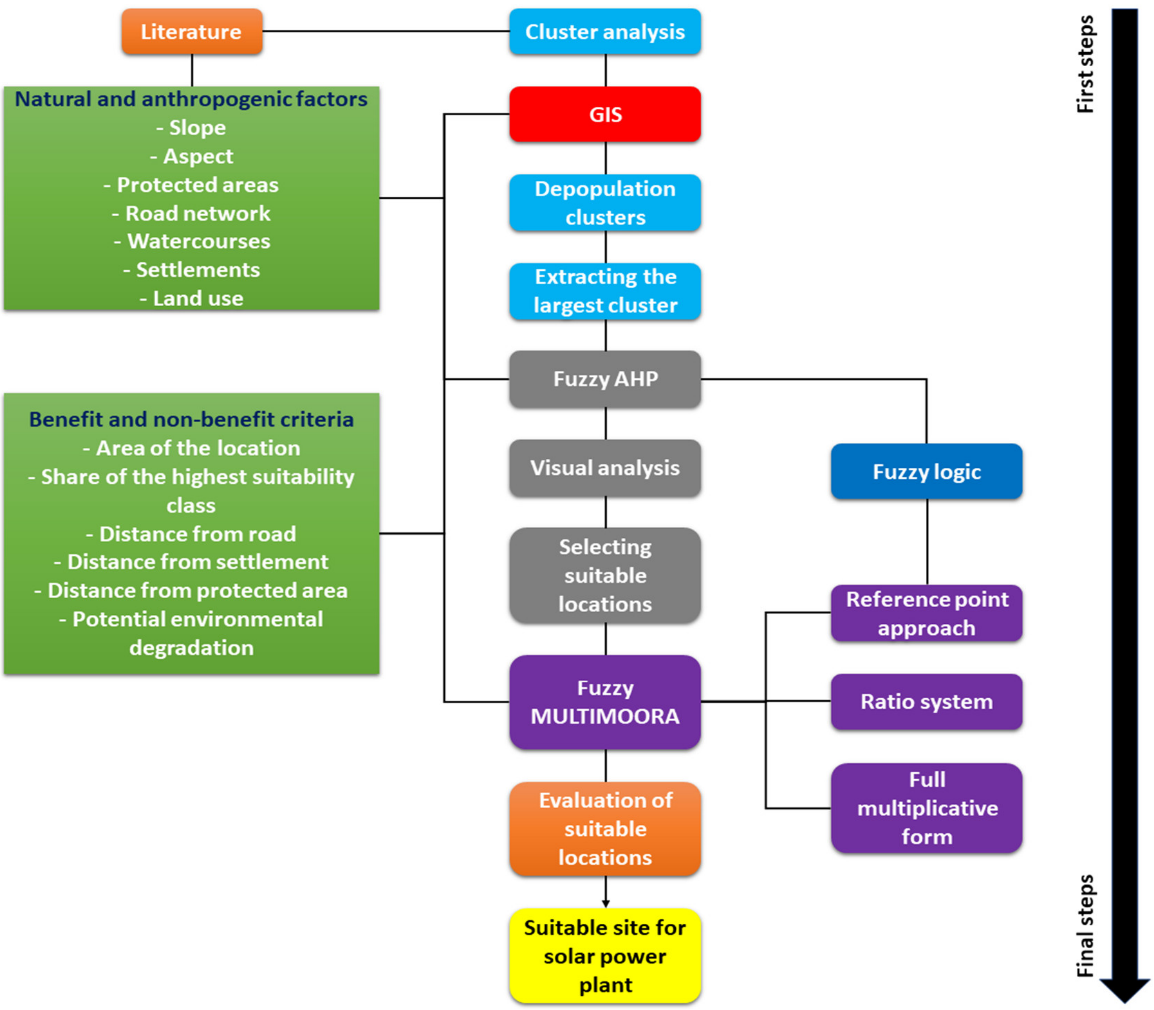


Figure 3. Flow chart with all the procedures and methods used in this research.

In both cases (fuzzy AHP and fuzzy MULTIMOORA), the criteria were evaluated by six experts from different fields: geography, energy, computer science, sustainable development, ecology, spatial planning, etc. (Table 5). The evaluation was performed in a group, so it is unique and consistent.

Table 5. Expert experience and scientific field.

Decision Makers	Years of Experience	Scientific Fields
Expert 1	15	Fuzzy logic, multi-criteria analysis, solar energy
Expert 2	10	Solar energy, GIS, environmental protection
Expert 3	34	Sustainable development, spatial planning, energetics
Expert 4	26	Geoinformatics, fuzzy logic, environmental management
Expert 5	25	Multi-criteria decision-making, cluster analysis, settlement geography
Expert 6	27	Globalization and integration, sustainable development, cluster analysis
Expert 7	17	Geographical regions of Serbia, energetics, ecology

4. Results

4.1. Results of the Fuzzy AHP Method Application

The problem-oriented approach to applying the fuzzy AHP method involved the use of numerous analytical tools to clearly identify opportunities, limitations, and potential conflicts, and to define measures to address them. Several criteria were selected to reflect the spatial and socio-economic conditions relevant for assessing the suitability of terrain for solar power plant construction. The criteria were determined based on a review of relevant literature data, the spatial context of the study area, and the specific requirements of solar energy development (Table 6). During the evaluation process, valuable contributions were made by experts in regional geography, spatial planning, and environmental protection. Their prior involvement in similar projects, spatial plans, and development programs provided a solid foundation for the analysis. Their expertise was directed toward assessing the current situation and proposing optimal strategies for the sustainable utilization of Serbia's natural, demographic, and economic potentials. Equally significant was the transfer of knowledge and accumulated professional experience of the authors, which further strengthened the analytical framework and enhanced the overall reliability of the study. Each criterion contributes a distinct value to the evaluation process and is assigned a weight reflecting its relative influence on project feasibility (Table 7).

Aspect (exposure) directly affects the energy production potential of the system. In the Northern Hemisphere, south-facing slopes receive the greatest intensity of solar radiation, making them the most favorable for photovoltaic installations. Accordingly, southern, southwestern, and southeastern exposures were assigned the highest scores, while northern exposures received the lowest.

Slope is a key topographic parameter in terrain suitability analysis. Gently sloping areas (up to 5%) are considered most appropriate for solar panel installation, offering benefits such as structural stability, reduced land preparation costs, and simplified construction. However, completely flat terrain (0–0.5°) may present drainage issues and was therefore considered less favorable. As the slope increases, both technical challenges and investment costs also rise.

Table 6. Criteria for the fuzzy AHP analysis.

Criterion	Categories	Mark	Area (km^2)	Percentage of Cluster Area (%)
Aspect	S	5	28.70	9.22
	SW, SE	4	69.29	22.25
	W, E	3	86.58	27.80
	NW, NE	2	86.27	27.70
	N, non-exposed	1	39.69	13.03
Slope	0.5–5°	5	30.68	9.85
	5–10°	4	81.96	26.32
	10–15°	3	83.15	26.71
	0–0.5°; 15–20°	2	67.41	21.65
	>20°	1	48.14	15.46
Distance from roads	<300 m	5	124.36	39.95
	300–6000	4	79.65	25.58
	600–900	3	52.04	16.72
	900–1200	2	29.70	9.54
	>1200	1	25.59	8.21
Distance from settlements	<500 m	1	59.91	19.24
	500–1000	2	69.26	22.25
	1000–1500	3	65.96	21.19
	1500–2000	4	49.70	15.96
	>2000	5	66.49	21.36
Land use	Meadows, pastures, degraded areas	5	42.10	13.52
	Urban areas	4	0.71	0.23
	Agricultural areas	3	1.61	0.52
	Forests	2	266.90	85.72
	Water bodies	1	0.02	0.01
Distance from rivers	>600 m	5	10.82	3.50
	450–600	4	15.14	4.86
	300–450	3	38.76	12.45
	150–300	2	95.48	30.66
	<150	1	151.04	48.53
Distance from protected areas	>1500 m	5	170.61	54.83
	1200–1500	4	7.23	2.32
	900–1200	3	8.71	2.80
	600–900	2	8.98	2.88
	<600	1	115.71	37.17

Table 7. Fuzzy matrix with decimal values.

Criteria	Aspect	Slope	Distance from Roads	Distance from Settlements	Land Use	Distance from Rivers	Distance from Protected Areas
Aspect	1.000, 1.000, 1.000	2.000, 2.500, 3.000	3.000, 4.000, 5.000	5.000, 6.000, 7.000	6.000, 7.000, 8.000	8.000, 9.000, 9.000	8.000, 9.000, 9.000
Slope	0.333, 0.400, 0.500	1.000, 1.000, 1.000	2.500, 3.500, 4.500	3.000, 4.000, 5.000	4.500, 5.500, 6.500	5.000, 6.000, 7.000	6.000, 7.000, 8.000
Distance from Roads	0.200, 0.250, 0.333	0.222, 0.286, 0.400	1.000, 1.000, 1.000	2.000, 3.000, 4.000	3.500, 4.500, 5.500	3.500, 4.500, 5.500	5.000, 6.000, 7.000
Distance from Settlements	0.143, 0.167, 0.200	0.200, 0.250, 0.333	0.250, 0.333, 0.500	1.000, 1.000, 1.000	2.000, 3.000, 4.000	3.000, 4.000, 5.000	4.000, 5.000, 6.000
Land Use	0.125, 0.143, 0.167	0.154, 0.182, 0.222	0.182, 0.222, 0.286	0.250, 0.333, 0.500	1.000, 1.000, 1.000	2.000, 3.000, 4.000	3.000, 4.000, 5.000
Distance from Rivers	0.111, 0.111, 0.125	0.143, 0.167, 0.200	0.182, 0.222, 0.286	0.200, 0.250, 0.333	0.250, 0.333, 0.500	1.000, 1.000, 1.000	2.000, 3.000, 4.000
Distance from Protected Areas	0.111, 0.111, 0.125	0.125, 0.143, 0.167	0.143, 0.167, 0.200	0.167, 0.200, 0.250	0.200, 0.250, 0.333	0.250, 0.333, 0.500	1.000, 1.000, 1.000

Proximity to roads is crucial, as access to road infrastructure reduces transportation costs and facilitates both the construction and maintenance phases of the project. Sites located within 500 m of the nearest road received the highest score, due to their logistical advantage.

Distance from settlements has a dual implication. While proximity facilitates grid connection and workforce availability, it can also cause land use conflicts, landscape disruption, or opposition from local communities. A moderate distance from urban areas is therefore considered optimal.

Proximity to watercourses presents both environmental and technical risks in the planning process. Areas near rivers and surface water bodies may be exposed to flooding, erosion, or legal restrictions related to riparian protection zones. Avoiding these areas reduces risk and simplifies the administrative approval process.

Distance from protected areas is another critical constraint, as construction within or near protected natural assets is subject to strict regulations and could threaten ecologically valuable habitats. Such areas should therefore be excluded from development.

In terms of land use, the most suitable locations are those that are not actively used for agriculture, forestry, or urban purposes and are not subject to seasonal flooding. Degraded lands, abandoned agricultural plots, or meadows are considered acceptable, as utilizing such areas reduces the potential for social or environmental conflict.

The results of the fuzzy AHP analysis (Table 8) indicate that slope is the most influential criterion in selecting suitable locations for solar power plant construction, with a defuzzified weight of 0.3859. This highlights the importance of an optimal slope for achieving maximum energy efficiency and facilitating the installation process of solar panels.

Aspect (0.2465) also emerges as a highly significant criterion, which is expected given that southern-oriented surfaces receive greater levels of incident solar radiation, directly influencing production capacity. This is followed by distance from roads (0.1487), which reflects the importance of site accessibility and logistical feasibility during construction.

Distance from settlements (0.0956) and land use (0.0607) hold moderate importance, primarily due to their implications for regulatory compliance, grid connection, and potential social acceptance.

Table 8. Defuzzified weight coefficients of the criteria.

Criteria	L	M	U	Defuzzified Weight Coefficients
Slope	0.2854	0.3921	0.5330	0.3859
Aspect	0.1690	0.2451	0.3591	0.2465
Distance from roads	0.0984	0.1469	0.2213	0.1487
Distance from settlements	0.0634	0.0943	0.1423	0.0956
Land use	0.0408	0.0600	0.0897	0.0607
Distance from rivers	0.0271	0.0379	0.0561	0.0386
Distance from protected areas	0.0187	0.0237	0.0328	0.0240

Finally, distance from watercourses (0.0386) and protected areas (0.0240) received the lowest weights, as these factors primarily represent spatial constraints or environmental restrictions, rather than offering direct technical advantages in site selection.

After applying the defuzzification procedure, precise priority values were obtained for each criterion. Based on the resulting normalized matrix, a consistency check was conducted by calculating the maximum eigenvalue, the consistency index (CI), and the consistency ratio (CR), following the classical method proposed by Saaty [72].

The resulting value (CR = 0.0246) is well below the commonly accepted threshold of 0.10, indicating a satisfactory level of consistency in the priority judgments and confirming the reliability of the model (Table 9).

Table 9. Consistency test in the fuzzy AHP analysis.

Indicator	Value
Maximum Eigenvalue (λ_{max})	7.195
Consistency Index (CI)	0.0325
Consistency Ratio (CR)	0.0246

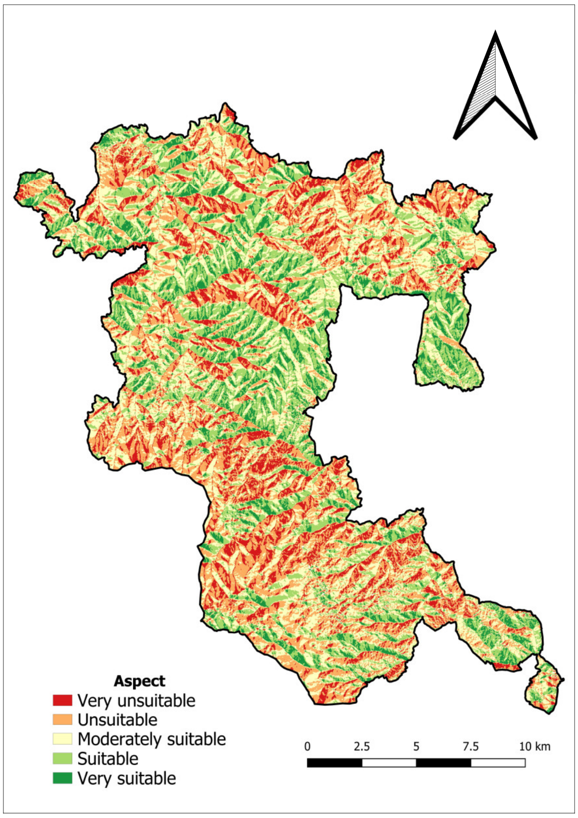
For each of the selected criteria, a corresponding map was generated (Figure 4).

By analyzing and evaluating seven criteria within the fuzzy AHP methodology, a synthetic suitability map for constructing solar power plants was developed for the territory of the largest depopulation cluster in Serbia (Figure 5). The excluded area, corresponding to the protected zone of the Radan Nature Park, accounts for 31.15% of the total cluster area, or 96.41 km^2 out of 311.30 km^2.

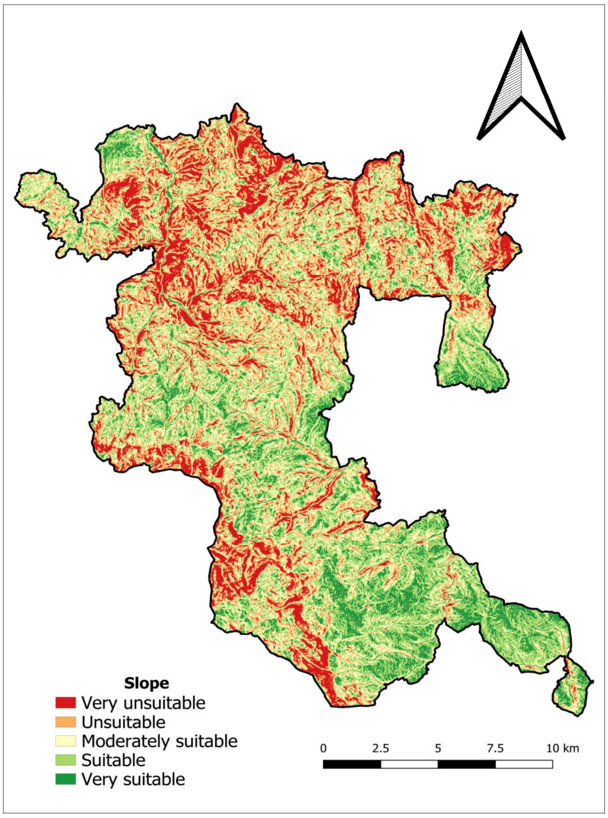
The unsuitable area covers approximately 4.37% of the cluster (13.52 km^2). It includes terrain with northern exposure, slopes steeper than 20°, distances from roads exceeding 1200 m, and proximity to settlements (less than 500 m) and protected areas (less than 600 m). This class also encompasses water bodies.

The unsuitable area (15.56%, or 48.16 km^2) includes terrain with northeastern and northwestern exposures, slopes ranging from 0 ° to 0.5° and 15 ° to 20°, relatively large distances from roads, and proximity to settlements, rivers, and protected areas. These are often forested areas, less favorable for development.

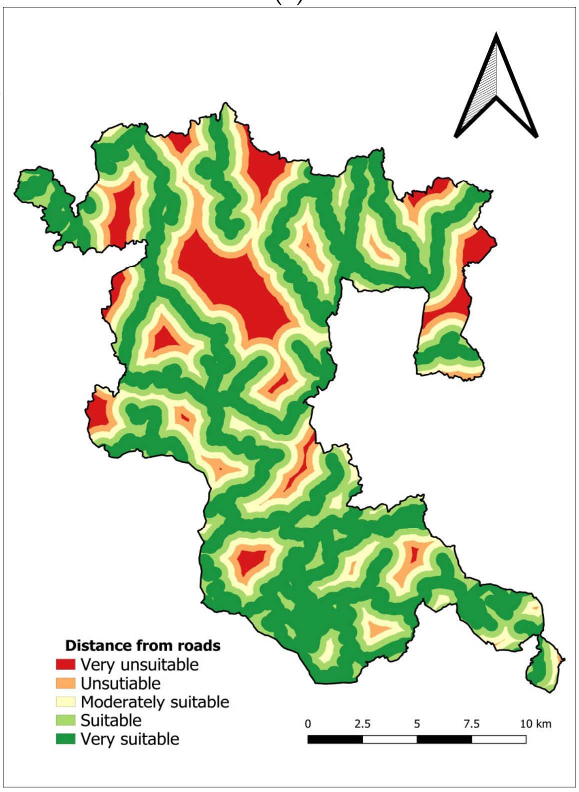
The moderately suitable area comprises 27.42% of the cluster (85.25 km^2) and consists of locations that meet some but not all of the suitability criteria. Typically, these areas are characterized by unstable exposure, gentle to moderate slopes, or zones located near settlements or watercourses. This class represents a potential reserve for solar development, subject to further technical and environmental assessment.



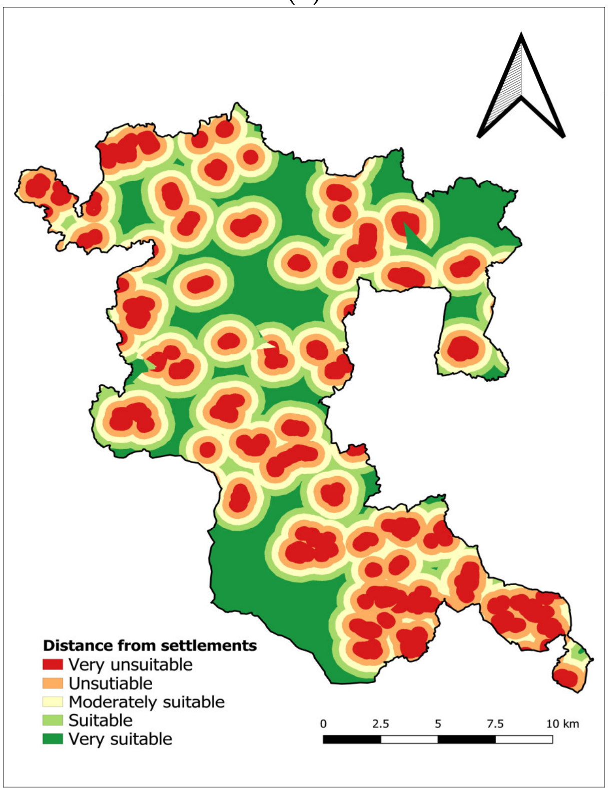
(**a**)



(**b**)



(**c**)



(**d**)

Figure 4. *Cont.*

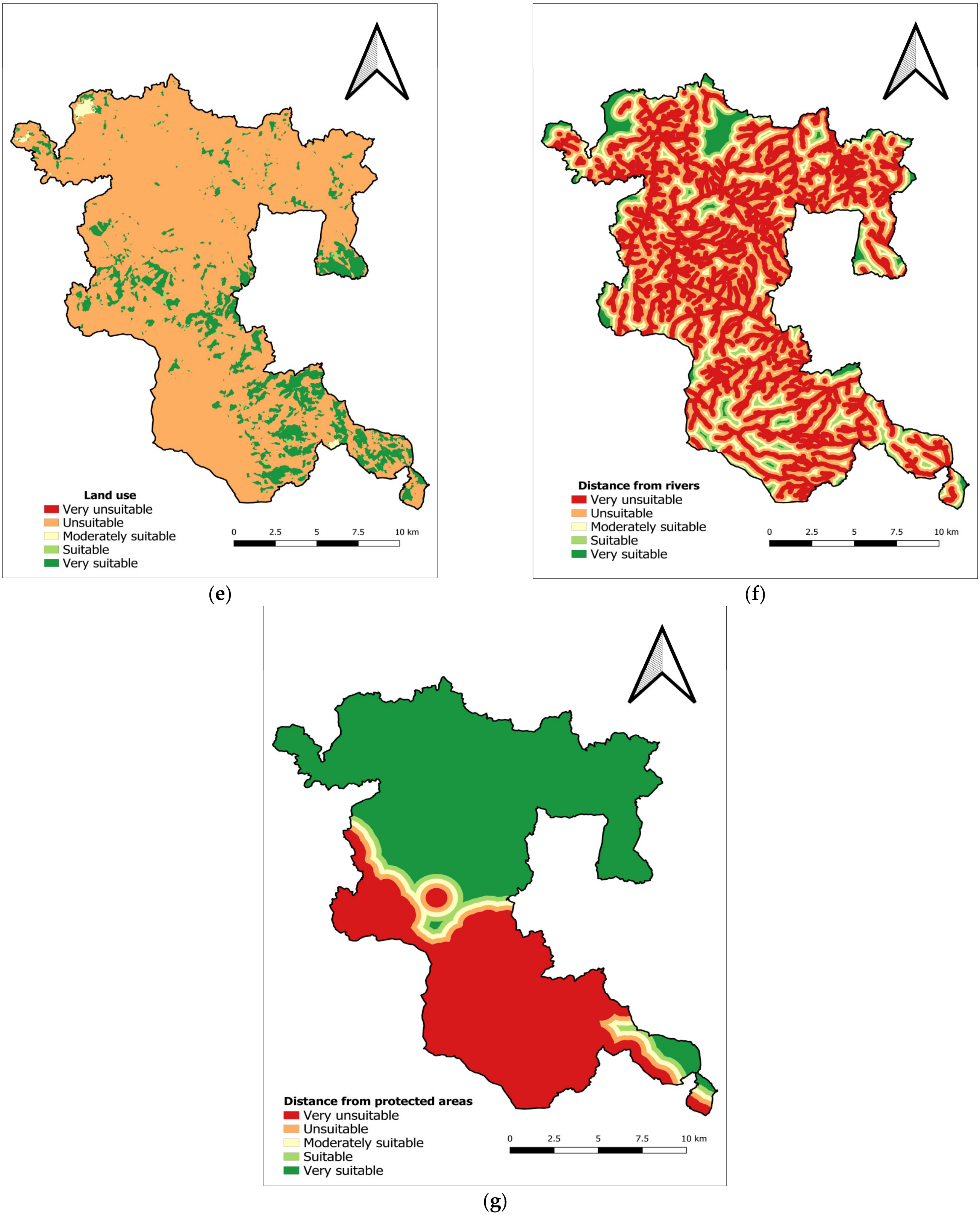


Figure 4. Suitability maps derived from the fuzzy AHP analysis for each criterion: (**a**) aspect, (**b**) slope, (**c**) distance from roads, (**d**) distance from settlements, (**e**) land use, (**f**) distance from rivers, (**g**) distance from protected areas.

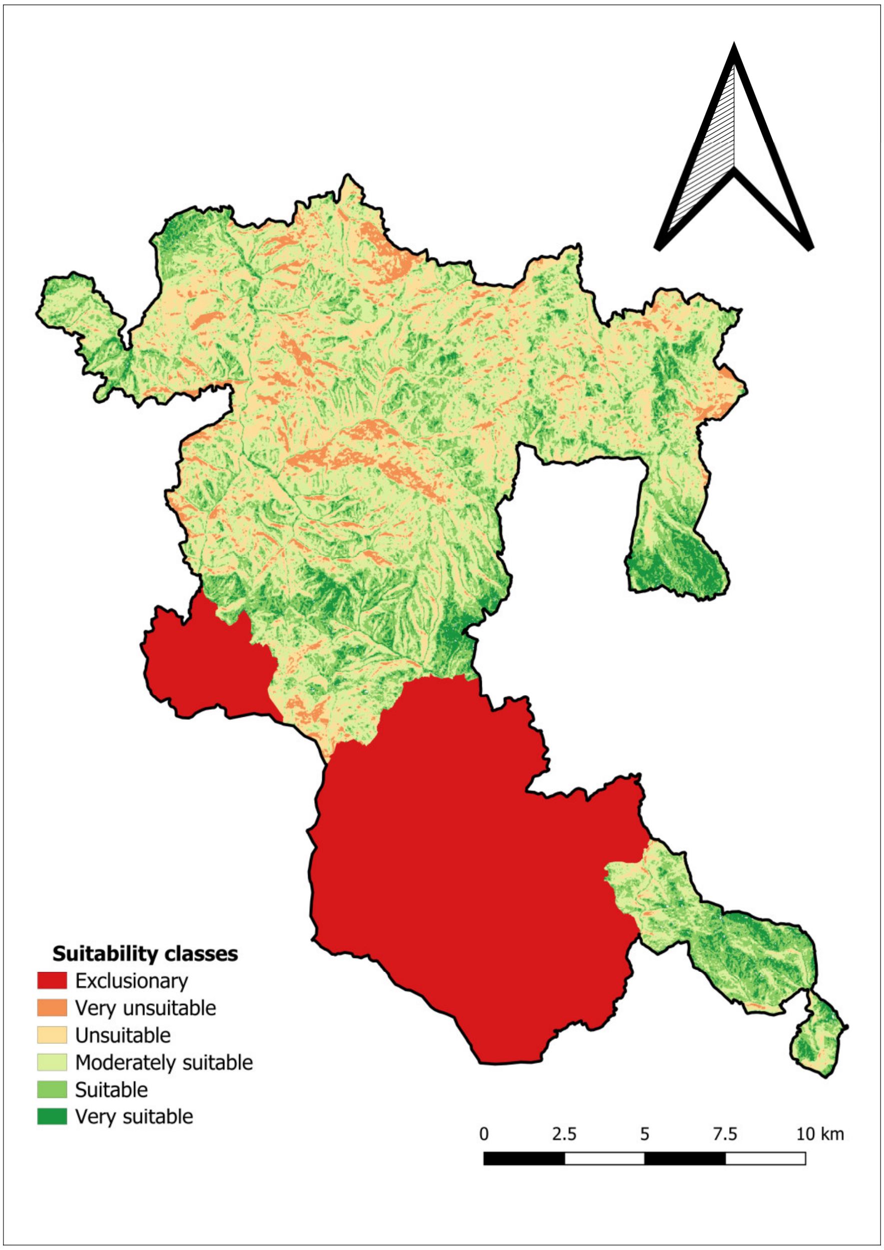


Figure 5. Synthesized suitability map for solar power plant development in the Vidojevičko–radanski cluster.

The suitable area comprises 16.49% (51.05 km^2) of the cluster. It includes zones with favorable topographic features—primarily gentle southwest- and southeast-facing slopes, a moderate distance from roads, and a greater distance from settlements and protected areas. These sites are promising for the development of small-scale solar systems, though they may still require infrastructure assessments.

Finally, the most suitable class accounts for 5.01% of the cluster (16.94 km^2). This area is characterized by southern exposure, flat terrain, proximity to roads (enhancing economic viability), and sufficient distance from settlements, protected natural areas, and rivers, thus minimizing potential environmental and anthropogenic conflicts.

4.2. Results of the Fuzzy MULTIMOORA Method Application

After identifying the most spatially favorable zones for solar panel installation using the fuzzy AHP method, the next phase of the research involved the application of the fuzzy

MULTIMOORA method to select the most optimal, or the "best of the best", locations from among all potential zones. For the fuzzy MULTIMOORA analysis, ten locations were selected based on two key criteria (Figure 6). The selection of locations for the fuzzy MULTIMOORA analysis was based on expert judgment, relying on the previously outlined expertise of the research team in spatial analysis, renewable energy planning, and regional development. Guided by this background, two thresholds were established to ensure the relevance and feasibility of selected sites. The first criterion was a fahp_mean value greater than 4.5, which reflects a high degree of suitability as determined by the fuzzy AHP analysis. The second criterion was a minimum area of 0.5 hectares, ensuring sufficient space for the installation of small-scale solar systems. The combination of these two criteria guarantees a balance between the qualitative suitability of the location (as indicated by the fuzzy AHP score) and its practical applicability for solar energy development.

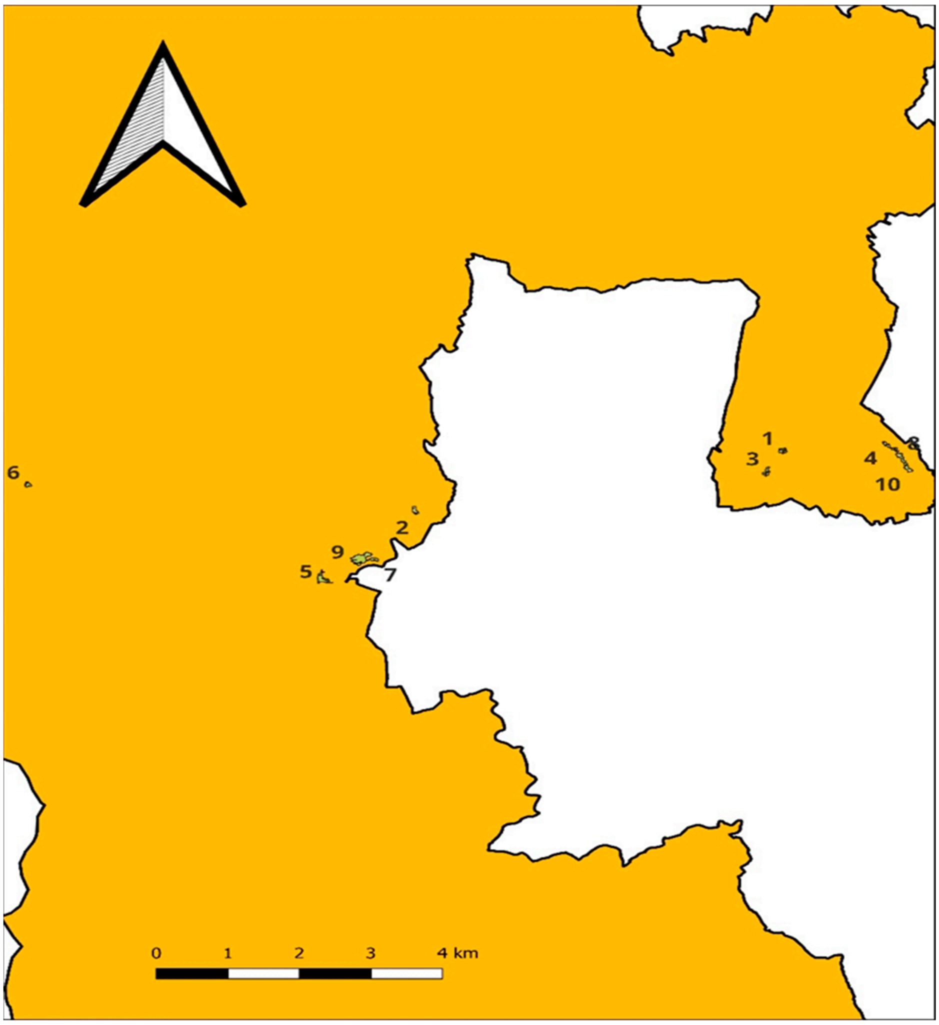


Figure 6. Ten selected locations used in the fuzzy MULTIMOORA analysis.

For each of the ten selected locations, the values of six relevant criteria were calculated (Table 10). Based on these values, a final ranking of the most favorable locations for constructing solar power plants within the analyzed depopulation cluster was established. This ranking provides a clear decision-making framework for identifying priority sites with the highest development potential.

Table 10. Criteria used in the fuzzy MULTIMOORA analysis.

Criterion	Type of Criterion	Justification	Weight Coefficient
Area of the location	Positive	A larger area implies better economic feasibility	0.25
Share of the highest suitability class (from fuzzy AHP)	Positive	Indicates the internal qualitative suitability of the location	0.15
Distance from the nearest road	Negative	Closer proximity to roads is favorable for transport and reduces costs	0.20
Distance from the nearest settlement	Positive	Helps avoid land use conflicts (e.g., visual impact, community resistance)	0.15
Distance from protected area	Positive	Avoids environmental pressure on sensitive zones	0.15
Potential environmental degradation	Negative	Indicator of environmental impact; lower values are more favorable	0.10

Based on the results of all three components of the fuzzy MULTIMOORA method—the fuzzy reference point approach (FRPA), the fuzzy ratio system (FRS), and the fuzzy full multiplicative form (FFMF)—a final ranking list was created for the ten selected locations that meet the criteria for solar power plant construction (Table 11). While certain similarities in rankings are evident, notable differences between individual alternatives across the components highlight the sensitivity of results depending on the analytical approach used.

Table 11. Fuzzy MULTIMOORA results: three approaches and final ranking.

Location No.	Fuzzy Reference Point Approach		Fuzzy Ratio System		Fuzzy Full Multiplicative Form		Final MULTIMOORA Rank
	z	Rank	y	Rank	p	Rank	
1	0.157924	8	0.043708	10	0.641184	10	10
2	0.151584	6	0.089058	7	0.839175	6	6
3	0.151008	5	0.072728	9	0.77946	9	9
4	0.138904	4	0.103351	4	0.901381	5	4
5	0.099135	2	0.195779	2	1.663826	2	2
6	0.161959	9	0.091113	6	0.802588	8	8
7	0.164264	10	0.119875	3	1.024749	3	5
8	0.130259	3	0.10104	5	0.904334	4	3
9	0.058805	1	0.281084	1	1.674751	1	1
10	0.15389	7	0.081291	8	0.816022	7	7

Location no. 9 stands out as the absolute leader, ranking first across all three analyzed variants: FRPA (lowest value, z = 0.0588), FRS (highest value, y = 0.2811), and FFMF (highest value, p = 1.6748). This high degree of consistency across methods confirms the reliability of the results and indicates strong alignment of all criteria in favor of this location. Similarly, location no. 5 shows exceptional consistency—it is ranked second in all three methods and in the overall ranking, further affirming its spatial and functional suitability. In contrast, some locations display notable discrepancies in rankings. For instance, location no. 7 is ranked tenth in the FRPA but reaches third place in the FFMF analysis and fifth in the FRS method. Although this location performs well in certain criteria, the FRPA method positions it lower due to its greater distance from the ideal reference point—a measure this method interprets as lower suitability. Similarly, location no. 3 ranks relatively high in the FRPA method (fifth) but drops to ninth in the FFMF analysis, indicating weaker synergy among criteria in the multiplicative sense.

Overall, the highest agreement in rankings exists between the FRS and FFMF methods, which is expected given that both are based on the quantification of ratios between beneficial and non-beneficial criteria. FRPA, as a method based on distance from the ideal solution, often introduces greater variation in rankings and serves as a useful complementary perspective. However, it may be more sensitive to extreme values in individual criteria. Therefore, the final ranking was derived as a synthetic result, incorporating all three methodological perspectives.

This analysis suggests that the top three locations (nos. 9, 5, and 7) are the most promising candidates for further technical and economic evaluation in the context of solar power plant development. At the same time, the results highlight the need for a comprehensive multicriteria approach that includes not only technical factors but also spatial, environmental, and socio-economic aspects in the decision-making process.

The spatial verification of the most favorable location identified through the fuzzy MULTIMOORA analysis is presented on a map using the Google hybrid base layer (Figure 7). Location no. 9, determined as the most suitable for the construction of a solar power plant, is situated within the boundaries of the Vidojevičko–radanski depopulation cluster. Satellite imagery confirms that the site is not forested, contains no water bodies, and is free from other natural obstacles, which further validates the analytical findings. The open and gently undulating terrain indicates favorable technical conditions for installing photovoltaic panels, effectively aligning the results of geospatial analysis with actual field characteristics.

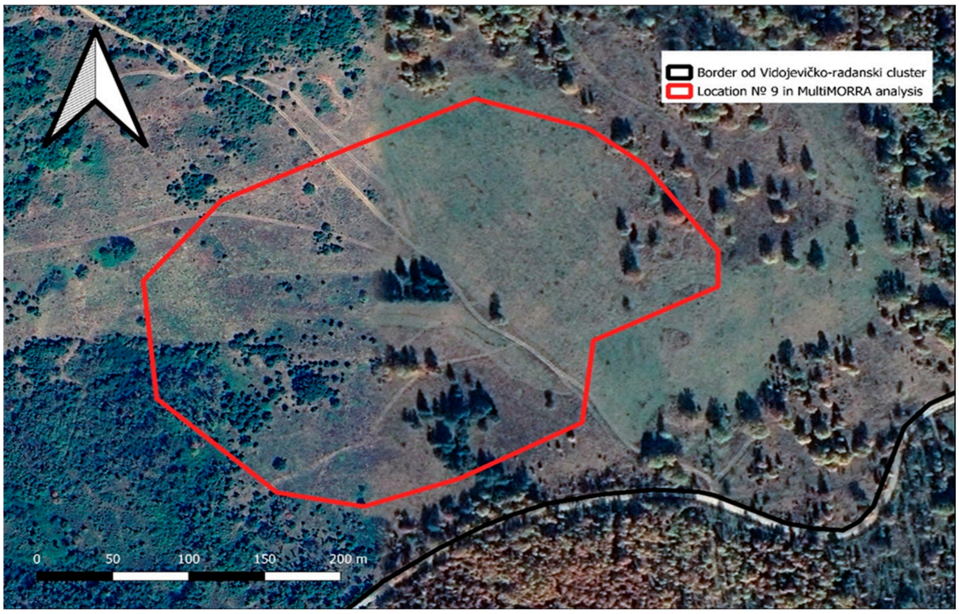


Figure 7. Location No. 9—spatial verification of the most favorable site identified through the fuzzy MULTIMOORA analysis (Google hybrid base layer).

5. Discussion

5.1. Sensitivity Analysis

To evaluate the robustness of the obtained results, a sensitivity analysis was performed on the fuzzy AHP weight coefficients of the criteria (Figure 8). The analysis focused on assessing how changes in the weight values influence the relative importance ranking of the criteria. The defuzzified weights indicated that the slope (0.3859) is the most influential factor, followed by aspect (0.2465), distance from roads (0.1487), distance from settlements (0.0956), land use (0.0607), distance from rivers (0.0386), and distance from protected areas (0.0240). To test the stability of this ranking, two approaches were applied:

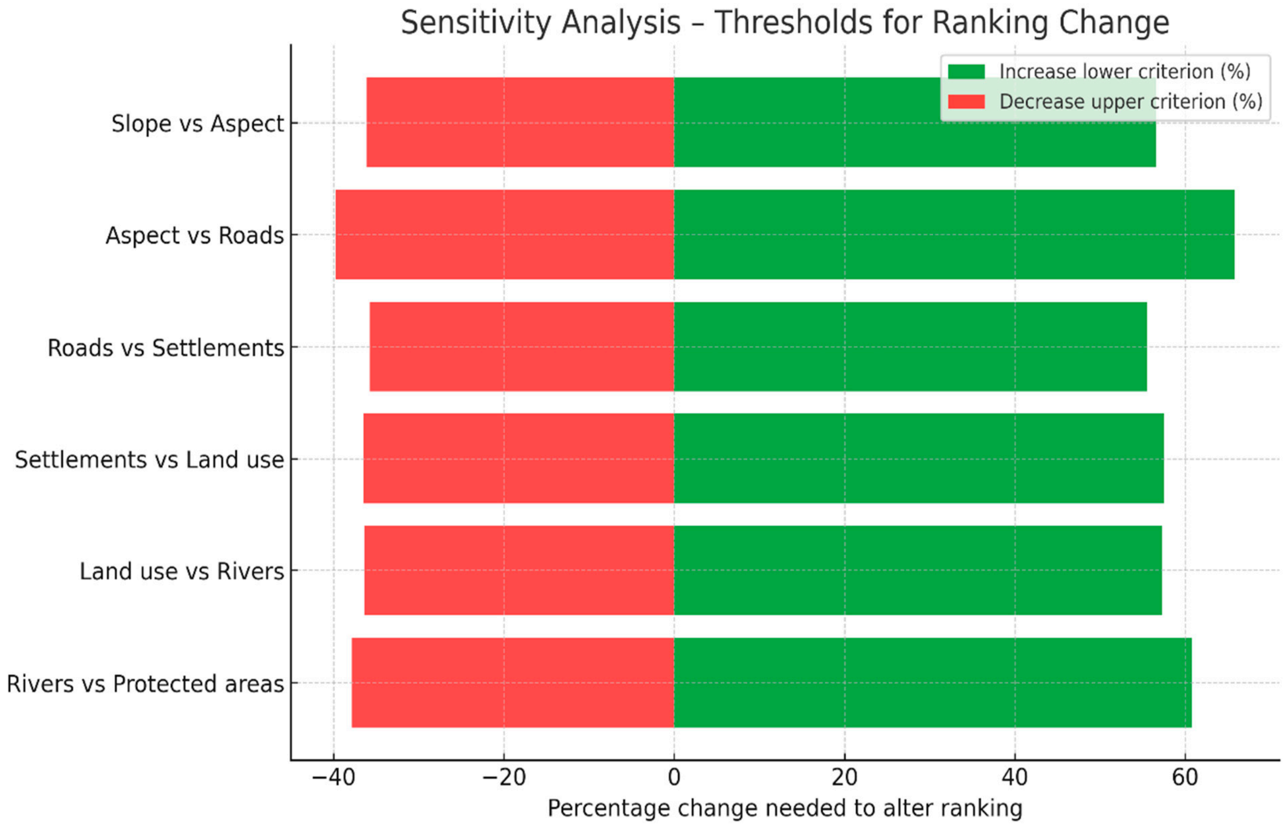


Figure 8. Sensitivity analysis of ranking criteria thresholds.

1. Triangular fuzzy limits (L–M–U)

When comparing the lower (L), middle (M), and upper (U) values of each fuzzy weight, the overall order of importance remained unchanged across all three scenarios. For example, the weight of slope ranged between 0.372 and 0.406, aspect between 0.240 and 0.250, and distance from roads between 0.140 and 0.154. This indicates that the priority ranking of criteria is not sensitive to the uncertainty inherent in the fuzzy judgment process.

2. Single-factor variation analysis

Each weight was individually increased and decreased while the others were proportionally normalized. The threshold values at which one criterion would surpass its immediate neighbor in the ranking were calculated. Results showed that significant changes are required to alter the order. For instance, for aspect to overtake slope, its weight would need to increase by approximately +56.6%, or the weight of slope would need to decrease by −36.1%. Similarly, distance from roads would require an increase of +65.8% to exceed aspect, while land use would need +57.5% to surpass settlements.

These results demonstrate that the ranking of criteria is highly stable. Even with significant adjustments to the weights, the order of importance among criteria remains unchanged. Therefore, the selection of slope, aspect, and distance from roads as the three most critical factors for solar site selection can be considered robust and reliable.

Sensitivity analysis was also conducted for the fuzzy MULTIMOORA model with the aim of assessing the robustness of the results. The comparison of rankings obtained through the three fuzzy MULTIMOORA approaches (Reference Point, Ratio System, and Full Multiplicative Form) revealed a strong overall agreement, with Kendall's coefficient of concordance (W = 0.779) indicating a high level of consistency and Spearman's rank correlations showing very strong similarity between the Ratio System and Full Multiplicative approaches (ρ = 0.952). In contrast, the Reference Point approach was slightly more conservative but remained directionally consistent. The integration of results using different aggregation rules, including leave-one-out and Borda count procedures, further confirmed the stability of the top-ranked locations, with Locations 9 and 5 consistently occupying the first and second positions across all scenarios. In contrast, Locations 8 and 4 remained robustly within the top five. A systematic what-if analysis, in which the relative weights of the three approaches were varied across the full decision space, demonstrated that Location 9 retained the first rank in 100% of the cases, while Location 5 remained second under all conditions; only mid-ranked alternatives (e.g., Locations 8, 4, and 7) exhibited variability, shifting between the third and fifth ranks depending on the weighting scheme, whereas the lowest-ranked locations (1, 2, 3, 6, and 10) consistently remained unfavorable regardless of parameter changes.

This high degree of robustness reflects the dominance of key criteria such as location area (weight 0.25) and distance from roads (weight 0.20), which strongly determine site suitability and are not easily offset by moderate adjustments in the weights of other criteria. Overall, the findings confirm that the fuzzy MULTIMOORA method provides highly stable results: the identification of Location 9 as the optimal solar site and Location 5 as a second-priority alternative is reliable and resilient to both methodological and parametric uncertainty, while the variability observed in the middle ranks offers decision-makers flexibility to incorporate additional strategic or policy considerations.

Figure 9 shows the range of possible ranks for each site under different combinations of access weights in fuzzy MULTIMOORA. Locations 9 and 5 have completely stable positions (always 1st and 2nd place), which confirms their dominance in the decision-making process. Sites 8, 4, and 7 show moderate variability, rotating between 3rd and 5th place, while the remaining sites are consistently in the lower part of the range and do not represent competitive alternatives. This visualization confirms the robustness of the top-2 picks and the relative sensitivity of the mid-ranked locations.

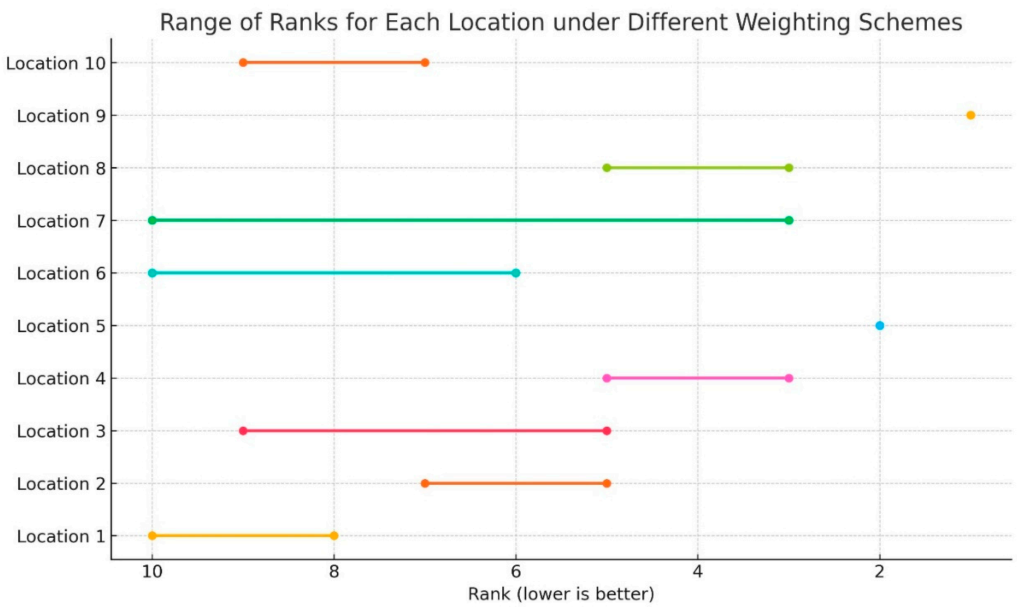


Figure 9. Rank stability of locations under alternative weighting schemes.

5.2. Implications and Future Research Directions

The research findings demonstrate that depopulation clusters of Serbia—despite being demographically and economically marginalized—can serve as significant spatial assets for the development of renewable energy, particularly solar power plants. The selection of the largest depopulation cluster in Serbia (Vidojevičko–radanski) as a case study enabled a detailed spatial and functional analysis across more than 300 km^2, offering a sufficiently large area for identifying locations suitable for solar exploitation.

Using the fuzzy AHP method, the most suitable zones were identified based on seven criteria, with the highest weights assigned to terrain slope and exposure—a result that aligns with similar studies conducted both regionally and globally [89–92]. This confirms that, after insolation, topographic factors play a decisive role in the efficiency of solar energy systems. After classification and filtering, ten locations were selected based on their fahp_mean values (>4.5) and a minimum area of 0.5 ha, thereby ensuring both technical feasibility and spatial adequacy for small-scale photovoltaic installations.

In the following phase, the application of the fuzzy MULTIMOORA method, based on six relevant criteria, enabled the identification of the most optimal sites among the top candidates, i.e., the "best of the best." The three components of the fuzzy MULTIMOORA method (FRPA, FRS, and FFMF) provided complementary perspectives, with a high level of agreement, particularly regarding locations 9 and 5. Location 9 emerged as the most promising, ranking first across all three analyses. It distinguished itself not only in terms of individual criterion values but also in terms of overall synergy.

Furthermore, by introducing a criterion such as "potential environmental degradation", this study extended the evaluation beyond purely technical factors, incorporating an ecological dimension. Although assessed qualitatively, this index contributed an important layer to the understanding of risks and environmental impacts. Such an approach reflects a shift from traditional technical-economic frameworks toward models more compatible with the principles of sustainable development.

The results showed that proximity to roads, moderate distance from settlements, and the absence of nearby protected areas are important for final site suitability, but are not sufficient without favorable terrain (slope and aspect) and adequate surface area. For this reason, models like fuzzy AHP and fuzzy MULTIMOORA, which integrate multiple criteria and enable synthetic ranking, prove to be effective tools in spatial decision-making.

Among the limitations of the research is the need for manual data processing and classification in certain cases (e.g., environmental degradation), which highlights opportunities for methodological enhancement through the use of more quantitative indicators. Additionally, due to the unavailability of data, proximity to energy infrastructure was not included, despite its relevance for implementation feasibility.

Nevertheless, the study opens several avenues for further research—particularly the application of this model to other depopulated clusters in Serbia—the integration of economic cost–benefit analysis, and the simulation of energy productivity on an annual basis. Such developments would contribute to the creation of comprehensive models for rational and sustainable management of rural brownfield areas, offering benefits not only for the energy transition but also for broader regional development.

While the current study was expert-driven, future research could incorporate stakeholder perspectives, including those of local communities, environmental organizations, and energy developers, to ensure alignment with local needs, values, and development visions. This would not only enhance the legitimacy of spatial decisions but also facilitate implementation and long-term sustainability.

A significant increase in installed capacities using renewable energy sources (primarily wind power plants, solar power plants, and hydropower plants) has been officially accepted as a key strategic commitment in Serbia's electricity sector [93]. Serbia plans to increase the share of renewable energy sources to 33.6% of gross final energy consumption and 45% of gross final electricity consumption by 2030 [16]. Since the installation of photovoltaic systems requires the occupation of large areas, depopulated clusters are of key importance, as they possess large areas of abandoned, inexpensive, and empty land (rural brownfield), which is in short supply in other parts of Serbia. In this sense, continuing our research in other rural parts of Serbia may help identify and select the best locations for future projects.

Finally, the methodological framework developed here may serve as a transferable template for other post-socialist and post-industrial rural regions facing similar demographic and spatial challenges. Depending on the specific local conditions of the researched region and the planned activities, new criteria can be introduced into the methodological model (both in the fuzzy AHP phase and in the fuzzy MULTIMOORA phase), so that the obtained results more faithfully reflect the situation on the ground and meet the needs. The adaptability of the applied methodology to different regional contexts and datasets reinforces its practical utility for national energy planning, climate action, and rural revitalization strategies.

The proposed integrated model, combining spatial analysis, multi-criteria evaluation, and the principles of sustainable development, effectively identified the most suitable locations for solar power plant construction within a depopulated cluster. This approach provides a valuable foundation for shaping public policy, regional strategies, and development programs aimed at the rational use of abandoned or underutilized rural areas. The construction of solar power plants in abandoned areas of Serbia represents a real possibility for economic revitalization, with full awareness that, in the current demographic and socioeconomic conditions, it is not realistic to expect even partial demographic revitalization. Part of the research can be conducted in the form of case studies, which can provide recommendations and ideas to investors and local authorities in depopulated rural areas of Serbia.

6. Conclusions

The research demonstrated that depopulation clusters, despite pronounced demographic decline and functional marginalization, possess significant potential for the development of renewable energy sources—specifically, through the installation of solar power plants. By integrating GIS-based spatial analysis with the fuzzy AHP and fuzzy MULTIMOORA methodologies, the study identified locations that satisfy topographic suitability, spatial accessibility, and environmental acceptability criteria. The final ranking, produced using the fuzzy MULTIMOORA method, enabled not only the classification of sites by technical feasibility but also by their potential environmental impact, thereby ensuring a more balanced and holistic approach to site selection.

The findings highlight the spatial applicability of the proposed model and its potential for replication in other areas experiencing depopulation. Furthermore, this approach holds relevance for shaping regional development and energy transition policies. The study also paves the way for future research, particularly in incorporating economic indicators, analyzing proximity to the electricity transmission network, and simulating solar energy production. Through such advancements, depopulated areas of Serbia may be repositioned as valuable assets in the context of energy transition and rural revitalization. Beyond technical optimization, this approach supports a more just and sustainable territorial development, integrating neglected rural spaces into Serbia's broader development and energy agenda.

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