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GIS Approaches to Spatial Planning for Renewable Energy Facility Siting

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SUMMARY

The development of renewable energy infrastructure has become a strategic priority for ensuring energy security, supporting decarbonisation, and enabling sustainable post-war reconstruction in Ukraine. However, spatial planning of renewable energy facilities requires careful identification of suitable land resources, particularly in regions affected by land degradation and military activities. Traditional land suitability models often focus on environmentally stable areas and insufficiently address the potential of degraded and war-affected territories. This study develops a geographic information system-based multi-criteria decision-making framework for assessing land suitability for solar energy development. The approach integrates spatial analysis with a structured decision model based on the analytic hierarchy process. Five groups of criteria were considered: technical, infrastructural, land-related, environmental, and socio-legal factors. Spatial datasets, including solar radiation, terrain characteristics, land cover, infrastructure networks, protected areas, and war-affected land, were processed in a unified geographic information system environment with a spatial resolution of 100 by 100 meters. Criterion weights were derived through pairwise comparisons and consistency verification, ensuring the reliability of the decision model. The results reveal a heterogeneous spatial distribution of land suitability across the study area. Technical and infrastructural factors exert the strongest influence on suitability patterns, while environmental and socio-legal constraints act as limiting factors. A substantial share of moderately and highly suitable areas overlaps with degraded and war-affected lands, indicating their potential for renewable energy development without significant pressure on productive agricultural land. The proposed framework provides a robust spatial decision-support tool for identifying priority areas for solar energy deployment and can be applied to other regions undergoing land-use transformation or post-conflict recovery.

Keywords: Geographic information systems; Spatial planning; Multi-criteria decision analysis; Analytic hierarchy process; Land suitability assessment; Renewable energy; Solar energy; Degraded land; War-affected land.

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Introduction

The transition toward renewable energy development has become a strategic priority for ensuring energy security, supporting decarbonisation, and promoting sustainable development, particularly in the context of Ukraine's post-war reconstruction. Unlike conventional energy resources, renewable energy systems are highly dependent on spatially variable environmental and climatic conditions, which necessitates the integration of land-use considerations into energy infrastructure planning. For instance, solar power plants require substantial land areas, making the selection of suitable sites a critical spatial planning challenge. At the same time, it is essential to avoid the conversion of productive agricultural land out of economic use. In Ukraine, however, the extent of degraded, disturbed, and technogenically altered lands, as well as areas affected by military activities, has significantly increased. These territories may represent a valuable spatial resource for renewable energy development; however, their utilisation requires robust, scientifically grounded spatial assessment approaches.

Recent studies demonstrate the extensive application of Geographic Information Systems (GIS) and multi-criteria decision analysis (MCDA) methods for identifying optimal locations for renewable energy facilities (Prieto-Amparán et al., 2021; Olivero-Ortiz et al., 2021; Raza et al., 2023; Bertsiou et al., 2025). These approaches typically integrate technical, environmental, and infrastructural factors, and often employ fuzzy logic and multi-factor weighting schemes to improve decision accuracy (Noorollahi et al., 2022). In the Ukrainian context, existing research has mainly focused on land degradation assessment and renewable energy potential evaluation using GIS-based methods and the analytic hierarchy process (AHP) (Kuznichenko et al., 2024; Antoniuk and Kulczycka, 2022).

Despite the considerable body of research, a significant gap remains regarding the explicit inclusion of degraded, disturbed, and war-affected lands as a distinct spatial category in site selection models for energy infrastructure. Most existing GIS–MCDA frameworks are designed for relatively stable and environmentally favourable areas, while the spatial potential of non-productive or post-conflict lands remains insufficiently explored. This limitation reduces the applicability of such models in post-conflict spatial planning contexts and limits their relevance for regions undergoing large-scale land-use transformation. Therefore, the aim of this study is to develop a GIS–AHP approach for assessing the suitability of degraded, disturbed, and war-affected lands for solar energy development and to establish a system of spatial criteria for post-conflict planning.

Method

In this study, Geographic Information Systems (GIS) were employed as a tool for spatial processing, normalization, and visualization of data related to land resources, infrastructure, and environmental constraints. Spatial analysis was performed using overlay analysis of multi-layer geospatial datasets, enabling the derivation of an integrated land suitability assessment. The Analytic Hierarchy Process (AHP) was applied to determine the relative importance of land suitability criteria. The resulting weights represent the contribution of each criterion to the overall suitability of areas for renewable energy infrastructure development.

The study was conducted for territorial communities in the Izium District of Kharkiv Region, Ukraine. Spatial datasets included solar radiation, terrain characteristics, land cover, infrastructure networks, protected areas, settlements, and war-damaged land. All spatial layers were transformed into a unified coordinate system and resampled to a common spatial resolution of 100 × 100 m, ensuring spatial consistency and compatibility for overlay operations.

The evaluation criteria were grouped into five categories: technical (solar irradiation, wind speed, slope, and aspect), infrastructural (distance to power transmission lines, substations, and transport networks), land-related (land cover type, parcel size, land degradation level, and degree of war-related damage), environmental (distance from protected areas and environmental restrictions), and

socio-legal (proximity to residential areas, land-use restrictions, and land-use conflicts).

Pairwise comparisons of criteria were conducted using the Saaty scale. The consistency of expert judgments was verified using the Consistency Ratio (CR), which did not exceed 0.1, confirming the reliability of the results. All criteria were normalized to a dimensionless scale ranging from 0 to 1. Stimulating factors were normalized using the min–max approach, while constraining factors were transformed using inverse normalization. Binary constraints were represented using a discrete scale (0–1). According to the AHP results, the highest weights were assigned to technical (0.37) and infrastructural (0.25) criteria, reflecting their dominant role in determining the technical feasibility and economic viability of renewable energy projects. Land-related, environmental, and socio-legal criteria received weights of 0.17, 0.12, and 0.09, respectively.

The Land Suitability Index (LSI) was calculated as a weighted linear combination of normalized criteria:

$$LSI = \sum_{i=1}^{n} W_i \times C_i$$

where $W_i$represents the weight of the i-th criterion, and $C_i$denotes its normalized value.

Results

The GIS–AHP model produced a continuous spatial distribution of the Land Suitability Index (LSI) ranging from 0 to 1. The resulting values were classified into four suitability classes: very high (0.80–1.00), high (0.60–0.79), moderate (0.40–0.59), and low (<0.40).

The spatial distribution of the LSI (Fig. 1) reveals a pronounced heterogeneity in the suitability of the Izium District of Kharkiv Region for solar power plant deployment. Areas with the highest suitability values are predominantly associated with open agricultural landscapes characterized by high solar radiation potential, well-developed transport and power infrastructure, and minimal environmental and socio-legal constraints. In contrast, low suitability areas are mainly located within forested zones, water bodies, protected areas, and residential zones, where solar energy development is restricted by environmental regulations, urban planning limitations, or land-use constraints.

After excluding masked areas and NoData zones, which account for 61.1% of the study area, the effective evaluable area was 4,486.1 km². The distribution of land across suitability classes is presented in Table 1.

***Table 1**. Distribution of land by suitability classes*

Suitability class	***LSI range***	***Area (km²)***	***Share (%)***
Very High	*0.80–1.00*	*448.6*	*10*
High	*0.60–0.79*	*1,794.4*	*40*
Moderate	*0.40–0.59*	*1,795.4*	*40*
Low	*<0.40*	*448.6*	*10*

The results indicate that approximately 80% of the evaluable area falls within the moderate to high suitability classes, highlighting significant spatial potential for solar energy development. Notably, a substantial proportion of highly and moderately suitable areas overlaps with degraded, disturbed, and war-affected lands. This finding confirms the potential of such territories for renewable energy deployment without the need to convert productive agricultural land into non-agricultural use.

A comparative analysis of the influence of individual criteria revealed that technical and infrastructural factors play a decisive role in shaping the spatial pattern of the LSI. In particular, solar irradiation levels

and proximity to existing power transmission lines and transport networks represent the most influential determinants of land suitability. Environmental and socio-legal criteria primarily act as restrictive factors, excluding areas where solar energy development may lead to land-use conflicts or adverse impacts on natural ecosystems. At the same time, land-related criteria, particularly the degree of land degradation and war-induced damage, enable the identification of alternative areas with high potential for solar power plant deployment.

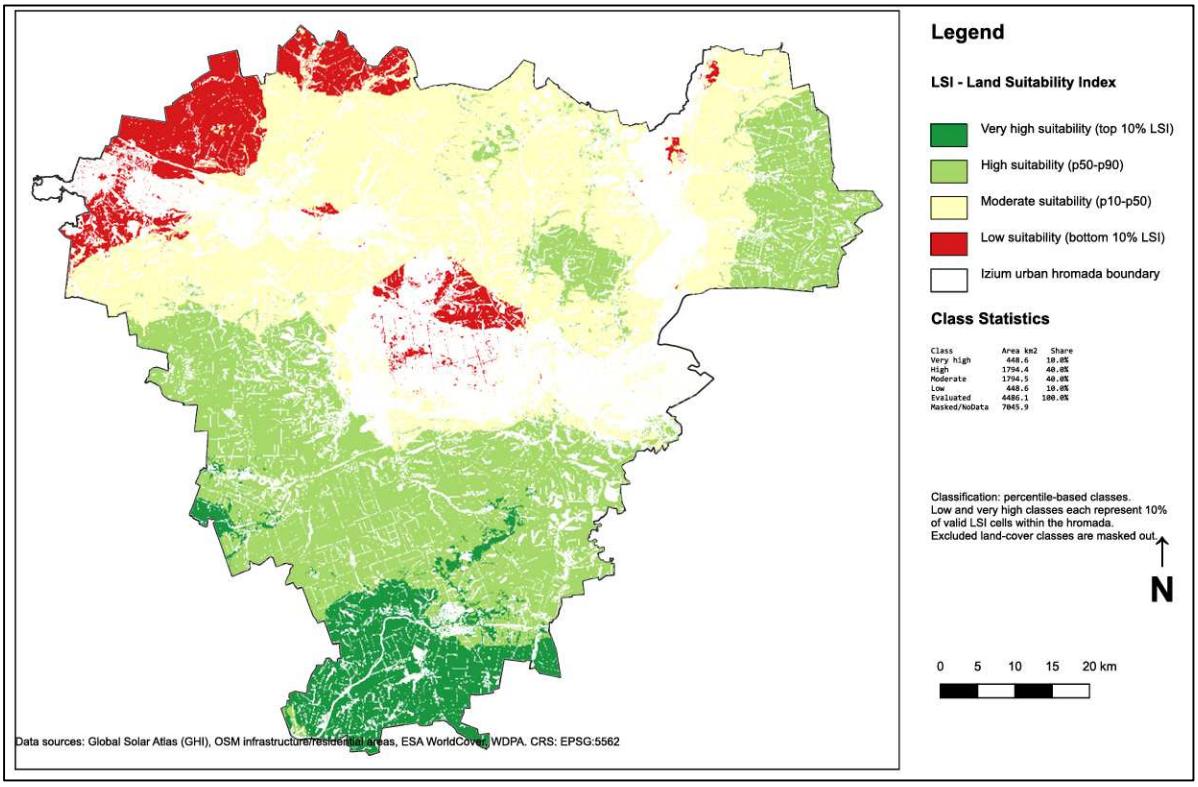

Figure 1. *Map of the spatial distribution of the Land Suitability Index (LSI) for solar power plant siting in the territorial communities of the Izium District, Kharkiv Region*

The resulting suitability map can serve as a decision-support tool for spatial planning of renewable energy development at the territorial community level, providing an evidence-based basis for selecting appropriate sites for solar energy infrastructure.

Conclusions

A GIS–AHP-based approach is proposed for the multi-criteria assessment of the suitability of degraded, disturbed, and war-affected lands for solar power plant deployment. The integration of Geographic Information Systems with the Analytic Hierarchy Process enables a comprehensive consideration of technical, infrastructural, land-related, environmental, and socio-legal criteria within the spatial modelling framework.

The results demonstrate that technical and infrastructural factors exert the strongest influence on land suitability patterns, while environmental and socio-legal criteria primarily act as constraining factors. It is established that a significant proportion of degraded and war-affected lands exhibits high potential for solar energy development, creating prerequisites for their reuse without the conversion of productive agricultural land.

The practical significance of the proposed approach lies in its applicability as a decision-support tool for spatial planning of renewable energy development at the territorial community level, as well as for the formulation of post-war land-use recovery strategies.

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