An Integrated MCA–GIS Framework for Ground Mounted Solar Photovoltaic (GMPV) Site Selection: Methodological Proposal for the Italian Context

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Abstract. The increasing demand for renewable energy has led to a growing interest in ground-mounted photovoltaic (GMPV) installations. However, the selection of suitable locations for these installations requires a multi-dimensional evaluation that integrates regulatory, environmental, and technical constraints. This study addresses the challenge of locating suitable land for GMPV systems in Italy. We develop a spatial decision support model that integrates Multi-Criteria Analysis (MCA) with Geographic Information Systems (GIS) to incorporate multiple factors, including regulatory requirements, hydrogeological and geotechnical hazards, land use attributes, solar irradiation potential, proximity to infrastructures, and terrain morphology. Each criterion is assigned a weighted value reflecting its relative significance, and the combined analysis yields a priority index that supports decision-makers in identifying optimal sites for photovoltaic deployment. The methodology aims to reconcile the need for increased renewable energy production with broader environmental, social, and economic objectives, ensuring minimal conflicts with other land uses. By systematically evaluating risks such as flood vulnerability and slope instability, the framework facilitates the avoidance of high-risk zones. Furthermore, by considering variables like irradiation levels, land productivity, and ease of grid connection, it maximizes energy yields while limiting environmental impacts and infrastructural costs. This structured and transparent approach can guide regional authorities, urban planners, and private investors in implementing sustainable energy projects. The stakeholder perspective is integral to building consensus, facilitating more inclusive decision-making, and ensuring long-term acceptance and viability at the local level. This ultimately fosters more collaborative planning, aligning energy goals with societal and environmental demands.

Keywords: Sustainable Land Use · Multi-Criteria Spatial Decision Support System (MC-SDSS) · solar farm

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1 Introduction

The transition from non-renewable energy sources to renewable ones is an increasingly relevant issue, worldwide [1]. The deployment of renewable energy sources (RESs) supports the acceleration of the green transition and the achievement of greater energy autonomy [2]. Within this framework, the aim of the European Union to reduce greenhouse gas (GHG) emissions and to achieve climate neutrality is dependent on a significant expansion of renewable energies [3]. Among the different RESs, the growth of solar photovoltaic installations is crucial to the global energy transition. In particular, ground-mounted photovoltaic panels (GMPV) have become pervasive in Europe, driven by the deployment of large-scale solar power plants [2].

The large-scale and the dependence of energy production on solar features make GMPV location a relevant issue. Additionally, their installation requires high construction costs and the consideration of long lifetimes with various benefits and impacts [4]. Therefore, selecting suitable sites for GMPV must consider multiple aspects, spanning regulatory, economic, environmental, social and technical constraints. Site selection of GMPV is thus a complex problem, where different aspects are in play and multiple stakeholders take part in the discussion and choice. The evaluation procedure must therefore be able to include these different aspects, often conflicting, and include the opinions and preferences of the stakeholders in a comprehensive framework. At the same time, strong locational dependence requires the integration of the spatial dimension into the evaluation procedure.

Multicriteria Analysis (MCA) is particularly suitable for synthetizing the full range of aspects involved, taking into account the stakeholders' perspectives. However, to include the spatial heterogeneity of impacts and aspects in the evaluation procedure, the integration of Geographic Information Systems (GIS) into MCA is fundamental. Recent literature trends show the adoption of S-MCA in different contexts and for different decision-making processes, spanning from allocation of infrastructures and services, site selection problems, ecosystem services distribution, mitigation of natural risks, and enhancement strategies for cultural built heritage [5]. Furthermore, S-MCA has recently become widely applied in GMPV site selection, considering regulatory requirements, hydrogeological and geotechnical hazards, land use attributes, solar irradiation potential, proximity to infrastructures, and terrain morphology, among others.

Within this context, this study addresses the challenge of locating suitable land for GMPV systems in Italy, proposing a common framework to be applied in different contexts. Italy, in particular, has to manage a critical issue related to the lack of alignment between geographic information (cartographic data) and existing regulations, despite the fact that legislative frameworks often reference spatial data. This misalignment creates barriers to efficient planning and implementation. Nationally and globally, GMPV mapping mostly relies on data from measurement campaigns, existing standardized databases, or crowdsourcing projects like OpenStreetMap [6]. As a result, the mapping data's coverage, quality, and currency vary greatly, relying mostly on the work of each community and must be confirmed and validated by knowledgeable users [6].

This contribution tries therefore to answer the following research questions: is it possible to define a common national framework for GMPV site selection? Which MCA

method is most appropriate for this purpose? Is it possible to address the lack of alignment between regulatory frameworks and spatial evaluation?

After this introduction, the remaining paper is structured as follows. Section 2 contains the research background, which explores the literature regarding the use of S-MCA for GMPV site selection. Additionally, this section describes the regulatory framework in Italy for this technology. Section 3 is devoted to the illustration of the methodological proposal, which combines MCA and GIS potential. Section 4 presents the list of criteria and indicators selected according to the specific problem under analysis, its context, and the methodological proposal. Finally, Sect. 5 contains the concluding remarks and implications of the research undertaken.

2 Research Background

2.1 Multi-criteria Techniques for GMPV Site Selection

The integration of GIS and MCA methodologies has become a cornerstone in GMPV site selection, leveraging spatial analysis alongside structured decision-making frameworks. GIS facilitates the incorporation of diverse environmental, infrastructural, and regulatory datasets, while MCA methods systematically evaluate competing criteria, ensuring that site selection processes are both rigorous and transparent. The studies analyzed can be categorized into two main groups: those employing a single MCA method with GIS and those utilizing comparative or hybrid approaches to enhance decision reliability. A systematic literature search was conducted using the Scopus database to identify peer-reviewed journal articles related to photovoltaic site selection. The search criteria focused on studies incorporating both GIS and MCA methodologies, using keywords such as "Photovoltaic site selection," "PV site suitability," "Ground-mounted photovoltaic," and "Solar farms," combined with "MCA", "MCDA," "MCDM," "GIS," "Multi-Criteria Analysis," and "Spatial Decision Support." This query yielded a total of 96 relevant publications.

Among the most used multicriteria methods[1], the Analytic Hierarchy Process (AHP) has been widely applied in combination with GIS due to its effectiveness in structuring complex decisions through hierarchical decomposition and expert-driven weight assignment. Giamalaki and Tsoutsos (2019) employed AHP to identify optimal solar farm locations in Crete, Greece, incorporating techno-economic and socio-environmental criteria [7]. Their findings underscored AHP transparency in decision-making, particularly in engaging stakeholders, though its reliance on expert judgment introduced subjectivity, potentially biasing the weight assignments. Finn and McKenzie (2020) applied a similar AHP approach in Northern Ireland, integrating a weighted sum overlay with pairwise comparisons [8]. Their study demonstrated the advantages of high-resolution spatial data in improving site selection accuracy but highlighted limitations in adaptability due to the exclusion of dynamic variables such as real-time solar irradiation. Guaita-Pradas et al. (2019) also utilized AHP in Valencia, Spain, to assess PV potential based on solar radiation, land use, and environmental constraints [9]. Their research emphasized

[1] To further expand knowledge on the differences between MCA techniques, please refer to Greco et al., 2016 [48].

the benefits of GIS visualization for stakeholder communication. These applications illustrate the strengths of AHP in structuring decision problems and improving spatial accuracy, but they also reveal challenges related to subjectivity in weight assignments.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has also been frequently integrated with GIS to enhance PV site selection, ranking alternatives based on their relative proximity to an ideal solution. Asrami et al. (2023) applied TOPSIS in a regional suitability study, emphasizing economic constraints and filtering unsuitable areas before ranking potential sites [10]. Vagiona et al. (2022) extended the use of TOPSIS to offshore solar PV selection in the Aegean Sea, incorporating marine spatial constraints [11].

Although PROMETHEE has been used less frequently as a standalone method, it remains a valuable tool in decision-making for PV site selection. Ayough et al. (2022) integrated PROMETHEE with GIS to assess solar power deployment, emphasizing its ability to handle conflicting criteria effectively [4]. While the method provided structured rankings, defining preference functions proved to be a challenge, potentially affecting decision robustness.

Other studies adopted a comparative or hybrid approach to improve decision reliability. Sánchez-Lozano et al. (2016) systematically compared AHP, TOPSIS, and ELECTRE TRI in a GIS framework for solar farm site selection in Murcia, Spain, revealing inconsistencies in rankings between methods and reinforcing the necessity of sensitivity analysis in GIS-based MCA applications [12]. Vagiona (2021) compared AHP, TOPSIS, and PROMETHEE for solar farm site selection in Greece, demonstrating that different MCA techniques yield varying rankings [13]. PROMETHEE was found to offer a more detailed evaluation due to its use of preference functions, but it was also sensitive to weight assignments, a limitation shared with AHP and TOPSIS. Nagababu et al. (2022) implemented a two-stage MCA approach, using GIS to filter potential sites before applying AHP and TOPSIS for final ranking based on technical, environmental, and economic trade-offs [14]. This structured methodology improved computational efficiency and ensured that only relevant sites were included in the MCA analysis. These findings reinforce the importance of integrating validation mechanisms, as the combination of multiple MCA methods can mitigate individual weaknesses and increase decision-making robustness.

The widespread integration of GIS with MCA methods in PV site selection underscores several key advantages. GIS efficiently processes spatial data, enabling the visualization and exclusion of unsuitable areas based on environmental and infrastructural constraints. Meanwhile, MCA techniques such as AHP, TOPSIS, ELECTRE, and PROMETHEE provide a structured framework for weighing and ranking site suitability criteria, ensuring transparency and replicability, stakeholder participation, and the ability to communicate results visually. These methodologies also allow for application across multiple scales. Moreover, these techniques employing sensitivity analyses help to assess the impact of uncertainty. However, challenges persist in the subjectivity of weight assignments and the computational complexity of some MCA techniques, which future research should aim to refine.

Despite the extensive use of GIS-MCA integration in PV site selection, no applications of Multi-Attribute Value Theory (MAVT) were identified in the reviewed studies.

This omission is notable given MAVT advantages over other MCA methods. Unlike AHP, TOPSIS, PROMETHEE or ELECTRE, MAVT explicitly constructs value functions that model decision-makers' preferences, ensuring consistent and compensatory trade-offs between criteria. This structured approach enhances transparency, robustness, and interpretability, making MAVT particularly suited for complex, large-scale energy planning scenarios that require balancing environmental, economic, social, and technical factors. Furthermore, MAVT allows for systematic stakeholder preference integration and advanced sensitivity analysis, making it a powerful tool for supporting well-informed decisions. Given its strengths, this research explores MAVT application in ground mounted solar PV site selection to support decision-making providing a systematic approach for integrating stakeholder preferences, allowing decision-makers to reflect diverse perspectives while maintaining methodological consistency.

2.2 Regulatory and Policy Framework in Italy

In the selection of suitable sites for GMPV systems in Italy, regulatory and policy considerations are as essential as technical, environmental, and economic factors. National regulations provide the general framework, starting with the Legislative Decree 199/2021 (implementing the EU Directive 2018/2001/UE - RED II), which defines "suitable areas" for renewable energy development and streamlines authorization procedures. The Legislative Decree 190/2024 further facilitates the installation process for projects located in industrial, commercial, and degraded areas, while ensuring compliance with environmental requirements. Additionally, the Decree-Law 63/2024 introduces restrictions on the use of agricultural land for PV systems, allowing exceptions only for projects aligned with renewable energy community initiatives or the objectives of the National Recovery and Resilience Plan (PNRR).

Beyond national legislation, regional and local authorities hold significant responsibilities in implementing these directives. Regions can establish additional zoning regulations and environmental protection measures tailored to their specific territorial needs, while municipalities regulate land-use planning and issue building permits, often imposing stricter conditions in areas subject to landscape or cultural heritage protection. This multi-level governance structure requires that any suitability framework incorporate both national directives and local regulatory contexts.

Considering these regulatory dimensions within the suitability framework is fundamental to ensuring that selected sites meet both technical requirements and legal compliance. Integrating national, regional, and municipal regulations into the decision-making process allows for the identification of locations where PV development is not only feasible but also aligned with broader environmental, social, and policy objectives. This approach strengthens the framework's relevance in supporting sustainable energy strategies and facilitating the implementation of projects in accordance with Italy's regulatory landscape.

3 Methodology Proposal

The implementation of integrated evaluation methodologies proves particularly beneficial in supporting decision-makers (DMs) [15]. They address the complexity of urban issues, equipping DMs with the necessary tools to formulate comprehensive responses to the diverse challenges faced by cities and territories [16–18]. Specifically, S-MCA assists DMs in the generation of geographical alternatives, integrating geographic data (i.e. criteria maps) with stakeholders' preferences and uncertainties (i.e. value judgements) [19, 20]. This process also fosters stakeholder dialogue and mitigates conflicts by providing a clear and accessible representation of suitable and unsuitable areas in the resulting maps [21].

On the one hand, MCA facilitates the management of the full range of aspects, both quantitative and qualitative, involved in the transformation [22, 23]. On the other hand, GIS have the capacity to collect, store, retrieve, transform and display spatial data [24]. Specifically for urban and territorial decision problems, GIS makes it possible to conduct spatial analyses, providing integrated knowledge about territory and explicitly considering the spatial dimension of the decision-making problem [25–27].

S-MCA considers the contribution and reinforcement of the two methodologies along the entire evaluation process. In particular, the flow of activities (Fig. 1) starts with the classical MCA phase called problem definition (phase 1), where the evaluation objectives are clearly defined, as well as the stakeholders involved. Subsequently, the analysis is devoted to the identification of the criteria and the most suitable MCA technique (phase 2). After the criteria identification, spatial data are collected, processed and analyzed in GIS environment (phase 3). In phase 4, MCA contributes with weighting and standardized procedures, in order to assign different importance to the set of criteria and make them comparable. Finally, it is possible to aggregate all maps with the set of weights in GIS, in order to obtain the final maps of suitability (phase 5). Additionally, sensitivity analysis (phase 6) could be conducted in the last phase of the analysis to verify the robustness of the evaluation performed.

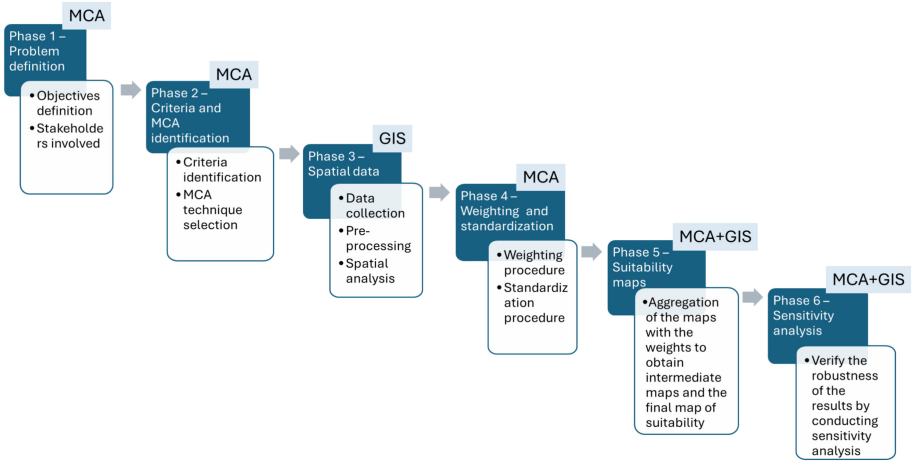

Fig. 1. S-MCA flow of activities

The detailed description of the different steps of the methodological proposal for GMPV suitable location in Italy is illustrated in separate sections below.

3.1 Problem Definition - MCA

The first step is constituted by problem definition. This phase is devoted to identifying the aim of the MCA, as well as DMs, key actors and stakeholders [28, 29]. Although this phase might seem trivial, a clear definition of the objective of the MCA helps to establish the tasks and steps of the evaluation and to maintain transparency in the entire evaluation process [30, 31]. For the purpose of our contribution, the aim of the evaluation should be expressed as the need to "find the most suitable location of GMPV in Italy".

This step also highlights the stakeholders involved or affected by the decision problem. Their different viewpoints and needs are fundamental and must be included, as much as possible, since the first step of the evaluation process, to avoid conflicts and oppositions in the subsequent phases. According to our evaluation aim, the main stakeholders involved are: landowners and land users, local and national authorities, electricity providers, investors and possible lenders, local communities, environmental organizations, construction companies/suppliers, planners and operators/maintainers, and eventually research bodies or universities.

3.2 Criteria Identification and MCA Technique Selection - MCA

The second phase is devoted to the identification of the criteria. Criteria and sub-criteria are the performance measures through which evaluate alternatives [32]. Therefore, the definition of the set of criteria for evaluation is a key phase for the proper development of MCA, since the criteria are the basis for evaluation [30]. Their identification must consider, at the same time, technical aspects related to the objective of the evaluation, the specific context in which the analysis is conducted, and the different points of view of the main stakeholders involved. For their proper selection, it could be necessary to examine the regulatory and legislative framework, to conduct a literature review and interviews with specific interest groups.

In S-MCA, this phase requires particular attention in the consideration of the spatial component embedded in the evaluation by the integration of GIS. Therefore, the set of criteria must respect completeness, operativity, dimension and multiple time effects and avoid redundancy, as in all MCA, but also the ability to explain the spatial heterogeneity of phenomena and aspects [27].

Based on the GMPV location, the selection of the criteria started with an in-depth literature review (see Sect. 4.1). The results of this analysis highlighted multiple aspects in play, spanning technical, environmental, social and economic once (e.g., solar irradiation, land use constraints, proximity to infrastructure, landslide risks).

According to the problem definition (step 1) and the set of criteria selected, this phase must also identify the most appropriate MCA technique to be used. There are different MCA techniques used to solve different site selection problems, such as PROMETHEE, ELECTRE, TOPSIS or AHP (see for references [33]). Also in GMPV locational problems, different techniques are applied, as explained in detail in Sect. 2.1. In our proposal,

the use of MAVT is proposed on the basis of its capacity to explicitly construct value functions that model DMs' preferences [34], thereby ensuring consistent and compensatory trade-offs between criteria.

3.3 Data Collection, Processing and Spatial Analysis - GIS

After the criteria identification, it is necessary to source useful data and information in order to create a map for each criterion. Existing open data is the easiest way to create maps of each criterion. Governmental agencies, municipal and regional databases, but also crowdsourcing projects provide a useful starting point for data collection [5]. The data required can include geospatial layers for land use, topography, irradiation, infrastructural network, hydrogeological risks, among others. The data collection requires a strong effort by the analyst, who should be able to create a database of spatial data as up-to-date and complete as possible with respect to the elements to be considered in the evaluation process.

This phase also requires pre-processing work in a GIS environment to make all the data in the same coordinate system. In some cases, it could be also useful to execute some initial spatial operations, such as overlay analysis, clipping, buffering and reclassification, to make the data usable in the following steps. These analyses can be performed using QGIS, a free software, or ArcGIS Pro, a software licensed by ESRI.

On the resulting georeferenced maps, different spatial analyses have to be conducted in order to make the maps operational with respect to the purpose of the evaluation. Generally, two main spatial calculations are used in urban and territorial evaluation problems, i.e., Kernel Density and Euclidean Distance. Kernel Density creates a density map, calculated based on the number of points in a location [35]. Larger numbers of clustered points result in larger values [35]. Euclidean Distance calculates the distance between two points, namely the measure of the segment having as extremes the two points. Both Kernel Density and Euclidean distance require the definition of a specific radius and distance, that require the consultation of references and validation by experts. This consultation of references and experts is generally conducted during the definition of the standardization function, as detailed in Sect. 3.4.

3.4 Weights and Standardization Procedure - MCA

The spatial analysis in GIS produces a number of maps, one for each criterion considered. These maps are characterized by different units of measurement, but they have the same importance with respect to the achievement of the evaluation objective. This fourth step is therefore devoted to making all maps on the same scale (e.g., from 0 to 1) and assigning their different importance [36, 37]. According to the MCA technique chosen (Sect. 3.2), specific standardization and weighted procedures have to be implemented. As anticipated, MAVT was suggested as the most appropriate for the purpose of our work. According to this technique, the analyst develops specific value functions that could be used in GIS for map standardization [38]. The definition of the value functions could incorporate experts' and stakeholders' feedbacks, in order to ensure reliability. Additionally, experts and stakeholders could be engaged in workshops, focus groups

or surveys to assign weights to the different criteria (and maps). In MAVT, the following weighting techniques are generally used [29, 32]: swing-weights, rating, pairwise comparison, trade-off, and qualitative translation. Among these approaches, our methodological proposal suggests a swing-weights procedure. The main advantage of the Swing method is that weight assignment is independent of value function shape, requiring only knowledge of attribute ranges [29].

3.5 Composite Index and Suitability Mapping – MCA + GIS

The fifth step of the proposal considers the integration of MCA and GIS. In particular, once all maps are standardized and the set of weights is defined according to MCA, it is possible to aggregate them in GIS. The easiest way to combine the single maps, considering the set of weights assigned by experts and stakeholders, is through a weighting sum [39], expressed as follows:

$$S_j = \sum W_i X_i$$

where S_j is the suitability for pixel j, W_i the weight of factor i, and X_i the standardized criterion score of factor i.

This aggregation results in a composite index, which is visualized through a map of suitability. In particular, the composite index expresses the degree of suitability of each cell of the area under analysis, with respect to all the criteria considered. The index of suitability varies from 0 to 1, where values close to 0 mean low suitability, while values close to 1 show high suitability. The resulting map graphically expresses these variations of suitability on the territory, using a colored scale from red (low suitability) to green (high suitability). The representation through maps facilitates the debate among the various stakeholders that take part in the process. In particular, they can observe the entire process of analysis, which starts from the single maps and ends with the final map of suitability which also includes the weights (i.e., the different opinions) of the experts and stakeholders involved.

3.6 Validation and Sensitivity Analysis – MCA + GIS

An additional phase regards the validation of the model performed. This phase is devoted to checking if the results obtained are reliable or if uncertainty was accumulated during the process [20]. In particular, the weighting phase is influenced by the subjective judgements of the stakeholders involved. To verify the robustness of the model with respect to the weighting system, sensitivity analysis is conducted. Sensitivity analysis conducted on the weights is developed by implementing and comparing different scenarios where weights are varied. One of the most applied approaches to sensitivity analysis is the One-At-Time method, which, as the name suggests, varies weights one after the other [40]. According to this approach, the results of the evaluation are compared with a balanced scenario (i.e., where the same weight is assigned to all criteria) and a number of other scenarios to give priority to one criterion at time.

Sensitivity analysis is particularly relevant in site selection to present to all parties involved the results obtained through the different sensitivity scenarios. The ability of

the model to maintain stable results simplifies and supports public debate, avoiding oppositions [5].

4 Results

From literature reviews, because this study aims to develop a model adapted to the Italian context, only studies conducted in the European Union were selected. This is because the specific environmental conditions and regulatory constraints of the European energy sector can significantly influence the installation of GMPV systems. Understanding the approaches and methodologies used in other European countries can provide a basis for developing a context-specific model that addresses Italy's unique challenges and opportunities. Then, the dataset was filtered to select appropriate indicators, only studies focused on European regions, resulting in a total of 22 articles.

4.1 Criteria and Indicators Definition

Selecting suitable sites for renewable energy projects is rarely straightforward, it is a multifaceted process shaped by diverse criteria that consistently align across eight key domains: technical, economic, environmental, social, physical-geographical, cultural, natural hazard, and legal considerations.

When it comes to technical factors, the literature consistently highlights the importance of access to strong solar radiation, favorable topographical conditions, and proximity to infrastructure like power grids, substations, and transportation networks. These elements are essential for maximizing energy generation and ensuring ease of operation [11, 41, 42].

In terms of economic feasibility, studies frequently emphasize the weight of financial factors such as initial capital costs, operational expenses, and financial indicators like net present value (NPV), discount rates, and payback periods [9]. Market conditions, project efficiency, and expected returns also emerge as recurring themes, underlining the importance of a solid financial foundation for project viability.

Environmental sustainability is often at the forefront of research, with numerous studies assessing issues like land-use conflicts, biodiversity conservation, and soil conditions, including fertility and erosion risks. Additionally, the proximity of potential sites to protected areas and wildlife habitats is frequently analyzed to minimize ecological disruption [43, 44].

Physical and geographical features also play a critical role. Factors such as slope, elevation, proximity to water bodies, and distance from coastlines can significantly influence both technical performance and environmental impact [7, 45]. At the same time, natural hazards like floods, landslides, and extreme weather events are increasingly seen as vital considerations that could affect infrastructure resilience and long-term sustainability [9, 46].

Though sometimes overlooked, cultural and heritage factors carry significant weight, especially for sites near archaeological or historically important locations. Respecting these areas not only meets legal requirements but also helps foster positive relationships with local communities and increases project acceptance [13, 43].

The role of social acceptance is equally pivotal. Public perception, landscape impacts, and potential job creation are often highlighted as influential factors, particularly in areas where community engagement and rural development are key to gaining local support [47].

From a legal and regulatory standpoint, adherence to zoning laws, spatial restrictions, and renewable energy policies is non-negotiable. Additionally, the ease of obtaining permits and access to government incentives can often make or break a project's success [12].

Table 1. Review of indicators for GMPV site delection in European studies.

Domain	Indicator	Unit of Measure	Source
Technical	Battery efficiency / Number of cycles	Percentage (%) / Number of Cycles	[41]
	Distance from electrical grid / Ease of connection	Kilometers (km) / Qualitative Index	[11, 13, 41]
	Distance from power lines / Power network	Kilometers (km)	[12, 42, 43, 45]
	Distance from cities / urban areas / residential areas / buildings	Kilometers (km)	[12, 42, 43, 45]
	Distance to electrical substations	Kilometers (km)	[12, 43]
	Distance to roads / main roads / road network accessibility	Kilometers (km)	[12, 42, 43, 45, 47]
	Energy yield	kWh/year	[41]
	Features of land	Qualitative Index	[41]
	Global solar radiation levels	kWh/m^2/day	[42]
	Pv efficiency / Efficiency after 25 years	Percentage (%)	[41]
	Presence of obtrusive objects causing shading	Presence/Absence	[41]
	Self-consumption fraction	Percentage (%)	[41]
	Serving population	Population Size	[11]

(*continued*)

Table 1. (*continued*)

Domain	Indicator	Unit of Measure	Source
Economic	Discount rates	Percentage (%)	[9]
	Initial capital cost	Currency (e.g., Euro)	[9]
	Lifetime of the project	Years	[9]
	Net present value (npv)	Currency (e.g., Euro)	[41]
	Payback period	Years	[41]
	Project efficiency	Efficiency Index	[9]
	Land rent price	Currency (e.g., Euro)	[9]
Environmental	Absolute humidity	Grams per cubic meter (g/m^3)	[47]
	Annual sunshine hours	Hours per year	[47]
	Distance from protected areas	Kilometers (km)	[11, 13]
	Ground concurrency	Presence/Absence	[41]
	Habitat loss	Presence/Absence	[41]
	Installation site area limitations	Square Kilometers (km^2)	[11, 13]
	Land cover	Category	[13]
	Landscape and visual impacts	Visual Impact Index	[41]
	Life cycle carbon emission reduction	Tonnes CO_2e/year	[41]
	Life cycle environmental impact	Environmental Impact Score	[41]
	Solar irradiation	kWh/m^2/year	[44, 45]
	Temperature	Degrees Celsius (°C)	[47]
	Trade-offs between renewable energy sources and agricultural productivity	Trade-off Score	[43]

(*continued*)

Table 1. (*continued*)

Domain	Indicator	Unit of Measure	Source
	Water use	Cubic Meters (m^3)	[41]
Social	Landscape visual impact	Visual Impact Index	[43]
	Potential demand	Electricity Demand Index	[47]
	Social acceptance of renewable energy projects	Social Acceptance Scale	[43]
Physical-Geographical	Aspect / Orientation	Degrees (°)/Classes	[7, 12, 45]
	Altitude / Elevation	Meters (m)	[7, 13]
Cultural	Distance from archaeological areas	Kilometers (km)	[13]
	Cultural heritage proximity	Kilometers (km)	[43]
Natural Hazard	Flood hazard zones / wind risk	Categorical/Index	[46]
	Landslide risk	Risk Index	[9]
	Natural deposits	Category or index	[46]
Legal	Aquaculture zones	Presence/Absence	[11]
	Areas licensed for exploration and exploitation of hydrocarbons	Presence/Absence	[11]
	Areas with existing or planned offshore renewable energy projects	Presence/Absence	[11]
	Agricultural areas with high-value food production (DOP, IGP, DOCG)	Protected Area Classification	[43]
	Military exercise areas	Presence/Absence	[11]
	Ports and shipping routes (for offshore plants)	Kilometers (km)	[11]

(*continued*)

Table 1. (*continued*)

Domain	Indicator	Unit of Measure	Source
	Renewable energy policy constraints	Policy Constraint Index	[43]
	Distance from airports	Kilometers (km)	[13]

Notably, the results from the literature review are consistent with Italian regulatory constraints, particularly those defined in the Legislative Decree 199/2021 and Decree-Law 63/2024, which emphasize environmental protection, land-use regulations, and restrictions on agricultural land for renewable energy development. The alignment between the literature and the Italian regulatory framework reinforces the relevance of the selected indicators and validates their applicability within the Italian context.

5 Conclusions and Future Perspectives

The paper presented a methodological proposal that supports the identification of suitable locations for GMPV in Italy. The proposal took into account both the regulatory framework of GMPV installations and the multiple aspects in play. In particular, a spatial decision support model was proposed, that integrated MCA and GIS. This integration allow to consider the spatial heterogeneity of technical, regulatory, environmental, and social aspects. At the same time, it made it possible to include experts' and stakeholders' opinions with respect to the proper site selection of these technologies.

The proposed framework could potentially inform various land use policies and energy strategies, not only identifying suitable locations of GMPV, but also suggesting priority interventions, guiding investment decisions, preventing conflicts with existing land uses, and aligning with environmental and landscape goals. Additionally, it could be applied in different contexts, by selecting the most appropriate set of criteria, according to the area under investigation, as well as the set of weights assigned by stakeholders and DMs.

Future perspectives of this work will regard the application of the proposed framework to a real-world case study, in the Piedmont region (Italy). This application could highlight the pros and cons regarding the methodology proposed, the availability of the data, and the multi-scalarity of the problem under investigation.

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