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Multi-Criteria Decision Analysis to Evaluate the Geographic Potential of Alternative Photovoltaic Types

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Abstract: This paper contributes to the expansion of green energy production, which is being pursued in order to mitigate climate change and carbon emissions from energy production. It addresses the delineation of areas that are suitable for the application of photovoltaics in the context of agricultural areas, water bodies, and parking spaces. Three specific photovoltaic types are examined in order to find out which criteria influence their geographic potential and whether spatial multi-criteria decision analysis methods are suitable for identifying suitable areas. The proposed approach consists of four steps: (1) collecting factors through expert interviews and questionnaires; (2) mapping the criteria to the spatial datasets; (3) deriving weighted scores for individual criteria through expert interviews; (4) applying the multi-criteria decision analysis method to compute and aggregate the final scores. We test our methodology at selected sites in the state of Styria, Austria. The test sites represent the topographical characteristics of the state and are about 5% of the size of Styria, approximately 820 km². The key contributions are a weighted set of criteria that are relevant for the geographic potential of alternative photovoltaic types and the developed methodology to determine this potential.

Keywords: multi-criteria decision making; spatial analysis; photovoltaic; green energy

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1. Introduction

Carbon-neutral energy production is a cornerstone of the energy transition and is necessary in decarbonizing energy production. The global energy system is the largest source of CO_2 emissions. Global final energy consumption increased by 6.6% in the period from 2015 to 2019 and CO_2 emissions from the global energy system increased by 4.6%, with greenhouse gas emissions from energy supply rising by 2.7%. Hence, the reduction in energy sector emissions is essential in order to limit global warming. The energy systems of the future should be different compared with contemporary ones if the world is to successfully limit global warming by two degrees Celsius [1].

In order to facilitate the production of climate-neutral energy, photovoltaics (PV) could utilize the solar radiation potential on the earth's surface [2]; solar energy is the largest inexhaustible source of green energy in the world [3]. According to [4], solar energy accounted for 10% of the world's electricity production in 2022. Further, Ref. [5] states that global additions to renewable power capacity increased by 36 % in 2023, with photovoltaic accounting three quarters of it.

The objective of this paper is to contribute to finding suitable sites for photovoltaic production in the densely populated areas of Central Europe. We focus on the geographic potential of alternative PV types, as described by Fakhraian et al. [6]. In the literature, many different PV types are analyzed, such as rooftops [7–12], vertical facades [13,14], floating PV [15–18], and Agri-PV [19–22].

In this paper, we contribute to the expansion of solar energy production by finding suitable areas for the deployment of PV in the following geographic contexts:

- Agricultural areas, denoted as Agri-PV.
- Water bodies, denoted as Floating-PV.
- Parking facilities, denoted as Parking-PV.

We use multi-criteria decision analysis (MCDA) methods [23] and spatial analysis methodologies in order to find areas with suitable geographic potentials. Hence, this paper answers the following research questions:

- Which criteria influence the geographic potential of the specific PV types?
- Are spatial MCDA methods suitable for delineating the areas that are suitable for the specific PV types?

The study was carried out as part of a research project in the state of Styria, Austria. Within Styria, about 5% of the area was selected as test sites. This corresponds to about 820 km². The test regions are defined by municipal boundaries and are proportional to the urban–rural typology [24] of Styria so as to ensure that the characteristics of the entire state are well represented in the test sites.

The paper is organized as follows. Section 2 brings this study into a broader context by looking at related work. Section 3 outlines the research methodology—i.e., the general methodology for deriving the MCDA results as well as the experimental setup for answering the research questions. Section 4 presents the results of this work. On the one hand, the derived criteria for the PV types are explained and, on the other, the MCDA results are shown. We conclude this paper in Section 5 with a discussion and future prospects.

2. Related Work

2.1. Multi-Criteria Decision Analysis

MCDA is a comprehensive approach for assessing sustainability. It provides an operational evaluation and decision-support framework suitable for tackling intricate issues characterized by significant uncertainty, competing goals, varied data types, multiple stakeholder interests, and the need to consider complex and dynamic biophysical and socioeconomic systems. It usually consists of four main stages: (1) criteria selection, (2) criteria weighting, (3) evaluation, and (4) final treatment and aggregation [25].

There are multiple methods used for criteria selection, such as the (1) least mean square method or (2) the Delphi method [25]. The second relies on experts and is based on the principle that predictions from a guided group of experts have a higher quality than those from an unguided group of individuals [26]. It is an iterative process in which the judgments of the experts are retrieved through questionnaires and reflections. Over multiple rounds, this process leads to a convergence toward the "best" criteria. It is stopped when a predefined stop criterion is met, such as a certain number of rounds [25].

Criteria weighting is a vital step in MCDA, as the assigned weight indicates the relative importance of a feature. This step relies on methods such as the (1) equal weights method or the (2) rank–order weighting method. The latter is structured in subjective, objective, and combined weighting methods. The Delphi method can be applied in subjective weighting methods as the criteria weights are determined based on the preferences of the decision makers. The advantage of this method over the objective and quantifiable methods is that the judgment of decision makers can fully depend on their knowledge or information [25].

Wang et al. [25] list over 20 different MCDA methods. The more elementary ones include the weighted sum method (WSM) and the weighted product method (WPM); more sophisticated ones include the unique synthesizing criteria methods (e.g., analytical hierarchy process [27]) and the outranking methods. For instance, WSM is a widely used approach in which the score of an alternative is computed by summing up the weighted criteria. In the final step of the MCDA, the best alternative is usually selected based on ranking orders.

2.2. Photovoltaic Potential

Fakhraian et al. [6] analyzed multiple studies concerning the determination of urban solar photovoltaic potential. They extracted four levels of photovoltaic potentials from

these studies. (1) The first level is concerned with the physical potential of the area of interest. Thus, the total sun energy which the area receives is computed. (2) The second level focuses on the geographic potential, which involves identifying suitable areas to install PV. (3) The next level is called technical potential and deals with calculating the maximum electricity production for the area of interest. (4) The final level looks at the economic potential by evaluating the economic attractiveness of the photovoltaic potential.

Aside from the differentiation between types of photovoltaic potential, we can also differentiate the types of PV that are in the focus of the research. In general we distinguish between horizontal PV (e.g., rooftop) and vertical PV (e.g., facades).

For instance, there are many publications focusing on urban areas and the analysis of rooftops [7–12,28], while others are concerned with the analysis of vertical facades [13,14,28].

However, there are only a few rather recent publications related to Floating-PV potential [15–18].

In their paper, Dupraz et al. [19] use the term agrivoltaic systems, which refers to systems that combine solar panels and food crops on the same land to maximize land use. They go on to analyze the photovoltaic potential of such systems. Although there are a few further studies researching agrivoltaic systems, they mostly look into the effects on crop yields [20–22].

We could not find any studies analyzing the potential of Parking-PV in particular. However, the analysis of photovoltaic potential in urban environments is similar.

2.3. MCDA for Photovoltaic Potential

MCDA is applied widely in energy related research. Research areas include, but are not limited to, energy planning and selection, energy resource allocation, energy exploitation, energy policy, buildings energy management, and transportation energy systems [25]. There are related papers which use MCDA to identify photovoltaic potential across different spatial scales, regions, and PV types. For instance, Vasudevan et al. [29] use remote sensing, GIS-technologies, and MCDA to determine the suitability of PV sites. They derive environmental, technical, and topographical criteria and apply a weighted overlay MCDA. Their objective is to find areas highly suitable for large photovoltaic power plants. Similar work was performed by Kocabaldir et al. [30], who also used a GIS-based MCDA to determine optimal sites for solar power plants. Aside from looking into the geographic potential of the sites, they also determined the economic and physical potential. Sward et al. [31] provide an extensive review of research concerning the determination of photovoltaic potential with MCDA. They show that most papers focus on criteria that directly or indirectly affect economic payback. Further, they state that the most commonly used criteria in such studies are solar insulation, distance to electric infrastructure, and the slope of the land. The top three exclusion criteria are protected lands/legal restrictions, farmlands, and open water and wetlands. They go on to list other commonly used criteria in solar siting studies, such as land cover, aspect, or elevation. They also argue that there is a lack of consideration given to the social aspects of these MCDA studies.

3. Research Methodology

3.1. Methodology

The approach in this paper uses MCDA to determine the geographic potential of Agri-PV, Floating-PV, and Parking-PV. The analysis of the geographic potential focuses on the detection of suitable areas to install PV. Our MCDA approach consists of four main stages as shown in Figure 1: (1) factor collection/selection, (2) mapping criteria to their corresponding attributes in the datasets, (3) classifying the criteria values into weighted scores, and (4) applying the MCDA method and final treatment.

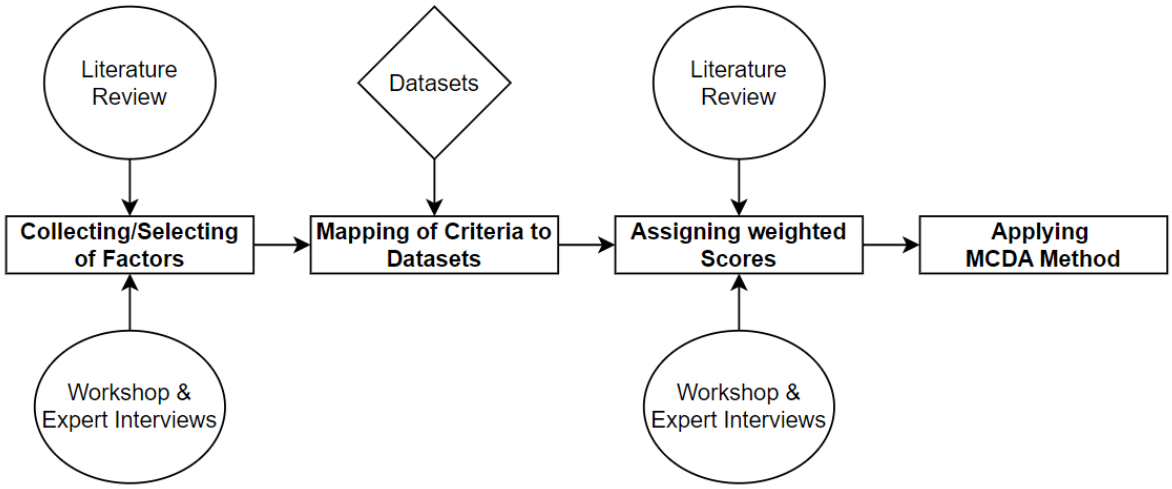


Figure 1. Workflow of the applied methodology, consisting of four major steps with several inputs.

In the first stage, we selected relevant factors for the geographic potential of the PV types by conducting expert interviews. The experts had a variety of backgrounds, from PV planning to PV construction and PV operation. Our approach for determining the criteria most relevant for the photovoltaic potential is related to the Delphi method, which follows the principle that a guided group of experts will converge towards the "most suited" criteria over multiple iterations of questionnaires and interviews. Therefore, we conducted a focused workshop as well as multiple individual questionnaires.

In the second stage, we prepared the collected criteria for the following steps by mapping them to the corresponding attributes in the datasets. This is a vital step as we can only use those criteria which are present in our datasets. For example, if the experts determine the proximity to a power grid as an important criterion, then we require a dataset that allows us to compute the distance of a potential site to the power grid.

The third stage of our approach is concerned with assigning weighted scores to the individual criteria. These scores depend on the importance and influence of the criteria on the geographic potential of areas. To derive the weighted scores, we applied a subjective weighting method similar to our approach from the first stage. In an iterative process of questionnaires and interviews, we utilized the domain knowledge of the experts to evaluate the importance of each criterion. We gathered two different kinds of criteria. On the one hand, exclusion/inclusion criteria, which are binary masks with a weighted score of 0 (not suitable) or 1 (suitable). These are applied before the MCDA method to restrict the analysis to relevant sites alone. On the other hand, we classified the values of the criteria to weighted scores ranging from 0 to 1, with 1 representing the full suitability of that criterion for the PV type.

Finally, we retrieved the MCDA score for a site by computing the mean of the assigned weighted scores of each criterion for the site. The indices and constants for computing the MCDA score are given as follows: j = index of a criterion; n = number of criteria; i = index of a potential site; m = number of potential sites; w_{ij} = weighted score of criterion j for site i; S_i = weighted sum of site i. Therefore, the equation for computing the MCDA score of a site is given by the following equation:

$$S_i = \sum_{j=1}^{n} \frac{w_{ij}}{n}, i = 1, 2, ..., m \quad (1)$$

In a final treatment step, the scores are ranked. The areas with the highest values are ranked highest and represent those sites that have the greatest geographical potential for the respective PV type.

The final MCDA scores are aggregated by grouping neighboring sites with similar scores into classes. Further, a threshold, derived from the expert interviews, is introduced to distinguish between unsuitable sites (score below the threshold) and suitable sites (score above the threshold).

3.2. Experimental Setup

We conducted a focused workshop with over 40 subject-specific participants as well as individual questionnaires with experts to determine the factors most relevant for geographic PV potential. First, we collected as many factors of influence as possible by questioning the experts as well as looking through the literature. Next, we determined the relevance of the individual factors in an iterative process by asking the experts to evaluate them with regard to their relevance for photovoltaic potential. We stopped the process after the experts agreed on a stable set of criteria. As a result, we obtained a set of criteria for each PV type. After finishing the criteria collection, we mapped the geographic criteria to their corresponding attributes in the spatial datasets. For instance, for Agri-PV we mapped the "land use" criterion to the INSPIRE-Land Use dataset.

In the next stage, we used a similar approach as in the first stage to determine weighted scores for all criteria. In an iterative process of questionnaires and interviews, we utilized the domain knowledge of the experts to gather weighted scores for each criterion. We distinguish between general criteria that apply to all PV types (e.g., proximity to the power grid) and specific criteria that only apply to the given PV type (e.g., within a water body for Floating-PV). Next, we differentiate between exclusion/inclusion criteria and MCDA criteria. The former are used to exclude or include areas from the MCDA (e.g., certain land use classes), while the weighted scores of the others (e.g., solar irradiation) are used for the computation of the final MCDA score. In a final step, we computed the MCDA score for each potential site by applying Equation (1). We selected those areas with the highest scores as the ones most suitable for the respective PV type.

The first preprocessing step of our approach consists of clipping all available datasets for a specific PV type to the area of interest. This step is vital to reduce the complexity of the problem.

In this approach, we view each cell of our base raster, which has a spatial resolution of 1 m^2, as a potential site for PV. In the second preprocessing step of the MCDA, we have to match our datasets to this base raster. By executing this process for each vector and each raster dataset, we receive multiple raster sets containing the values of each MCDA criterion of the PV type. What complicates this process further is that each of these criterion layers can comprise multiple datasets. For instance, the exclusion raster of the hazard zones is combined from three datasets, the danger zones, the avalanche zones, and the flood zones of Styria. These raster sets form the basis for applying our MCDA method to the area of interest.

In the next step, we have to assign the weighted scores to each raster cell depending on the value of each raster cell. After this, we receive a raster mask for each exclusion criterion, as well as a raster for each MCDA criterion containing the assigned weighted scores. With these raster sets, we are now able to apply raster calculations to compute the final MCDA score.

First, the areas of each PV type are restricted to potentially suitable areas by applying the raster masks and excluding all completely unsuitable areas from the analysis. Such areas have a weighted score of 0 in the raster masks (e.g., red-flagged avalanche zones). In the next step, we apply raster calculations to derive the MCDA score for each site from the raster sets containing the weighted scores. We derive the MCDA score for each site (raster cell) by computing the mean of the weighted scores of all criteria of the PV type. This results in a suitability score that ranges from 0 to 1, with 1 representing the most suitable areas for the analyzed PV type.

In the post-processing stage, we vectorize the resulting raster containing the MCDA scores. By doing this, we are able to aggregate neighboring raster cells with similar scores into larger areas. This allows us to highlight suitable areas for PV more easily. Next, we introduce a suitability threshold of an MCDA score greater than 0.5. All areas with an MCDA score greater than or equal to 0.5 are suitable for the PV type. All areas below this threshold can be classified as unsuitable. This threshold was derived from expert interviews as well. Finally, we brought the final scores from the result raster into a range of 0–100.

There is one criterion that we applied after deriving the final MCDA scores, that is the proximity to the power grid. This is because it does not make sense to compute the distance of each site (cell) to the closest power grid entry point, as it would be enough for a suitable PV area if its edge were within the threshold range to the next power grid entry point. Further, the acceptable distance varies with the size of the PV power plant. However, the power grid is classified as "critical infrastructure" in Austria; thus, we do not have any direct information on the potential entry points. Therefore, as a workaround, we assume that buildings have access to a power grid and are representing points of consumption; therefore, proximity to a building also means proximity to the power grid. Therefore, we utilize a 500 m buffer around the buildings to determine whether a suitable site is close enough to the power grid or not.

We created a pipeline that executes all of these spatial processing steps using the QGIS Model Designer.

We apply our approach to seven research areas across Styria, Austria. These test sites cover about 5% of the area of Styria, which corresponds to about 820 km^2. They are defined by municipal boundaries and are proportional to the urban–rural topology of Styria so as to ensure that the characteristics of the entire state are well represented in the test areas. We tried to use only openly available data sources for our approach (see Table A1). However, there is no open-source dataset for the soil quality of agricultural land. Thus, we were forced to rely on a closed-source dataset in this case.

4. Results

4.1. Geographic Potential Criteria

In general, Agri-PV, Floating-PV, and Parking-PV can all be classified as horizontal PV types. Nevertheless, the geographic potential of each PV type depends on different factors. The following sections describe the identified criteria and their assigned weighted scores, which were derived from the iterative expert interviews and questionnaires. We begin with the general criteria applicable to all PV types and continue with criteria specific to particular PV types.

Criteria identified as major for all examined PV types are listed in Table 1. For instance, global solar irradiation is important for all PV types. Further, it is vital for Agri- and Floating-PV to avoid protected areas (e.g., nature conservation zones) and hazard zones (e.g., red flagged avalanche zones). However, there are also protected areas and hazard zones in which PV can be built, such as yellow flagged avalanche zones. Another relevant criterion is land use because areas such as forests or rivers can be excluded as unsuitable for all PV types. Further, solar irradiation was deemed a vital criterion by the experts, with areas with a yearly direct and diffuse irradiation below 700 kWh being classified as unsuitable for PV. All areas above a yearly irradiation of 900 kWh were deemed to be well suitable for PV. The final general criterion is the proximity to a power grid. Depending on the size of the planned power plant, the distance to the next power grid entry point can vary, mainly because of economic factors. Thus, whether an area with a suitable MCDA score can be used for PV depends on the size of the area and its distance to the next power grid entry point.

Table 1. The main criteria derived for the overall analysis of the geographic photovoltaic potential are listed with their criterion type, their assigned weighted score, and example instances.

Criterion Name	Criterion Type	Assigned Weighted Score (w)	Comment	Relevant PV Type
Hazard Zones	Exclusion	0	Red flagged avalanche or flood zones	Agri-PV, Floating-PV
	MCDA	0.5	Yellow flagged avalanche or flood zones	Agri-PV, Floating-PV
Land Use	Exclusion	0	Forest areas, rivers, cemeteries etc.	Agri-PV, Floating-PV, Parking-PV
Protected Areas	Exclusion	0	Nature reserves of type b and c, etc.	Agri-PV, Floating-PV
	MCDA	0.5	Nature reserves of type a, etc.	Agri-PV, Floating-PV
	MCDA	0.75	National parks, etc.	Agri-PV, Floating-PV
Solar Irradiation	Exclusion	0	Yearly direct and diffuse irradiation below 700 kWh	Agri-PV, Floating-PV, Parking-PV
	MCDA	0.75	Yearly direct and diffuse irradiation between 700 and 900 kWh	Agri-PV, Floating-PV, Parking-PV
	MCDA	1	Yearly direct and diffuse irradiation above 700 and 900 kWh	Agri-PV, Floating-PV, Parking-PV

4.1.1. Agri-PV Criteria

The main criteria in terms of geographic potential determined for Agri-PV are:

1. Agricultural Use (Type of Crop or Plant)
2. Soil Quality

We define three different classes of agricultural use as relevant for the suitability of the area for PV: (1) cropland, which is land used for the cultivation of different crops (e.g., maize), (2) grassland, which is areas that are mowed regularly, and (3) vineyards, which are areas used for the cultivation of grapes. Vineyards have the highest score as there is a great synergy between cultivating grapes and PV. For instance, solar panels serve as a protection against harsh weather conditions, while also providing energy for the agricultural operation. The score decreases towards cropland as the synergy decreases and there is a conflict of interest between using this land for energy or food production.

The other factor is soil quality, which is divided into the soil quality of cropland and the soil quality of grassland. Table 2 shows that the assigned weighted score decreases when the soil quality of the land increases and vice versa. It starts with a low suitability of 0.25 for land with the best soil quality and ends with a high suitability for PV of 1 for land with poor soil quality. In addition to the type-specific criteria, all general criteria also apply to the Agri-PV potential.

Table 2. Derived criteria for the analysis of the geographic potential of Agri-PV are listed with their criterion type, their assigned weighted score, and example instances.

Criterion Name	Criterion Type	Assigned Weighted Score (w)	Comment
Agricultural Use	MCDA	0.5	E.g., cropland
		0.75	E.g., grassland
		1	E.g., vineyards
Soil Quality	MCDA	0.25	Soil quality class 1 for agricultural and grassland
		0.42	Soil quality class 2 for agricultural land
		0.5	Soil quality class 2 for grassland
		0.58	Soil quality class 3 for agricultural land
		0.75	Soil quality class 4 for agricultural land and class 3 for grassland
		0.92	Soil quality class 5 for agricultural land
		1	Soil quality class 6, 7 for agricultural land and class 4 for grassland

4.1.2. Floating-PV Criteria

The following main criteria in terms of geographical potential were determined for Floating-PV and are displayed in Table 3 in more detail:

1. Water body type (natural vs. artificial).
2. Water body usage (determines how much area of the water surface can be covered with PV modules).
3. Littoral zone.
4. Water level variability.
5. Depth of the water body.
6. Inflow/outflow.
7. Ownership.

PV and water bodies have great synergy as the floating PV modules can have a cooling effect on the water bodies and reduce the growth of algae. The first criterion to consider for the suitability of water bodies for PV is the water body type, as artificial water bodies are more suitable than natural ones. Further, it is important to consider the usage of an artificial or natural water body because large reservoirs are more suitable than smaller retention basins. Finally, it is not possible to build PV too close to the shore due, for example, to potentially low water levels. Therefore, it is vital to consider areas close to the shore less suitable than areas in the middle of the water body. Other criteria that were considered indirectly in the analysis are water level variability, inflow/outflow, and depth of the water body. The first two are represented by the exclusion of major flood zones, which can highly influence the water level. The last one is taken into consideration by the littoral zone, as water bodies tend to be shallow close to the shore. The ownership criterion specifies that publicly owned areas are more suitable than privately owned ones. However, this could not be included in the analysis as there was no dataset available representing this information. In addition to the type-specific criteria, all general criteria also apply to the Floating-PV potential.

Table 3. Derived criteria for the analysis of the geographic potential of Floating-PV are listed with their criterion type, their assigned weighted score, and example instances.

Criterion Name	Criterion Type	Assigned Weighted Score (w)	Comment
Littoral Zone	Exclusion	0	Area of the water body at a distance of 0–7 m from shore
	MCDA	0.75	Area of the water body at a distance of 7–15 m from shore
	MCDA	1	Area of the water body at a distance greater than 15 m from shore
Water Body Type	Exclusion	0	Type unknown
	MCDA	0.5	Type natural (e.g., lakes)
	MCDA	1	Type artificial (e.g., dredging pond)
Water Body Usage	Exlusion	0	E.g., retention basin
	MCDA	0.25	E.g., settling basin
	MCDA	0.5	E.g., landscape pond
	MCDA	0.75	E.g., larger pond systems
	MCDA	1	E.g., reservoirs

4.1.3. Parking-PV Criteria

The main criteria in terms of geographic potential determined for Parking-PV are:

1. Vegetation (e.g., trees)
2. Hazard Zone Areas

In the case of Parking-PV, the (1) vegetation plays a vital role for two reasons. First, larger vegetation (e.g., trees) can cover the area in shadow, thus reducing the amount of solar irradiation. This is taken into account in the analysis through the general criterion of solar irradiation. The second way vegetation influences photovoltaic potential is through covering the panels with leaves and pollen. However, this could not be taken into account in the analysis as there was no data available on that subject.

Contrary to the other PV types, (2) hazard zone areas are of interest for Parking-PV. This is due to the way the power plants could be built on parking areas. The analysis considers this through the general criterion "hazard zones".

4.2. MCDA Results

Figures 2–4 show examples of the resulting MCDA raster of each PV type, with a spatial resolution of 1 × 1 m, colored by the computed suitability score. This raster is overlayed with the vectorized aggregation of the MCDA scores into distinct classes. As stated above, areas with a mean score below 50 are not suitable, while areas above this threshold are suitable. Their suitability increases with a rising MCDA score.

Each of the PV-specific Figures shows various characteristics related to the PV type. For instance, Figure 2 shows that aggregation leads to the dissolution of smaller unsuitable areas into larger suitable areas. However, it also shows that more highly suitable areas (bottom right) dissolve in less suitable areas.

Figure 3 shows an example of a result for the Floating-PV type. In the bottom right corner, several small water bodies are identified as completely unsuitable for PV. Further, the effect of the binary mask for the littoral zones can be seen, as areas close to the shore are evaluated as unsuitable for PV. We can observe similar aggregation effects as for the Agri-PV because the more highly suitable central water body areas dissolve in the aggregated rating of the water body.

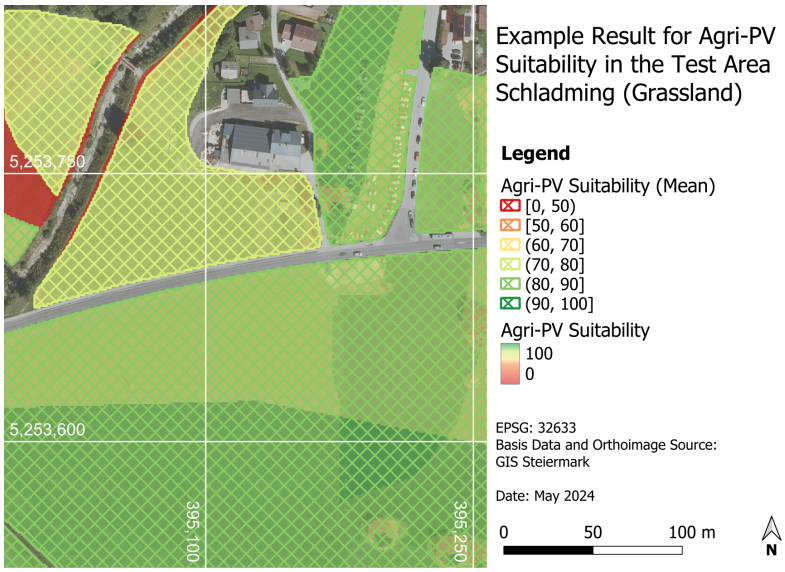


Figure 2. Example results for Agri-PV suitability showing an overlay of the 1 × 1 m raster containing the MCDA scores and their vectorized aggregation.

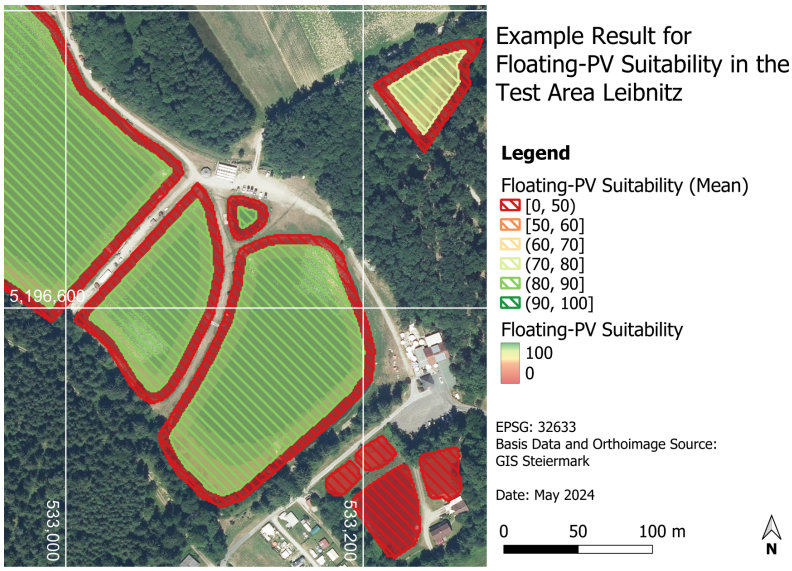


Figure 3. Example results for Floating-PV suitability showing an overlay of the 1 × 1 m raster containing the MCDA scores and their vectorized aggregation.

Figure 4 displays a result for the Parking-PV. We can observe that the displayed MCDA scores have a higher heterogeneity than for the other two types. Further, the aggregated scores are highly influenced by this heterogeneity as well-suitable areas from the 1 × 1 m raster dissolve with less suitable areas. We can also observe that areas to the north of buildings are evaluated as unsuitable for Parking-PV.

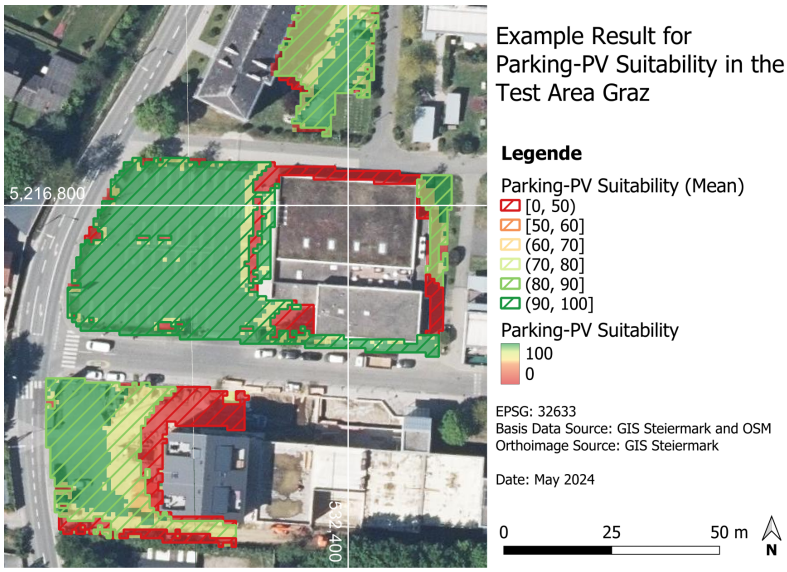


Figure 4. Example result for Parking-PV suitability showing an overlay of the 1 × 1 raster containing the MCDA scores and their vectorized aggregation.

5. Discussion and Future Prospects

In this paper, we propose an MCDA approach for determining the geographic potential of alternative PV types, such as Agri-PV, Floating-PV, and Parking-PV. These have the fact that they are horizontal PV types in common. However, different sets of MCDA criteria apply to each of them. We discuss MCDA, as well as different types of potential and PV. Further, we provide an overview on how MCDA was used for analyzing the geographic potential of different PV types.

Our methodology consists of four major steps: (1) deriving potential criteria from factors of influence; (2) mapping them to their corresponding attributes in the datasets; (3) assigning them weighted scores through expert interviews and questionnaires; (4) applying the MCDA method and a final aggregation step for the results. Steps (1) and (3) were achieved through an iterative process of expert interviews and questionnaires, as well as a literature review.

We demonstrate the capability of the approach by applying it to a real-world example in Styria, Austria. Our test sites cover about 5% of the area of Styria, which corresponds to about 820 km^2. The sites are defined by municipal boundaries and are proportional to the urban–rural topology of Styria so as to ensure that the characteristics of the entire state are well-represented in the test areas.

Our results show that there are different sets of criteria that apply to the specific PV types. There are some that are shared by all three PV types, such as solar irradiation or proximity to a power grid. Then, there are the PV type-specific criteria, such as agricultural use and soil quality for Agri-PV, or the water body type, water body usage, and littoral zone for Floating-PV. Parking-PV is highly influenced by its surrounding vegetation, as this can lead to more shadowed areas, as well as soiling of solar panels with leaves and pollen.

The final MCDA results show that the approach is capable of determining the geographic potential of potential sites. In all three resulting examples, the unsuitable areas are clearly distinguished from suitable areas. For instance, the result of the Parking-PV example shows that parking spaces on the northern side of buildings are identified as unsuitable. Further, the aggregation of similar MCDA scores has an averaging-out effect on the overall geographic potential of an area. Finally, the results of the Parking-PV shows a higher heterogeneity in MCDA scores compared with Floating- and Agri-PV. This results from the shadowing effects of the surrounding structures influencing the solar irradiation reaching the area. One should be careful when comparing the MCDA scores of the different PV types. On the one hand, they are derived from different sets of criteria and datasets

with varying spatial resolutions. On the other, placing PV on a lower-rated parking site might be preferable to placing it on grassland due to visual impairing and soil sealing.

The key contributions of this paper are as follows: we collect and weight a set of criteria that are relevant for the geographic potential of alternative PV types such as Agri-PV, Floating-PV, and Parking-PV. Further, we develop an MCDA methodology for determining the geographical potential of alternative PV types and prove its suitability by applying it to research areas across Styria, Austria. Our previous research also shows the applicability of MCDA methods in identifying suitable vertical areas for BIPV [13].

Future research topics will consist of a more detailed evaluation of the proposed methodology by either gathering ground truth data of existing PV power plants for the specific PV types or having experts evaluate the PV sites identified. In the case of Floating-PV, it would be of interest to obtain a more precise estimation of the littoral zones for each water body as some water bodies might be steep enough to build PV close to the shore, while others are too shallow, or the water level might vary greatly over time. This might be feasible by using semantically enriched remote sensing data, as our current research indicates [32]. Another future research topic is the inclusion of other MCDA methods and a comparison of results. Finally, the aggregation of the MCDA scores can be optimized by using different methodologies for determining the breaks between the classes (e.g., natural breaks).

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Data Availability Statement: All data sources used are listed in the Appendix A in Table A1.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Data sources.

Dataset Name	Description	Source
ALS Gebäudemaske Steiermark	Buildings of Styria (without Graz)	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=630, last accessed on 28 July 2024.
Bodenschätzung	Soil quality	Ordered from BEV (https://www.bev.gv.at/, last accessed on 28 July 2024.)
Digitales Geländemodell	Digital terrain model	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=1211, last accessed on 28 July 2024.
Digitales Kataster Modell-Nutzungsflächen	Digital cadastre model—land use	Ordered from Land Steiermark, A17 (https://www.verwaltung.steiermark.at/cms/ziel/74837988/DE, last accessed on 28 July 2024.)

Table A1. *Cont.*

Dataset Name	Description	Source
Digitales Oberflächenmodell	Digital elevation model	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=1199, last accessed on 28 July 2024.
Gebäudemaske Graz	Buildings (city of Graz)	Ordered from Stadt Graz (https://www.graz.at/, last accessed on 28 July 2024.)
Gefahrenzonen	Danger zones	Ordered from Land Steiermark, A17 (https://www.verwaltung.steiermark.at/cms/ziel/74837988/DE, last accessed on 28 July 2024.)
Geschützte Landschaftsteile	Protected landscapes	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=8, last accessed on 28 July 2024.
Hangneigungen	Slope	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=65, last accessed on 28 July 2024.
Hangrichtungen	Aspect	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=64, last accessed on 28 July 2024.
INSPIRE Feldstücke	Agricultural areas	https://www.data.gv.at/katalog/dataset/ae548d7f-c184-4895-ab31-3b797d76550a, last accessed on 28 July 2024.
Landschaftsschutzgebiete	Protected landscapes	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=9, last accessed on 28 July 2024.
Lawinenschutzzonen	Land- and snowslide protection zones	Ordered from Land Steiermark, A17 (https://www.verwaltung.steiermark.at/cms/ziel/74837988/DE, last accessed on 28 July 2024.)
Nationalparke	National parks	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=10, last accessed on 28 July 2024.
Naturdenkmäler	Natural monument	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=11, last accessed on 28 July 2024.
Naturparks	Natural preserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=12, last accessed on 28 July 2024.
Europaschutzgebiete-Natura2000	European protected areas	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=1, last accessed on 28 July 2024.
Naturschutzgebiete lit.a	Nature reserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=13, last accessed on 28 July 2024.
Naturschutzgebiete lit.b	Nature reserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=14, last accessed on 28 July 2024.
Naturschutzgebiete lit.c	Nature reserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=15, last accessed on 28 July 2024.

Table A1. *Cont.*

Dataset Name	Description	Source
OSM	Land use data	https://download.geofabrik.de/europe/austria.html, last accessed on 28 July 2024.
Ramsar Gebiete	Ramsar protected areas	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=16, last accessed on 28 July 2024.
Seen und Teiche	Standing water bodies	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=18, last accessed on 28 July 2024.
Verwaltungsgrenzen (VGD)	Administrative boundaries	https://data.bev.gv.at/geonetwork/srv/ger/catalog.search#/metadata/6854e2a0-166e-4679-9426-98c9d7a0a41d, last accessed on 28 July 2024.
Wasserschongebiete	Water preserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=457, last accessed on 28 July 2024.
Wasserschutzgebiete	Water reserve	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=1223, last accessed on 28 July 2024.
Wildbachschutzzonen	Torrent protection zones	Ordered from Land Steiermark, A17 (https://www.verwaltung.steiermark.at/cms/ziel/74837988/DE, last accessed on 28 July 2024.)
Solarstrahlungsdaten	Solar irradiation (average, measured)	https://solargis.com/maps-and-gis-data/download/austria, last accessed on 28 July 2024.
SP_Jahressumme	Solar irradiation (annual sum, generated)	Provided by Energie Agentur Steiermark (https://www.ea-stmk.at/, last accessed on 28 July 2024.)
UNESCO Welterbe	UNESCO protected areas	https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=393, last accessed on 28 July 2024.
Urban–rural	urban–rural typology	https://www.statistik.at/atlas/?mapid=topo_stadt_land, last accessed on 28 July 2024.

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