

Article

Assessment of Solar Power Plant Installations on Mining Sites—A Case Study [†]

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Abstract

The aim of the research is to assess the technical, environmental, and legal suitability of mining areas for dual purposes: both mineral exploitation and solar energy production. A comprehensive analysis of the Croatian legislative framework in the areas of mining, energy, spatial planning, and environmental protection was carried out. Spatial, environmental, and technical suitability were assessed using Geographic Information Systems (GIS) in combination with a Multi-Criteria Decision-Making Model (MCDM) applying the TOPSIS method. A total of 565 exploitation fields were analyzed based on twenty technical, environmental, and legal parameters. Three installation variants (Variant 1, Variant 2, Variant 3) correspond to different phases of mining operations, and three energy use models (Model 1, Model 2, Model 3) were proposed. The results confirm that exploitation fields represent a valuable but underutilized resource for the development of renewable energy sources, i.e., solar power plants installation.

Keywords: mining sites; renewable energy; solar power plants; GIS-MCMD model; TOPSIS

1. Introduction

Due to the increasing demand for energy, the world in general is increasingly turning to alternative renewable energy sources (RES). One of the objectives of the energy policy of the Republic of Croatia is to strengthen energy self-sufficiency, promote investments in RES, and increase their share in energy consumption. From 2018 to 2023, the Republic of Croatia saw a decrease in the production of electric energy with average annual decline rate of 1.9%, while the consumption of electricity increased at an average annual rate of 0.4%. During this period, there was a trend of increased production of electricity from renewable sources and non-renewable waste, while the production of other primary forms of energy decreased. In total energy consumption, the use of coal and coke, liquid fuels, hydropower, and electricity decreased, while energy consumption from wood and biomass, renewable sources, and non-renewable waste increased [1].

To increase the potential for energy production from renewable sources compared to the current state, primarily by utilizing solar energy, surface mines have been considered as potential areas for the installation of solar power plants. These land interventions represent potential for multifunctional use, serving both the exploitation of mineral resources and the



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installation of solar panels for electricity generation mainly due to their large surface areas, which range from several tens to several hundreds of hectares. Various authors in their research have examined the possibilities of using existing and/or abandoned (rehabilitated) open pit mines to produce electricity from RES.

With the aim of repurposing open pit mines, Mert [2] analyzes the possibility of installing a solar power plant (SPP) on a sand exploitation field in Adilcevaz (Turkey), while Kim et al. [3] consider the installation of an SPP on the site of an abandoned open pit mine in Seoul (Republic of Korea). Heib [4], in his study, examines the advantages and disadvantages of installing solar systems on landfills created by the deposition of mining waste from coal exploitation. Junaedi et al. [5] compare the efficiency of SPPs installed in urban areas with those installed within abandoned open pit mines, concluding that, on average, higher efficiency is achieved with solar panels placed in the open pit mine. Kanevce et al. [6] discuss the possibility of using mine lands and other brownfields for solar and wind power deployment and based on this, proposed several potential locations in North Macedonia. Given that mining operations in open pit mines require a significant amount of energy, the possibility of integrating RES (solar, wind, geothermal, etc.) into the mining processes during exploitation or for repurposing after mining activities are completed has also been considered [7,8]. Valikandi et al. [9] provide examples of using RES with a focus on wind and solar energy in both active and abandoned mining sites. It was found that integrating RES into the mining industry helps preserve the environment and has a positive economic impact. Qays et al. [10] efficiently integrate solar photovoltaic systems with battery storage as a solution to the energy challenges faced by the mining industry in Western Australia. By utilizing advanced renewable energy technologies, their research offers a reliable, cost-effective, and environmentally sustainable solution, significantly reducing reliance on conventional electricity grids.

To ensure multifunctional use of land affected by mining, an analysis of the legislative framework in Croatia, including mining, energy, spatial planning, and other related fields, was carried out, alongside technical feasibility studies for placing solar power plants in open pit mines [11,12]. Tomšić et al. [13] conducted an analysis of the attractiveness of areas, spatial capacities, and conditions for use of the potential of RES across the entire Republic of Croatia (including SPP installation), identifying potential zones for use. Krpan et al. [14] conducted a study in the Primorje-Gorski Kotar County, Croatia, to assess the possibilities of utilizing space for the construction of solar power plants.

When addressing problems involving multiple criteria for determining the optimal solution, various researchers often utilize Multi-Criteria Decision-Making techniques (MCDM), such as AHP, TOPSIS, PROMETHEE, and ELECTRE. Due to the simplicity of using MCDM methods, their application is exceptionally broad, spanning from technical and natural sciences to social sciences, all with the goal of selecting the optimal solution [15–20]. Additionally, when the analysis and selection of the optimal solution require processing a large volume of spatial data, Geographic Information Systems (GIS) are frequently incorporated into the analysis. GIS enables easy generation of a database, which serves as a starting point for applying MCDM techniques [21,22].

Khan et al. [23] analyzed the selection of potential sites based on criteria grouped into four categories (geographic, technical, economic, and flood susceptibility). Using a GIS-based non-linear multi-criteria optimization technique, they processed a suitability map, resulting in identified suitable locations for the installation of solar power plants in Pakistan. To leverage favourable geographic conditions, Hooshangi et al. [24], using a GIS-based Fermatean Fuzzy Technique for Order of Preference by Similarity to Ideal Solution method (FF TOPSIS), conducted an evaluation of potential sites for solar power plants in Iran. The results of the analysis show that as much as 13.81% of Iran's total territory is

suitable for this purpose. Ahadi et al. [25], applying the AHP method and considering only provincial centres, identified Zahedan as the best location for installing SPP.

It is often necessary to predict unsuitable locations to avoid potential damage to installed systems. For example, Kengpol et al. [26], using the Fuzzy AHP method and GIS, identified potential locations for the installation of SPP in Thailand, specifically to avoid potentially flood-prone areas.

The increasing demand for energy and the challenges of energy supply often arise in remote or isolated areas. Belaid et al. [27] consider the installation of solar systems in the agricultural region of Ghardaïa in southern Algeria. By applying GIS and the Fuzzy Analytic Hierarchy Process (FAHP), they identified suitable areas for installing solar panels, concluding that as much as 346,673.30 hectares are suitable for this purpose due to the high levels of solar radiation.

Bertsiou et al. [28], using GIS and the MCDM method, specifically AHP, analyze the legal regulations and imposed restrictions to select potential locations for the installation of solar and wind power plants on the island of Karpathos, Greece. The goal of their study is to meet energy needs by utilizing RES.

In contrast to rural areas, urban areas also face high energy demand, but with limited space. Liang et al. [29] explore the possibility of installing solar power plants on abandoned wastelands, which, due to their gentle slopes, are suitable for such purposes. In their study, they employ a multi-level evaluation system using the AHP-XGBoost-GIS method.

Hassan et al. [30], on the other hand, combine two MCDM methods, CRITIC (Criteria Importance Through Inter-criteria Correlation) and TOPSIS, using a wide range of criteria (such as climate, economic factors, etc.). They apply this hybrid framework to evaluate suitable locations and technical potential for large photovoltaic systems in five selected cities in Saudi Arabia. This approach helps identify optimal sites for SPP in urban areas while considering various influencing factors.

To highlight the potential and possibility of multifunctional land management within mining sites in the Republic of Croatia, and to increase the use of solar energy, an analysis was conducted that includes both legislative frameworks and technical possibilities for the installation of solar power plants within these areas. Based on the analysis, alternative solutions for the placement of solar power plants within exploitation fields were proposed, along with models for the use of electricity depending on the needs of the open pit mine, and recommendations for necessary amendments to the legislative framework. The goal of the study is to determine the optimal potential areas within the Republic of Croatia for multifunctional use, based on selected criteria that influence the attractiveness of these areas, using a GIS-MCDM model.

While previous studies have thoroughly explored the technical feasibility, efficiency, and legislative considerations for installing solar power plants on former mining sites and other brownfields, several gaps remain in the literature. Notably, many works focus on individual case studies or specific geographic regions, with limited attention to comprehensive frameworks that integrate both legislative and technical criteria for multifunctional land use. Furthermore, there is a lack of research addressing the practical challenges of harmonizing mining and renewable energy regulations to enable the simultaneous exploitation and deployment of SPP. This study aims to fill these gaps by proposing an integrative GIS-MCDM model tailored to the Republic of Croatia, combining spatial analysis and legal review to identify optimal areas for multifunctional land use and to recommend necessary amendments to the legislative framework.

2. Materials and Methods

For selecting optimal areas in the Republic of Croatia that can be used for multifunctional purposes, simultaneously for the exploitation of mineral resources and the installation of solar power plants, a variety of data was analyzed. Analysis includes spatial data on exploitation fields (Ministry of Economy, Zagreb, Croatia (MOE) [31]), legal regulations governing the exploitation of mineral resources, and those related to the use of RES, including the installation of solar power plants. The methodology of the study is illustrated in Figure 1.

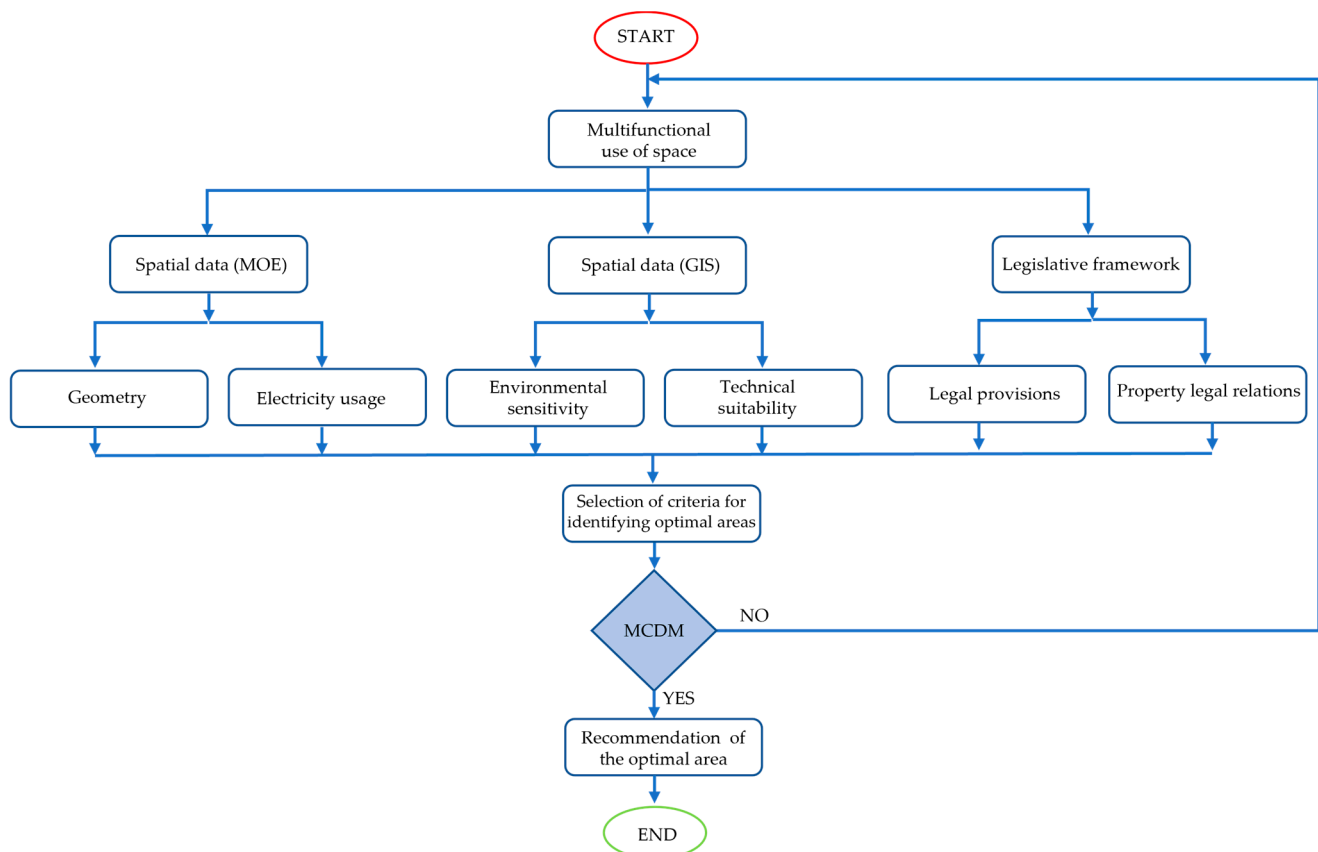


Figure 1. The study methodology algorithm.

Spatial data analysis was used to identify suitable sites for solar power plants in open pit mines, considering mine geometry and electricity consumption. Environmental and technical constraints, such as protected areas and regulatory requirements, were assessed to exclude unsuitable locations. Legal frameworks were reviewed to recommend necessary amendments for effective multifunctional use of mines. The optimal areas for installation were chosen based on clear criteria, ensuring technically and legally viable options for solar energy generation.

2.1. Spatial Data (MOE)

2.1.1. SPP Geometry Installation Variants

Depending on the dynamics of mineral exploitation (i.e., the performance of mining operations), there are three variants of installing solar panels (Figure 2) whose positions within the boundaries of the exploitation field can be temporary or permanent. Temporary solar power plant (SPP) installations are used at active or pre-concession mining sites, offering flexibility to relocate panels as operations change. These installations last only as long as exploration or mining works continue, ending when a concession is granted or

activities conclude. Permanent SPPs are recommended once mining ends and the land stabilizes, enabling long-term solar energy production without relocating equipment.

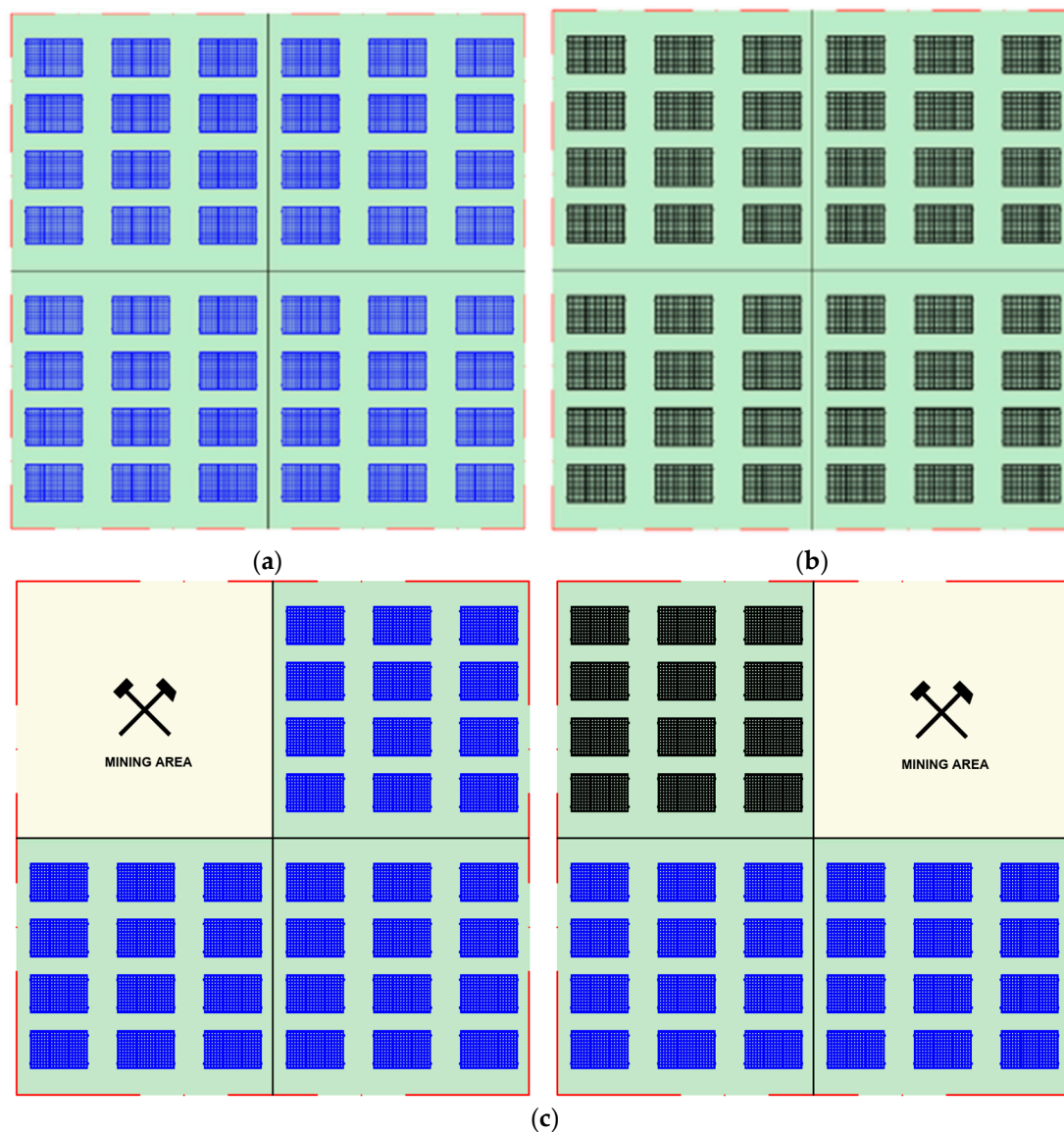


Figure 2. Possibility of placing SPP depending on the dynamics of mining works (panels shown in blue indicate temporarily positioned SPP, whereas panels shown in black denote permanently positioned SPP): (a) temporary positions, (b) permanent positions, (c) combination of temporary and permanent positions [12].

When conducting an analysis of potential mining sites (MS) for the installation of solar power plants, it is essential to determine both the size of the exploitation field and the current operational status of the site (Table 1). The surface area of each mining site is a crucial factor, as it influences the capacity for solar panel installation and the overall technical feasibility of the project. Additionally, the activity status—whether the site is active, non-active, or closed—plays a significant role in deciding the most appropriate installation model for solar panels, as well as in assessing long-term sustainability and adaptability of the site for energy production.

Table 1. MS criteria ratings.

Criteria	Ratings			
	MS surface area	MS activity		
	<25 ha	25–75 ha	75–100 ha	>100 ha
	Active	Non-Active	Closed	-

Variants that occur depending on the dynamics of mining operations are as follows:

- Variant 1—installation of solar panels before granting a mining concession (Figure 2a)—temporary positions—SPP is installed on the 100% surface of MS.
- Variant 2—installation of solar panels for the duration of mining works with the obtained mining concession (Figure 2c)—combining both temporary and permanent placements. Initially, solar panels are installed on 75% of the mining site temporarily. As mining progresses, the allocation shifts to 25% permanent and 50% temporary installation, followed by 50% permanent and 25% temporary, and ultimately culminating in 100% permanent installation.
- Variant 3—installation of solar panels after the completion of mining works (Figure 2b)—permanent positions of SPP—SPP is installed on the 100% surface of MS.

Variant 1 (Figure 2a) would include all new or future exploitation fields that are currently in the process of obtaining a mining concession in the identified exploitation field. Upon completion of mining works for the purpose of exploring mineral resources and after confirming mineral reserves, it would be possible to install temporary solar panels within the boundaries of the future exploitation field. After obtaining the concession, the panels can be relocated in accordance with the projected dynamics of mining works.

Variant 2 (Figure 2c) would include exploitation fields where mining works are or will be carried out. Planning the development of mining works and their dynamics, as well as the simultaneous placement of solar panels within the exploitation field, will need to be defined through verified mining project documentation. By planning works on the installation of solar panels on free surfaces within exploitation fields in the mining verified project documentation, the smooth development of exploitation and production of electricity from solar panels will be enabled. Depending on the dynamics of exploitation of mineral reserves, the solar panels will have to be moved.

On the exploitation fields where the mining activity has stopped, that is, on the parts that have been technically rehabilitated, the possibility opens for the permanent installation of solar panels, that is, for Variant 3 (Figure 2b). The advantage of using the surface of the exploitation fields where the mining activity has stopped is that there is no need to harmonize the dynamics of the mining works in relation to the positions of the installation of solar panels. Also, there is no occurrence of harmful effects on the installed solar panels, such as fly rock, accumulation of rock dust on the panels, and the like.

For alternative solutions that involve the relocation of solar panels or their installation in temporary positions (Variant 1 and partially Variant 3), the use of mobile systems is proposed. If necessary, they can be moved from one location to another quickly and easily. In alternative solutions where the installed solar power plants remain permanent (Variant 2 and partially Variant 3), fixed, non-mobile solar plants will be installed.

2.1.2. Electricity Usage Models

Every exploitation field in which mining works are conducted, i.e., the exploitation of mineral reserves in their technological process, depends on some type of energy source. Thus, diesel fuel is most often used for the operation of mining machinery, electricity from the distribution network or from aggregates for the refining plant, lighting, or heating. All

these forms of energy that are necessary for a mining operation to function can be efficiently replaced by electricity produced at solar power plants located within the exploitation fields.

Depending on the electricity needs within the exploitation field and the method of electricity distribution, solar power plants can be categorized into three models (Figure 3):

- Model 1—all produced electricity is used for the needs of the exploitation field (Figure 3A);
- Model 2—produced electricity is partly used for the needs of the exploitation field, and the excess is distributed to the power grid (Figure 3B);
- Model 3—all produced electricity is transferred to the power grid for further distribution (Figure 3C).

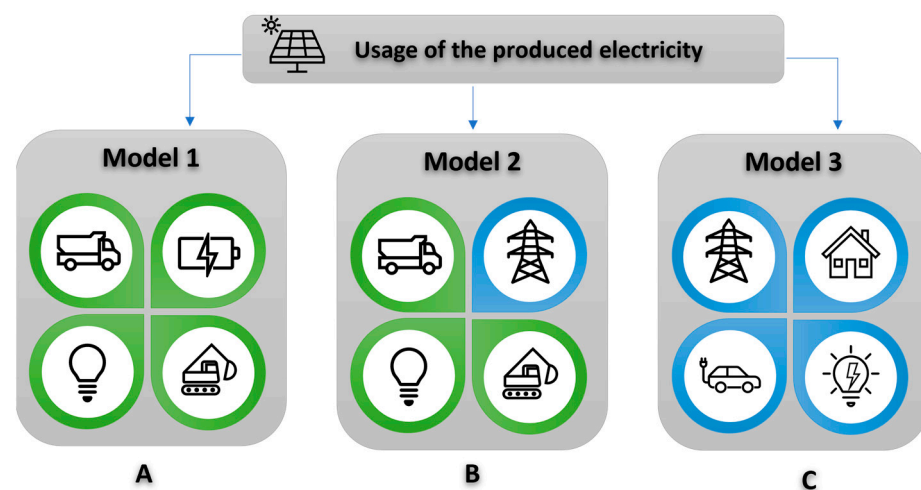


Figure 3. Models of electricity use: (A) Use of produced energy for the needs of surface mining, (B) Partial use of produced energy for the needs of surface mining, (C) Delivery of all produced energy to the electricity grid [12].

Figure 3 shows in green the amount of electricity used for work in the exploitation field, and in blue the amount of electricity delivered to the power grid for further distribution.

Within the exploitation fields that are in operation, the installation of solar panels would enable the production of electricity from renewable sources (solar energy) for own needs using Model 1 (Figure 3A). All electricity produced in this way can be used to supply mining facilities and plants in the mining process and for heating and lighting the employees' rooms. Also, it can be used for the purpose of reducing emissions of harmful gases (CO_x, NO_x, etc.) resulting from mining machinery, given that it is possible to use machinery equipped with an electric drive.

In Model 2 (Figure 3B), the electricity generated from solar power plants is used for mining and for heating and lighting the premises within the exploitation field. Depending on the required amount of electricity for the mining operations, part of the energy can be used, and the excess can be delivered to the electricity grid for further distribution. Electricity can also be used in inactive exploitation fields if the conversion of the space requires the need for electric energy.

Using Model 3 (Figure 3C), all electricity produced by solar power plants is delivered to the power grid. In this scenario, solar power plants would be installed on inactive or erased exploitation fields after mining activities have finished, and the area would be repurposed as a solar power plant location.

2.2. Spatial Data (GIS)

Sensitivity maps of spatial areas in the Republic of Croatia for the development of solar and wind power plants were created: Nature Sensitivity Map for Solar Power Plant Development and the Technical Suitability Map for Solar Power Plant Development [32]. These maps aim to provide guidelines for spatial planning and the development of future wind farms (WF) and solar power plants (SPP). The sensitivity of nature and technical suitability for non-integrated solar photovoltaic plants greater than 1 MW and wind power plants were considered.

2.2.1. Environmental Sensitivity of Mining Sites for the Installation of SPP

During the analysis and identification of suitable mining sites (MS) for the installation of SPP from the perspective of environmental sensitivity, the Nature Sensitivity Map for Solar Power Plant Development was used [32].

Assessment of environmental sensitivity is based on the integration of biological, habitat, and spatial protection data relevant to photovoltaic power plants. The datasets include observations of birds, bats, and large carnivores (including telemetry), habitat typology, and spatial data on protected areas and the Natura 2000 network. Species distribution is modelled using the Probabilistic Random Forest method, with data bias correction and the inclusion of additional criteria (key habitats, migration corridors, ecological barriers). The resulting species sensitivity areas are integrated using the maximum pixel value to maintain the conservativeness of the assessment. The final sensitivity map is produced by overlapping species sensitivities, habitats, protected areas, and the ecological network, with the final assessment defined as the arithmetic mean. Areas are then classified into five classes of relative sensitivity (1–6), from low risk to areas with the highest potential for conflict [33].

2.2.2. Technical Suitability of Mining Sites for the Installation of SPP

Technical suitability for installation of the SPP is determined by using Technical Suitability Map for Solar Power Plant Development that was developed for this purpose [32].

Technical suitability is determined by integrating three sets of criteria: natural potential (insolation), terrain configuration (slope, exposure, morphology), and the possibility of connecting to the electricity grid. For each criterion, a suitability raster (0–5) has been created, where a score of 0 automatically excludes the area due to technical infeasibility. The criteria are combined by applying weighting factors, resulting in a synthetic map of technical suitability. The results are interpreted at a pixel level of 100×100 m, with necessary subsequent spatial generalization to define actual project areas. Areas assessed as highly technically suitable (≥ 3) serve as a basis for overlaying with ecological sensitivity maps to identify optimal areas for the development of photovoltaic power plants [33].

Additional factor for installing the SPP on the MS is that the technical feasibility of installing solar panels within exploitation fields primarily depends on the type of mineral resource being mined (due to varying exploitation technologies) and the final open pit geometry. Within the scope of this study, given the land requirements for the installation of SPP, a detailed analysis of the predominant exploitation fields was carried out. The MS were selected based on their total size and accessibility, with an emphasis on spatial characteristics that allow for the installation of SPP.

According to data from the Ministry of Economy [31], there are more than 800 mining sites in the Republic of Croatia, which include active, inactive, and closed exploitation fields (Figure 4).

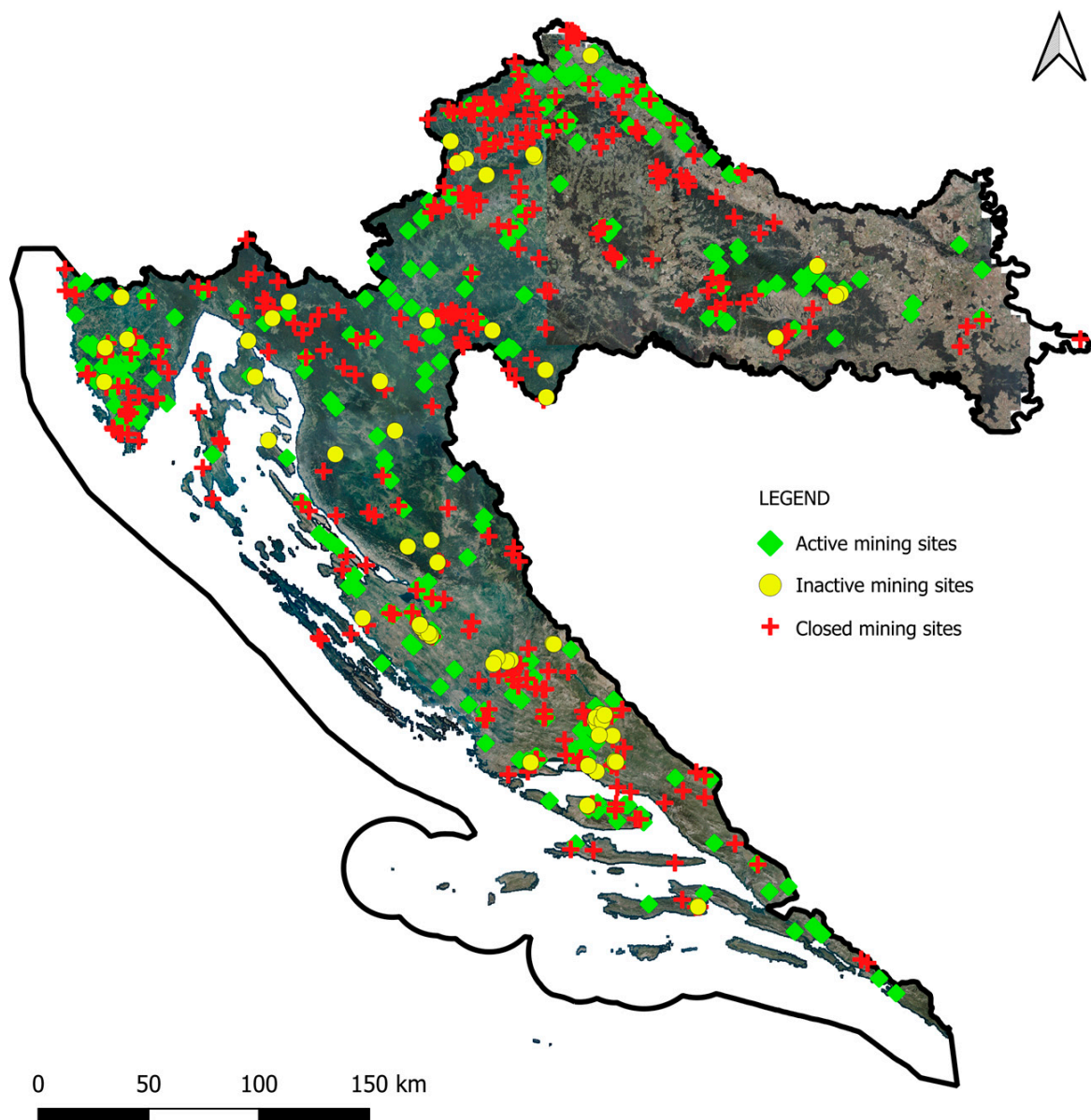


Figure 4. Overview of the mining sites in the Republic of Croatia.

Based on the specified requirements for SPP installation, the MS with the largest total surface area were selected [31]:

- Technical-building stone (TBS);
- Dimension stone (DS);
- Construction sand and gravel (CSG);
- Clay (including brick, bentonite, ceramic, refractory, and porcelain clay; CL).

The surfaces that can be used for the placement of solar panels and benches (berms) are created by the exploitation of technical-building stone, architectural-building stone, and clay (Figure 5a–c). The exploitation of these mineral reserves is carried out by drilling and blasting (technical-building stone), cutting out blocks with a chainsaw or diamond wire saw (architectural-building stone), or, in the case of clay mining, mechanized with excavators. When mining construction gravel and sand, floating excavators are used, and as a result, water surfaces (lakes) are created that are suitable for the installation of floating solar panels (Figure 5d).

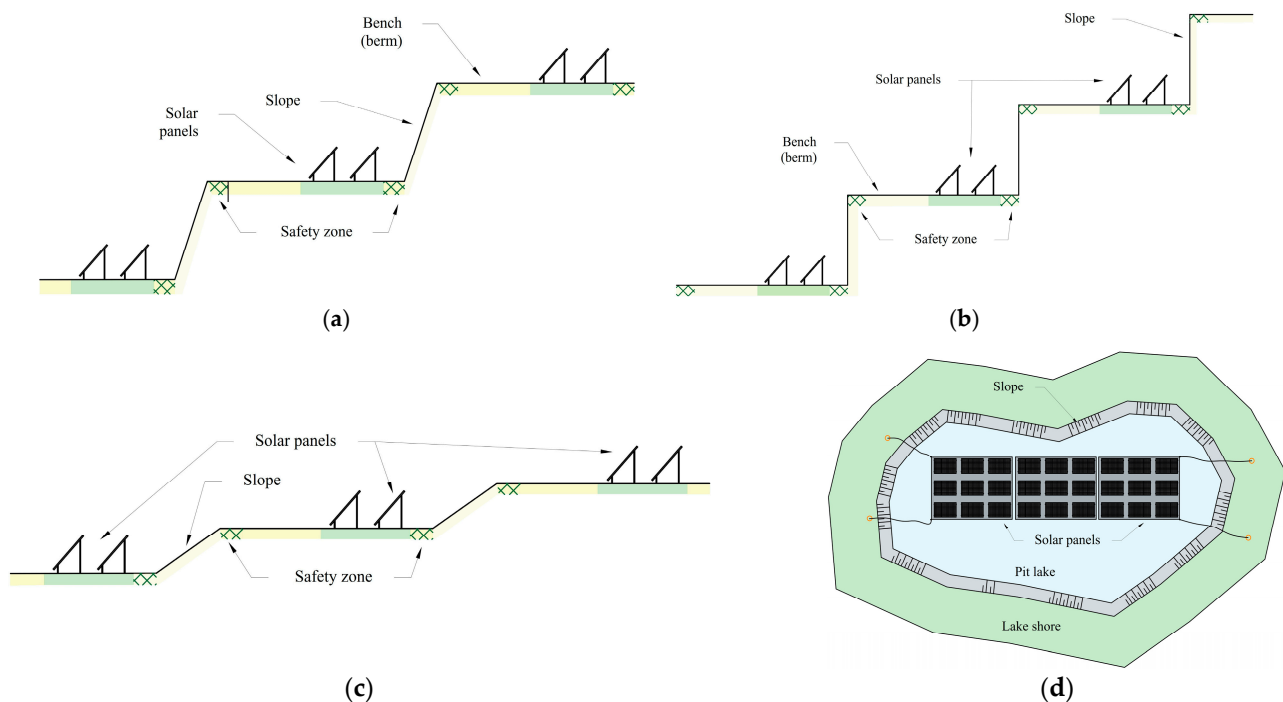


Figure 5. Possibility of placing SPPs depending on the geometry of open pit mines: (a) technical-building stone, (b) dimension stone, (c) clay, (d) construction sand and gravel [12].

2.3. Legislative Framework

Since potential locations for the installation of solar power plants are considered in areas where mining is or has been undertaken, the legislative framework of the Republic of Croatia in the fields of mining, spatial planning, construction, environment, and energy was analyzed. Figure 6 shows the mentioned legislative areas, highlighting the most important laws, regulations, and/or ordinances, as well as some of the documents or procedures that must be followed for obtaining the mining concession or installation of solar panels.

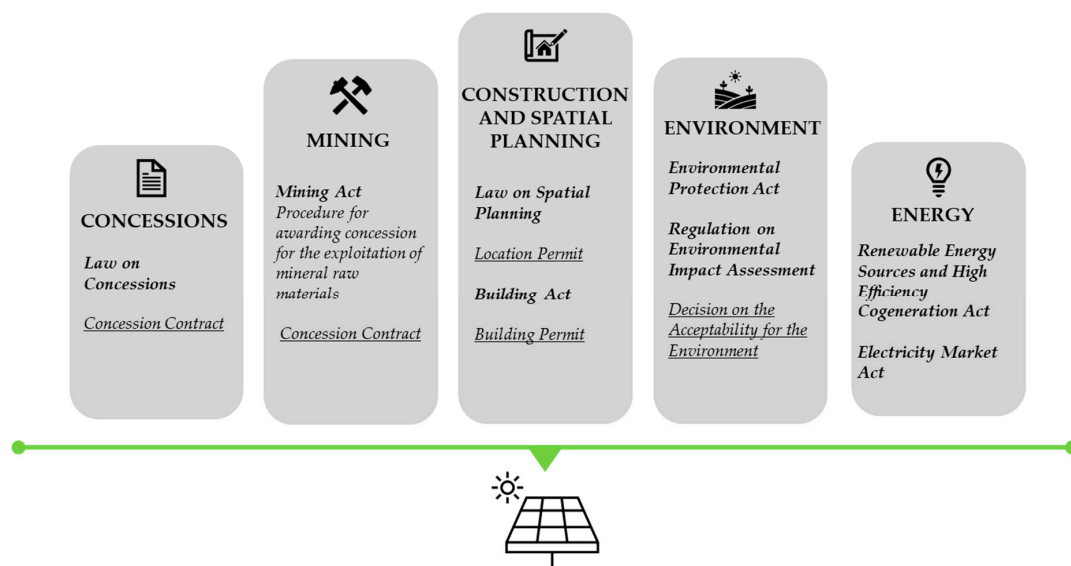


Figure 6. Legal provisions for the possibility of installing SPP [12].

Through the analysis of the separate legal provisions (Figure 6), a proposal was made for the necessary legal changes to agree on the possible multi-purpose use of open pit mines and to establish SPP.

2.4. MCDM Method for Selecting the SPP Site

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the MCDM (Multi-Criteria Decision-Making) methods used for selecting the best alternative among several options, which are evaluated based on multiple criteria [34].

The fundamental idea behind the TOPSIS method is that the selected alternative should have the smallest distance from the positive ideal solution (PIS) and the largest distance from the negative (anti) ideal solution (NIS) [34,35]. Considering the wide applicability of the TOPSIS method in various fields, as noted by the authors [36,37], the method has undergone numerous modifications and combinations with other MCDM approaches [38]. For selecting the optimal area for the installation of solar power plants in this study, the TOPSIS method was used [39].

Generally, the TOPSIS method follows two main steps and combines subjective assessment of criterion weights using the AHP method [40] and an objective mathematical model applied by the TOPSIS method [34]. The TOPSIS method is implemented through several steps, starting with the construction of a decision matrix and ending with the ranking of the selected alternatives [34,37–39].

Step 1: Creating the decision matrix (DM)

If the multi-criteria problem that needs to be solved contains n alternative solutions ($A_1, A_2, A_3, \dots, A_m$) and m criteria ($C_1, C_2, C_3, \dots, C_n$), an evaluation of all n alternatives according to m criteria is carried out, and a decision matrix $X(x_{ij}) = n \times m$ is constructed according to the following expression:

$$X = \begin{bmatrix} x_{11} & \dots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mn} \end{bmatrix} \quad (1)$$

For the expression $X(x_{ij}) = n \times m$, the following applies: $i = 1, 2, 3, \dots, m$; $j = 1, 2, 3, \dots, n$.

Step 2: Normalization of the decision matrix (NDM)

Through the process of normalization of criteria, which are often of different types and therefore expressed in different units, the criteria become dimensionless, making them comparable with one another. The normalized values r_{ij} for each x_{ij} from the decision matrix X are calculated according to expression (2).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (2)$$

For the vector-normalized matrix NDM according to expression (2), the following also applies: $i = 1, 2, 3, \dots, m$; $j = 1, 2, 3, \dots, n$, as in expression (1).

Step 3: Weighted normalized decision matrix (WNDM)

By applying the AHP method according to Saaty [40], weighting factors w_j were determined for each of the criteria ($C_1, C_2, C_3, \dots, C_n$) and added to the normalized decision matrix (NDM). According to Equation (3), the weighted normalized decision matrix (WNDM) was obtained.

$$V_{ij} = w_j \cdot r_{ij} \quad (3)$$

where terms are defined as follows:

V_{ij} —weighted decision matrix;

w_j —weighting factor;

r_{ij} —normalized decision matrix.

Equation (3) also applies $i = 1, 2, 3 \dots, m; j = 1, 2, 3 \dots, n$.

Step 4: Selection of the positive ideal solution (PIS) and the negative ideal solution (NIS)

The value of the positive ideal solution V^+ represents the best possible values from the matrix V_{ij} , while the worst values from the matrix V_{ij} represent the negative ideal solution V^- [38].

Positive ideal solution V^+ is determined by the following expression:

$$V^+ = \left\{ \left(\sum_i^{\max} V_{ij} / j \in J \right), \left(\sum_i^{\min} V_{ij} / j \in J' \right) / i = 1, 2, 3 \dots, m \right\}; V^+ = \{V_1^+, V_2^+, V_3^+ \dots V_n^+\} \quad (4)$$

The negative ideal solution V^- is determined by the following expression:

$$V^- = \left\{ \left(\sum_i^{\min} V_{ij} / j \in J \right), \left(\sum_i^{\max} V_{ij} / j \in J' \right) / i = 1, 2, 3 \dots, m \right\}; V^- = \{V_1^-, V_2^-, V_3^- \dots V_n^-\} \quad (5)$$

For both expressions, (4) and (5), the following applies:

J —beneficial criteria, i.e., criterion of useful type (see expression (6));

J' —non-beneficial criteria, i.e., criterion of cost type (see expression (7));

V_n^+ —value of PIS for n criteria;

V_n^- —value of NIS for n criteria.

$$J = (j = 1, 2, 3 \dots, n) / j \quad (6)$$

$$J' = (j = 1, 2, 3 \dots, n) / j \quad (7)$$

Step 5: Calculation of the distance from the positive ideal and negative ideal solutions

Given the basic concept of the TOPSIS method, as stated by Hwang et al. [34], the selected alternative should have the shortest distance from the positive ideal solution V^+ and the longest distance from the negative ideal solution V^- [34].

For each alternative ($A_1, A_2, A_3, \dots, A_m$) the Euclidean distances are calculated:

- Distance from the positive ideal solution S_i^+ (calculation according to expression (8));
- Distance from the negative ideal solution S_i^- (calculation according to expression (9)).

$$S_i^+ = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^+)^2}, \text{ where } i = 1, 2, 3 \dots, m \quad (8)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2}, \text{ where } i = 1, 2, 3 \dots, m \quad (9)$$

In expression (8), the value V_j^+ represents the positive ideal value for criterion j , and in expression (9), the value V_j^- denotes the negative ideal value for criterion j .

Step 6: Determining the relative distance from the ideal solution

The relative distance from the ideal solution R_i ranges in value between 0 and 1. The closer the value of R_i is to 1, the closer the alternative is to the ideal solution and the further it is from the worst solution. When the value of R_i approaches 0, the alternative is furthest from the ideal solution and closest to the worst solution. The value of the relative distance from the ideal solution is calculated according to the following equation:

$$R_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (10)$$

where terms are defined as follows:

$$\begin{aligned} S_i^+ &\geq 0; \\ S_i^- &\geq 0; \\ 0 &\leq R_i \leq 1. \end{aligned}$$

Step 7: Ranking the alternatives

The ranking of alternatives is conducted based on the value of R_i . The alternative that has the highest value of R_i (closest to 1) represents the best alternative, and in contrast, the alternative that has the smallest value of R_i (closest to 0) represents the worst alternative. The alternative that is ranked highest, i.e., has the highest R_i value, also represents the solution.

3. Results and Discussion

Based on previously conducted analyses, alternative options for locating solar power plants in open pit mines have been proposed, depending on the dynamics of mining operations (Variant 1, Variant 2, and Variant 3) and depending on electricity consumption (Model 1, Model 2, and Model 3). The analysis of legislative frameworks has provided suggestions for possible changes needed to enable the multi-purpose use of exploitation field areas. These changes would be implemented within the existing legislation. As a continuation for further detailed development, areas that would represent optimal locations for installing SPP within the mining sites have been proposed.

3.1. Proposal for Necessary Legal Amendments

Considering that the multi-purpose use of the space of mining sites requires the compliance of several legal acts and sub-acts covering different areas, some changes need to be made. For this to be possible, through legal legislation, it is necessary to clearly regulate the issues that arise when installing SPP in areas intended for mining [11].

First, it is necessary to harmonize the spatial planning documentation at the level of counties, cities, and municipalities, and legally enable the installation of SPP within the boundaries of both mining works and exploitation fields boundaries, if there are no spatial or technical obstacles for this. It is also crucial to resolve property–legal relations, because unresolved ownership issues often represent the biggest obstacle to the realization of projects. Furthermore, it is necessary to clearly define the authority for issuing building permits, i.e., setting up SPP within the boundaries of mining sites, whether they will be issued according to regulations in the field of construction or mining. It should also be noted that based on the extensive analysis conducted by Farkaš and Hrastov [11], the possibility of placing solar power plants was implemented in the new Spatial Planning Act [41] and the exploitation fields of solid mineral reserves and lakes created by exploitation are defined as areas for the construction of solar power plants.

Special attention should be paid to the installation of solar systems within the limits of confirmed reserves, that is, to consider the possibility of eliminating these areas within the exploitation field if the installation could affect the primary mining activity in such a way that the installation of SPP reduces the number of mineral reserves that can be mined. Additionally, any placement of SPP within mining sites needs to be processed through a mining project.

From an environmental protection perspective, if solar power plants are planned on mining sites for which an environmental impact assessment procedure has already been carried out, it is necessary to review the need for a repeat procedure or possibly carry out the procedure on a smaller scale. For future and inactive exploitation fields, the installation

and use of solar power plants should be separately processed within the framework of the environmental impact assessment procedure.

In the case of new spatial interventions, i.e., opening of new mining site, the installation of SPP within the boundaries of an open pit mine should be resolved in a single procedure in which the exploitation field will be determined and a concession for the exploitation of mineral reserves will be issued with all necessary documentation, which will also include the installed SPP. Finally, it is necessary to consider the obligation to conduct a tender for secondary activities, i.e., the installation of solar power plants on land for which a concession fee is already paid, to ensure transparency and equality of all market participants.

3.2. Optimal Areas for Locating Solar Power Plants

For the purposes of the analysis in this paper, the Nature Sensitivity Map for Solar Power Plant Development [32,33] was reclassified into four categories, such that the category in which a single nature element could have the highest level of sensitivity, and the category where at least all nature elements could have the highest level of sensitivity, were merged into one category. Table 2 shows the interpretation of the nature sensitivity categories, which was modified according to [33].

Table 2. Interpretation of the sensitivity of nature.

Category	Rating	Interpretation of the Category
Very high	1	Areas where all elements of nature have the highest or very high level of sensitivity. Very high or highest level of sensitivity.
High	2	An area where at least one element of nature may have the highest level of sensitivity, or several elements may have moderate or very high sensitivity. The potential for negative impact on nature is significant.
Moderate	3	An area in which individual elements of nature may have the highest individual rating of moderate or moderately high sensitivity. The area is sensitive to at least one element of nature and requires a more detailed analysis of each component of nature.
Low	4	An area where only one element of nature may have a low sensitivity rating, while the other elements have the lowest rating. No significant negative impact on nature is expected in this area.

The Technical Suitability Map for Solar Power Plant Development [32,33] was created by overlapping the following criteria: natural solar radiation potential, grid connection, and terrain configuration. The map was classified into four categories: marginally suitable area (low), suitable area (moderate), highly suitable area (high), and very highly suitable area (very high). Table 3 shows the interpretation of the technical suitability categories, adapted from [33].

Table 3. Interpretation of technical suitability.

Category	Rating	Interpretation of the Category
Low	1	An area with extremely poor, but not limiting, technical criteria for the development of renewable energy projects (RES). Solar power plants are not recommended for construction in this area.
Moderate	2	An area suitable for the development of RES projects, with certain expected technical challenges or impact on production.
High	3	An area suitable for the development of RES projects, with less expected technical challenges or impact on production.
Very high	4	Area with pronounced advantages for project implementation from the perspective of technical criteria.

This analysis exclusively covers locations where exploitation fields of mineral reserves (active, inactive, or closed) are located within the Republic of Croatia, where the following minerals are or have been mined: technical-building stone, dimension stone, construction gravel and sand, and clay (see Figure 4). These locations were then added to the previously mentioned maps. Mining sites are represented as points located at the centre of each field.

Figure 7 shows the reclassified maps, adapted from [33], with the depiction of the exploitation fields used in further analysis.

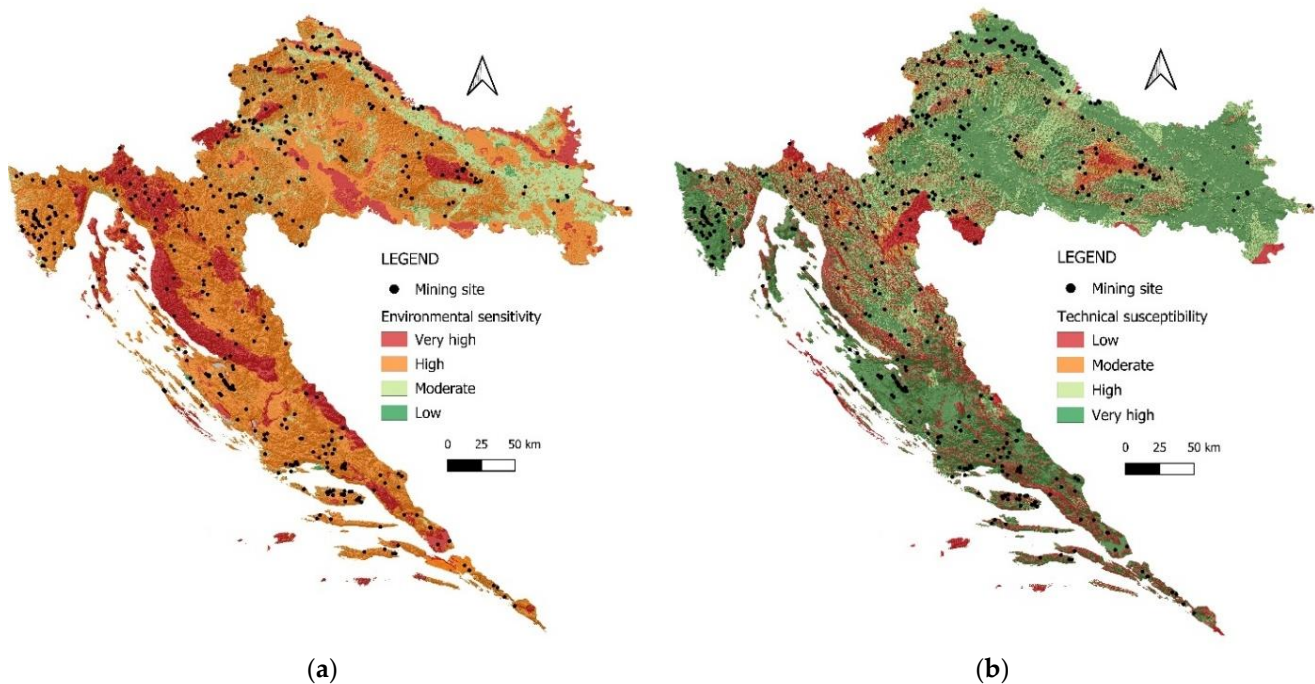


Figure 7. Republic of Croatia sensitivity maps for the development of solar and wind power plants: (a) Environmental sensitivity map, (b) Technical suitability map.

In order to obtain a unique map of the suitability of the area of the Republic of Croatia for SPP development (Figure 8), i.e., to single out the most suitable areas for the development of SPP, and taking into account the criterion of sensitivity of nature and technical advantages, the Nature Sensitivity Map for Solar Power Plant Development (Figure 7a) and the Technical Suitability Map for Solar Power Plant Development (Figure 7b) were overlapped (summarized), and the maps were assigned equal importance. The newly created Solar Power Plant Suitability Map is divided into four categories, of which the category 1 area (marked in red) is of low suitability for SPP accommodation, and the category 4 area (dark green) is of very high suitability. The newly created Solar Power Plant Suitability Map enables a spatially holistic assessment of suitability, ensuring that the evaluation incorporates both natural sensitivity and technical feasibility across the entire landscape. This map-based approach allows the identification and prioritization of zones with optimal characteristics for SPP development before considering individual mining sites in detail.

The evaluation of the categories (Table 4) was carried out using Tables 2 and 3. The potentially most favourable area (very high) for the installation of SPP includes high technical suitability (score 4) and an unfavourable impact on the environment (score 1). The high category includes a slightly less favourable environmental impact (score 2) but greater technical potential (score 3). The moderate category covers areas with lower technical potential (score 2) but also a lower environmental impact (score 3). The least suitable area

represents technically unsuitable areas for installing SPP (score 1), and therefore there are no negative impacts on the environment (score 4).

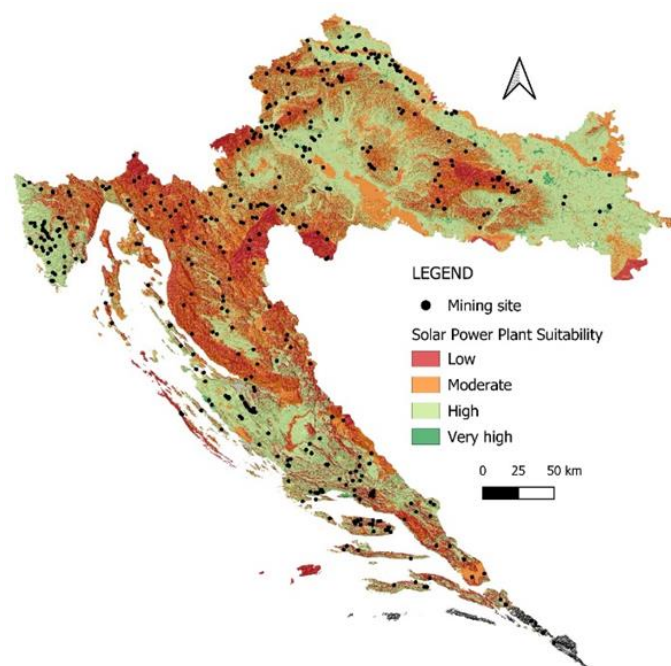


Figure 8. Solar Power Plant Suitability Map.

Table 4. Potential areas for SPP installation.

Category	Potential Area	Area, ha	Alternative (A)
Very high	Area A	5865.40	A1
High	Area B	265,334.80	A2
Moderate	Area C	173,751.50	A3
Low	Area D	119,341.00	A4

Based on the selected areas shown on the map (Figure 8, Table 4), three areas were selected as alternative solutions (A1, A2, and A3) which were considered in further analysis to select the optimal area for the placement of solar power plants on open pit mine sites. The category defined as the least favourable for the location of SPP (category low A4, Figure 8) was not considered as one of the alternative solutions or as a potential area for the location of the SPP. In this area, from the perspective of the sensitivity of nature (Table 2), the sensitivity level is very high or the highest, and from the point of view of technical suitability (Table 3), the construction of an SPP in this area is not recommended.

Based on the spatial data analysis, criteria were determined according to which the optimal area for the location of solar power plants on the surfaces of exploitation fields in the Republic of Croatia was selected. In total, the analysis included 565 exploitation fields of mineral reserves, detailed as follows:

- 267 exploitation fields of technical-building stone;
- 152 exploitation fields of dimension stone;
- 84 exploitation fields of construction sand and gravel;
- 62 exploitation fields of clay.

Figure 9 shows the distribution of mining sites by minerals exploited and the status of the exploitation field.

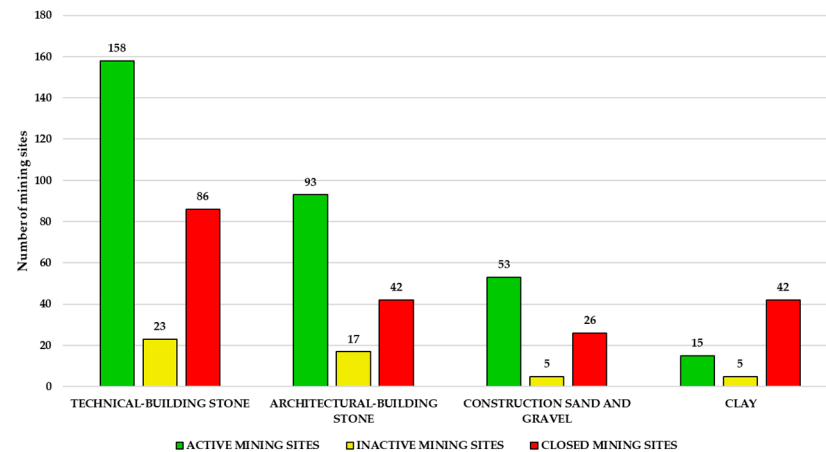


Figure 9. Distribution of mining sites by minerals exploited and activity.

Table 5 shows the criteria, a total of twenty of them labelled C1–C20, which were used to select the optimal area for placing solar power plants on open pit mine sites, and were selected based on the analyzed data (Figure 1).

Table 5. Criteria for selecting the optimal area.

Criteria	Criteria Mark	Value
Technical suitability	C1	– *
Environmental sensitivity	C2	– *
Number of MS depending on the surface area	C3	<25 ha
	C4	25–75 ha
	C5	75–100 ha
	C6	>100 ha
Number of MS depending on activity	C7	Active
	C8	Non-Active
	C9	Closed
MS number by type of mineral reserves	C10	TBS
	C11	DS
	C12	CSG
	C13	CL
Use of electricity	C14	Full use of electricity for mining operations
	C15	Partial use of electricity
	C16	Delivery of electricity for further distribution
Law provisions	C17	Recognized placement of SPP on MS
	C18	SPP placement on MS not recognized
Property and legal relations	C19	Resolved property and legal relations
	C20	Unresolved property and legal relations

* Criteria C1 and C2 were assigned values based on the categories shown in Tables 2 and 3. The ratings are summarized in Table 6.

Table 6. Ratings of technical suitability criteria C1 and nature sensitivity C2.

Criteria	Ratings for Categories			
	Low	Moderate	High	Very High
Technical suitability	1	2	3	4
Environmental sensitivity	4	3	2	1

A certain value was assigned to each criterion from Table 5 (area, open pit mine activity, mineral reserves, etc.) and the number of exploitation fields in each of the potential areas was analyzed (Table 4). By determining the number of exploitation fields, using a GIS system, for each of the criteria from Table 5, and within the three separate areas, a decision matrix was created, which is shown in Table 7.

Table 7. Decision matrix (DM).

A	Criteria for Optimal Area Selection																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	4	4	11	1	0	0	7	1	4	4	6	1	1	7	8	5	8	12	8	4
A2	3	3	225	58	4	5	188	23	81	114	97	49	32	188	211	104	211	292	211	81
A3	2	3	11	1	0	0	63	13	63	77	15	26	21	63	76	76	76	139	76	63

To determine the ideal area between the three offered or defined alternatives (A1, A2 and A3), the decision matrix (see Table 7) is normalized and the specified data for each criterion becomes dimensionless, which enables their mutual comparison. The normalized matrix NDM is presented in Table 8.

Table 8. Normalized decision matrix NDM.

A	Criteria for Optimal Area Selection																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	0.74	0.69	0.05	0.02	0.00	0.00	0.04	0.04	0.04	0.03	0.06	0.02	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
A2	0.56	0.51	1.00	1.00	1.00	1.00	0.95	0.87	0.79	0.83	0.99	0.88	0.84	0.95	0.94	0.81	0.94	0.90	0.94	0.79
A3	0.37	0.51	0.05	0.02	0.00	0.00	0.32	0.49	0.61	0.56	0.15	0.47	0.55	0.32	0.34	0.59	0.34	0.43	0.34	0.61

The next step is to assign weighting factors W to each of the criteria and create a weighted decision matrix WNDM. The weighting factors were determined using the AHP method [40]. Table 9 shows the calculated weighting factors for each of the criteria.

Table 9. Weighting factors.

Criteria	Criteria Mark	Weighting Factor, W
Technical suitability	C1	0.34
Environmental sensitivity	C2	0.42
Number of MS depending on the surface area	C3	0.08
	C4	0.38
	C5	0.39
	C6	0.15
Number of MS depending on activity	C7	0.07
	C8	0.51
	C9	0.42
MS number by type of mineral reserves	C10	0.22
	C11	0.19
	C12	0.50
	C13	0.09
Use of electricity	C14	0.26
	C15	0.41
	C16	0.33
Law provisions	C17	0.88
	C18	0.13
Property and legal relations	C19	0.88
	C20	0.13

As can be seen from Table 9, criteria C17 (recognized placement of SPP on MS) and C19 (resolved property and legal relations) have the highest weighting factors at 0.88. In real-world scenarios, clearly defined property rights and legal clarity are essential. If ownership or usage rights are not properly established, and placement is not defined, even well-designed and environmentally sound projects can experience significant delays or be cancelled altogether. Criteria C17 and C19 are therefore considered the most important, as resolving property and legal relations for the cadastral parcels planned for SPP installation, along with harmonizing legal provisions, helps accelerate and simplify the entire process. The following represent the second most dominant factors: criterion C8 (inactive mining sites) with a value of 0.51, and criterion C12 (exploitation fields of construction sand and gravel), whose weighting factor is 0.50. Inactive mining sites (criterion C8) represent extremely suitable areas for the installation of SPP, given that, in accordance with legal legislation, they need to be rehabilitated and repurposed, and exploitation fields of construction gravel and sand (criterion C12) are suitable for the installation of floating SPP, the installation of which is relatively simple compared to the others. The smallest amount of the weight factor was added to criterion C7, active exploitation fields, and is 0.07. The installation of SPP in active exploitation fields requires their constant relocation depending on the dynamics of surface mining, which can additionally affect the dynamics of mining works and cause additional costs, given that it is not a primary activity.

Using the weighting factors shown in Table 9, a weighted normalized decision matrix WNDM was created, which is shown in Table 10.

Table 10. Weighted normalized decision matrix WNDM.

A	Criteria for Optimal Area Selection																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	0.26	0.29	0.004	0.01	0.00	0.00	0.00	0.02	0.02	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.03	0.00	0.03	0.00
A2	0.19	0.22	0.08	0.38	0.39	0.15	0.07	0.44	0.33	0.18	0.19	0.44	0.08	0.25	0.25	0.26	0.82	0.11	0.82	0.10
A3	0.13	0.22	0.004	0.01	0.0	0.00	0.02	0.25	0.26	0.12	0.03	0.23	0.05	0.08	0.09	0.19	0.30	0.05	0.30	0.08

To determine the PIS and NIS values, each of the criteria for selecting the optimal area for the location of solar power plants is characterized as follows:

- Benefit type criterion (Benefit, mark B);
- Cost type criterion (Cost, mark C).

Table 11 shows the type (Benefit/Cost) of each criterion.

A total of fourteen criteria, out of twenty, were determined as beneficial criteria. The remaining six criteria (C2, C3, C9, C13, C18, and C20) were determined as cost criteria. Criterion C2, which refers to the sensitivity of nature when implementing any interventions in the area, requires additional investment of material resources in environmental protection as well as adherence to strict nature protection measures. The next cost criterion C3 represents exploitation fields with an area of less than 25 ha; it was not considered as useful given that a large number of exploitation fields in this group have an area of less than even 1 ha, which is not sufficient for a profitable installation of SPP. Criterion C9, or eraser exploitation fields, were also determined as costs given that such fields are most often rehabilitated or have already been repurposed. The last cost criterion is C13, or exploitation fields of clay, which with its properties (swelling, high plasticity, etc.) is not suitable for long-term installation of SPP. Criteria C18 and C20 are marked as cost criteria considering that their solution is often time-consuming and requires a lot of investment.

For the positive ideal solution, the maximum values were selected if the criterion was defined as beneficial (Benefit), or the minimum values if the criterion was defined as a cost criterion (Cost). When selecting the negative ideal solution, the maximum values

were selected in the case when the criterion was defined as a cost criterion (Cost), and the minimum values when the criterion was defined as a beneficial criterion (Benefit). The selected values of the positive ideal solution PIS and the negative ideal solution NIS are shown in Table 12.

Table 11. Criteria type.

Criteria	Criteria Mark	Type (Benefit/Cost)
Technical suitability	C1	B
Environmental sensitivity	C2	C
Number of MS depending on the surface area	C3	C
	C4	B
	C5	B
	C6	B
Number of MS depending on activity	C7	B
	C8	B
	C9	C
MS number by type of mineral reserves	C10	B
	C11	B
	C12	B
	C13	C
Use of electricity	C14	B
	C15	B
	C16	B
Law provisions	C17	B
	C18	C
Property and legal relations	C19	B
	C20	C

Table 12. Selection of positive and negative ideal solutions.

Solution	Criteria for Optimal Area Selection																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
PIS	0.26	0.22	0.00	0.38	0.39	0.15	0.07	0.44	0.02	0.18	0.19	0.44	0.00	0.25	0.25	0.26	0.82	0.11	0.82	0.10
NIS	0.13	0.29	0.08	0.00	0.00	0.00	0.00	0.02	0.33	0.01	0.01	0.00	0.08	0.01	0.01	0.01	0.03	0.00	0.03	0.00

Values for determining PIS and NIS (Table 12) are determined from the weighted normalized decision matrix WNDM (Table 11).

Using the Euclidean distance and according to expressions (8) and (9), the distance between each alternative and the positive ideal solution (Table 13) and negative ideal solution (Table 14) was calculated.

Table 13. Distance from the positive ideal solution S_i^+

A	Criteria for Optimal Area Selection																				S_i^+
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	
A1	0.00	0.01	0.00	0.14	0.15	0.02	0.00	0.18	0.00	0.03	0.03	0.19	0.00	0.06	0.06	0.06	0.63	0.01	0.63	0.01	1.48
A2	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.20	0.10	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56
A3	0.02	0.00	0.00	0.14	0.15	0.02	0.00	0.04	0.06	0.00	0.02	0.04	0.00	0.03	0.02	0.01	0.28	0.00	0.28	0.00	1.06

Table 14. Distance from the negative ideal solution S_i^-

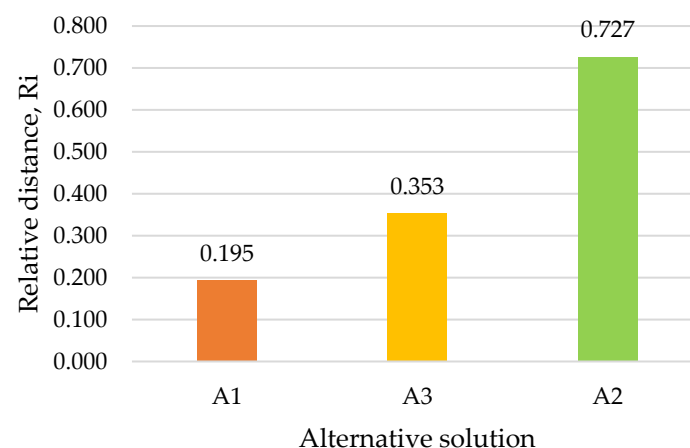
A	Criteria for Optimal Area Selection																				S_i^-
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	
A1	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36
A2	0.00	0.01	0.00	0.14	0.15	0.02	0.00	0.18	0.00	0.03	0.03	0.19	0.00	0.06	0.06	0.06	0.63	0.01	0.63	0.01	1.49
A3	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.05	0.01	0.01	0.00	0.05	0.00	0.01	0.01	0.03	0.07	0.00	0.07	0.01	0.58

From the data presented in Tables 13 and 14, it is evident that alternative A1 has the greatest distance from the positive ideal solution (PIS) which is 1.48 and the distance from the negative ideal solution (NIS) is 0.36. Alternative A2 is closest to the positive ideal solution (0.56) and is the furthest from the negative ideal solution (1.49). A3, as the third alternative, is 1.06 away from PIS and 0.58 away from NIS.

The relative distance from the ideal solution R_i , i.e., the distance from the optimal area for placing SPP, is shown in Table 15. The ranked alternatives are shown graphically in Figure 10.

Table 15. Relative distance from the optimal area for SPP placement.

Alternative Solution	Potential Area	Relative Distance
A1	Area A	0.195
A2	Area B	0.727
A3	Area C	0.353

**Figure 10.** Alternative solutions for selecting the optimal area.

Regarding the calculated values of the relative distance R_i (Table 15), Area A with a relative distance of 0.195 was determined as the most unfavourable area. Area C has a relative distance value of 0.353 and is ranked second. Area B has been determined as the optimal area for the placement of solar power plants. The amount of relative distance for that area is 0.727.

Area B stands out as the most suitable region for the installation of solar power plants, based on its relative distance value and balanced scores across technical and environmental criteria. Geographically, Area B encompasses regions characterized by a moderate climate and favourable topography, typically found in the central and eastern parts of Croatia, although the coastal areas have the most prominent levels of insolation.

Within Area B, mining is predominantly focused on technical-building stone and dimension stone, which are among the most frequently exploited resources in Croatia. The predominance of technical-building stone and dimension stone extraction creates large,

open mining sites that are particularly well-suited for the development of SPP due to their minimal vegetation cover and ease of access.

In terms of average size, mining sites in Area B are typically medium to large, often ranging from 25 to 75 hectares. This size range allows for significant solar panel installations while still accommodating ongoing or future mining operations. The relatively generous spatial availability, combined with resolved property–legal relations and technical suitability, ensures that these sites offer both immediate and long-term potential for SPP installation.

4. Conclusions

Multipurpose use of the space of exploitation fields, for the primary purpose, i.e., exploitation of mineral reserves, and the secondary purpose of installing solar power plants, represents an integral method of space management that the current legislation of the Republic of Croatia only partially recognizes.

The results of the analysis conducted as part of this work indicate the enormous potential of exploitation fields in the territory of the Republic of Croatia, i.e., their multi-purpose use. Thus, in addition to the primary mining activity, the approach simultaneously increases the share of renewable energy sources in total production, reduces greenhouse gas emissions, and promotes more rational space management.

By analyzing the current number of exploitation fields (active, inactive, and erased) and by extracting the most frequently exploited mineral reserves, variant solutions were proposed:

- Depending on the dynamics of mineral resource exploitation (Variant 1, Variant 2, and Variant 3);
- Depending on the use of produced energy (Model 1, Model 2, and Model 3).

Using the GIS–MCDM model, optimal areas suitable for the location of solar power plants were determined, with key criteria being technical suitability, sensitivity of nature, legal possibilities, and resolved property–legal relations. Area B was identified as the most favourable area for development, as it shows the best balance between environmental and technical requirements.

The installation of SPP on open pit mines contributes to reducing dependence on fossil fuels and increases the energy security of concessionaires, while at the same time reducing the costs of mining. The implementation of such solutions requires the harmonization of the legislative framework, especially in the part related to spatial planning, concessions, and environmental protection.

In the long term, the multi-purpose use of mining sites for solar power plants can become an important segment of Croatia's energy transition and green policy. To assess economic viability, it is necessary to conduct analyses that will determine, e.g., the specific costs of installing and maintaining such systems in open pit mines. Also, in further research, factors such as the lifespan of solar power plants, their removal and recycling should be included in the analyses to avoid negative environmental impacts and to achieve sustainable management of such interventions. Addressing these aspects ensures sustainable management and minimizes environmental impact. Further research should also provide detailed cost–benefit analyses, including upfront investment, operating and maintenance costs, estimated energy output, payback periods, and possible financial incentives or subsidies. Including these metrics would offer a more comprehensive understanding of the economic prospects and long-term benefits of integrating solar power plants into mining operations, thus supporting better strategic decision-making.

Realizing the multi-purpose use of open pit mines for the installation of SPP hinges on the implementation of targeted legislative amendments. These changes should focus on harmonizing existing mining sector regulations with the evolving requirements of

renewable energy development. Attention must be given to clarifying provisions related to spatial planning, concession allocation procedures, and environmental safeguards. Only through such necessary legal reforms can Croatia unlock the full potential of integrating mineral exploitation with solar energy generation on mining sites, thereby advancing towards a more sustainable and resilient energy future.

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Abbreviations

The following abbreviations are used in this manuscript:

DS	Dimension stone
CL	Clay
CSG	Construction sand and gravel
DM	Decision Matrix
MOE	Ministry of Economy
MS	Mining sites
NDM	Normalized Decision Matrix
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
RES	Renewable energy sources
SPP	Solar power plants
TBS	Technical-building stone
WF	Wind farms
WNDM	Weighted Normalized Decision Matrix

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