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# Aligning Post-Mining and Post-Quarrying Land-Use Decisions with Spatial Planning: The Case of Western Macedonia, Greece

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**Abstract**

Spatial planning plays a key role in sustainable resource management, particularly in mining and quarrying areas where post-extractive land-use decisions must balance environmental, regulatory, and social considerations. Taking Western Macedonia, Greece, as a case study, the objective of this research is to support sustainable regional development transition by proposing a decision-support framework for post-mining land-use planning that integrates spatial planning objectives, stakeholder perspectives, and land-use governance. The proposed methodology combines complementary decision-support tools to evaluate and prioritize alternative post-mining land uses. Integration Definition for Function Modelling is used to structure and visualize the decision-making process. Strengths–Weaknesses–Opportunities–Threats analysis identifies site-specific internal and external factors, the Analytic Hierarchy Process ranks land-use alternatives based on weighted evaluation criteria, and Force Field Analysis assesses the driving and restraining forces affecting the practical implementation of each option. This integrated framework supports both the technical assessment of alternatives and the evaluation of implementation feasibility. The results indicate a significant divergence between expert-based rankings and stakeholder preferences. Although the Analytic Hierarchy Process identifies recreation parks for quarries and waste-to-energy facilities for mines as the most suitable technical options, Force Field Analysis reveals important barriers related to social acceptance and economic feasibility. The findings demonstrate that technically optimal land uses may not always be socially or institutionally feasible. Therefore, post-mining land-use planning should adopt integrated, transparent, and participatory approaches that combine technical evaluation with stakeholder engagement to achieve sustainable and implementable outcomes.

**Keywords:** analytical hierarchy process; AHP; force field analysis; FFA; integration definition for function modelling; IDEF0; multicriteria decisions; SWOT analysis; transition

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## 1. Introduction

Land-use planning is a critical component of the sustainable management of post-mining and -quarrying landscapes, as the selection of appropriate land uses determines the social, economic, and environmental trajectory of regions historically dependent on mineral extraction and affected by significant environmental degradation. Regardless of the restoration approach adopted, the most important outcome is the avoidance of land abandonment.

The restoration and redevelopment of degraded mining areas can prevent further deterioration of local economic conditions while limiting additional environmental degradation,

which may in some cases be irreversible. Traditionally, mine and quarry rehabilitation focused on improving landscape aesthetics through slope regrading, tree planting, and, where necessary, soil and water remediation, aiming to restore the original ecosystem or establish an alternative stable one. More recently, however, diversified and multifunctional land-use strategies have emerged, supporting the transition of mining-dependent areas toward new socio-economic development models capable of sustaining long-term growth while reducing environmental pressures.

In this context, integrated interventions increasingly emphasize remediation, restoration, reclamation, rehabilitation, repurposing, and co-purposing of degraded lands and abandoned facilities [1]. Abandoned industrial infrastructure, for example, may be valorised as industrial heritage through tourism, while renewable energy installations in exhausted mines may preserve the energy-related identity of former mining regions and reduce their environmental footprint. Such approaches strengthen local resilience by fostering entrepreneurship, reducing adverse impacts, and reintegrating disturbed land into the surrounding landscape.

Strategic management constitutes a fundamental dimension of spatial planning, particularly in mining regions such as coal and lignite areas undergoing energy transition, where economic and territorial restructuring creates complex development challenges. In these contexts, it enables the synchronization of long-term development objectives, land-use priorities and institutional regulations, ensuring a more coherent and adaptive planning process. Spatial planning therefore functions as a governance framework that must simultaneously address environmental restoration, economic diversification, social cohesion, and climate policy objectives through integrated and flexible approaches [2,3]. This strategic role is particularly important in post-mining areas, where competing land-use demands and governance challenges require evidence-based planning to reduce conflicts and enhance regional resilience [4,5]. The integration of strategic management principles also strengthens institutional capacity to support sustainable redevelopment pathways in former mining regions [6,7]. At the same time, contemporary planning approaches highlight the importance of environmental justice and socially inclusive adaptation measures, ensuring that vulnerable communities affected by economic and climate transitions are not excluded from redevelopment strategies [8]. Landscape-based planning further demonstrates that strategic management is essential for balancing renewable energy development with environmental protection and territorial cohesion in post-extractive regions [9].

Achieving these objectives presupposes the lawful operation of mining and quarrying activities through proper licensing procedures. Legally authorized operations must comply with regulations ensuring rational exploitation and rehabilitation after extraction ceases, while systematic inspections by competent authorities are required to ensure the effective implementation of rehabilitation plans.

A wide range of MCDM approaches have been employed in the international literature, differing in terms of ranking logic, methodological steps, and underlying conceptual frameworks. Among the most commonly applied standalone methods are: Cost–Benefit Analysis [10], SWOT analysis [11–13], Internal–External (IE) matrix [11], Analytic Hierarchy Process (AHP) [13–21], Linear Programming (LP) [14], SMART [14], Boolean logic and fuzzy sets [15], TOPSIS [15,18], ELECTRE [17], Simple Additive Weighting (SAW) [18], PROMETHEE [19], Improved Analytic Hierarchy Process (IAHP) [22], Analytic Network Process (ANP) [23], fuzzy logic [24], Fuzzy Cognitive Maps (FCM) [25], Fuzzy Inference Systems (FIS) [25], Fuzzy Analytical Network Process (FANP) [25], Geographic Information Systems (GIS) [26,27], IDEF0 [28], SIMUS [29], and SMARTER [29]. In addition to these methods, hybrid approaches have been widely adopted, combining two or more techniques to improve decision-making performance and reduce uncertainty Goepel [11,13,14,22,23,29].

### *1.1. Post-Mining Land-Use Practices in Western Macedonia (Greece): Current Situation*

In Western Macedonia, the cessation of extraction activities was historically associated with abandonment, with limited rehabilitation measures implemented. The introduction of Greek environmental legislation, particularly framework law 1650/1986 and Joint Ministerial Decision (JMD) 69269/1990, established the legal obligation for environmental restoration and permitting procedures [30,31].

Since then, the management of exhausted mining and quarrying sites has focused mainly on remediation, restoration, and reclamation, with dominant post-mining land uses including forestry, agriculture, and livestock farming. A major example is the reclamation of the asbestos mine of Hellenic Asbestos Mines (MABE) in Zidani, Kozani, where four large-scale reclamation projects were implemented between 2003 and 2019 with a total cost of approximately EUR 42 million [32,33]. Despite such efforts, several abandoned small-scale surface mines remain unregistered due to legislative gaps that existed in the past and a lack of financial resources to implement rehabilitation projects under the public authorities' supervision.

For active mining operations, approved Environmental Impact Assessment (EIA) studies define site-specific rehabilitation plans, but the land-use criteria adopted mainly emphasize environmental and technical parameters, while typical post-mining land uses remain limited to agriculture, forestry, and waste disposal [34–37]. Similar practices are observed in an abandoned lignite mine [38], aggregate quarries [39–43], marble quarries [44–46], quartz quarries [47,48], and an attapulgite quarry [49], where rehabilitation programs are included in EIAs but generally prioritize environmental, technical, and economic considerations, with only a few examples of successful repurposing land uses, such as open-air theatres or municipal support facilities.

### *1.2. Emerging Challenges Under Rapid Energy Transition*

Historically, rehabilitation in the region was based mainly on ecological restoration, leading to land uses such as forestry, agriculture, and livestock farming [50]. More recently, however, approaches such as land repurposing, landscape restructuring, and co-purposing have emerged, allowing the introduction of new land uses not necessarily linked to the former productive profile of mining areas [51–53].

Moreover, the accelerated energy transition and lignite phase-out have increased the urgency of identifying realistic, socially accepted, and economically viable land-use alternatives [54,55]. Nevertheless, despite the extensive focus on lignite mine closure planning, the methodological evaluation of alternative land uses across different extractive activity types (lignite mines, metal mines, and quarries) remains limited. In addition, decision-making practices often rely on fragmented criteria sets, focusing primarily on environmental or technical parameters, while social acceptance, cultural identity, ethical considerations, and long-term economic resilience are not always systematically integrated into the evaluation process.

### *1.3. Research Aim and Research Questions*

This study proposes a structured and transferable multicriteria methodological framework for post-mining and quarrying land-use selection, designed to support sustainable spatial planning under conditions of rapid socio-economic transition. The proposed methodology integrates economic, social, cultural, environmental, technical, locational, ethical, governmental, and regional criteria into a unified evaluation process, enabling the systematic comparison of alternative land-use scenarios across different types of extractive sites. By providing a transparent and reproducible decision-support approach, the framework aims to reduce subjectivity in land-use planning, enhance stakeholder participation,

and improve the robustness of post-mining and quarrying redevelopment strategies. The methodological approach of this study is expected to support policymakers, local authorities, and mining and quarrying operators in prioritizing feasible and socially acceptable land uses while strengthening regional resilience and sustainability in Western Macedonia and other mining- and quarrying-dependent regions facing similar transition pressures.

To fulfil this aim, the study addresses the following research questions:

RQ1: How can an integrated multicriteria methodological framework support the systematic evaluation and prioritization of alternative land uses in post-mining and quarrying areas undergoing socio-economic transition?

RQ2: To what extent do the technically optimal land-use options identified through the Analytic Hierarchy Process (AHP) correspond to the practically feasible and socially acceptable options identified through Force Field Analysis (FFA)?

RQ3: Which economic, environmental, governance, and social criteria have the greatest influence on the prioritization of alternative land uses in inactive quarries, metal mines, and lignite mines?

RQ4: How do stakeholder perceptions, implementation barriers, and institutional constraints affect the final selection and feasibility of post-mining land uses?

RQ5: To what extent can the proposed methodological framework serve as a transferable decision-support tool for sustainable land-use planning in Western Macedonia and in other extractive regions undergoing transition?

## 2. Method

Selecting land uses for inactive or abandoned quarries, as well as metal and lignite mines (post-mining land uses—PMLUs), necessitates the precise determination of evaluation criteria for the proposed alternative land uses. This process involves integrating multicriteria decision-making methods and software to provide a qualitative and quantitative assessment, ultimately facilitating the selection of optimal uses.

Rather than introducing new decision-making techniques, the methodological contribution of this study lies in the purposeful integration of established methods into a coherent hybrid framework capable of addressing the complexity of post-mining land-use selection. As already mentioned, recent studies in multicriteria decision-making increasingly adopt hybrid methodological schemes. Following this rationale, the present framework combines IDEF0, SWOT, AHP, and FFA in a sequential and functionally interlinked structure, where each method supports a distinct stage of the decision-making process. This hybridization enhances the applicability of the framework to the Greek post-mining context, where land-use decisions require the consideration of strategic planning priorities, expert judgement, and stakeholder acceptance.

The sequence of methods was designed so that each analytical step informs the next one, creating a cumulative evaluation process in which qualitative diagnosis, quantitative prioritization, and implementation feasibility are progressively integrated into the final land-use selection. A combination of the following methods is proposed:

(i) IDEF0 method for process modelling and graphical representation: The IDEF0 method was employed to model the overall decision-making process and to provide its structured graphical representation, enabling the systematic depiction of inputs, outputs, controls, and mechanisms involved in post-mining land-use selection.

(ii) SWOT analysis for screening land uses based on region-specific characteristics: A SWOT analysis was applied to identify the main strengths and weaknesses of quarries, metal mines, and lignite mines, derived from their internal environment, as well as the opportunities and threats emerging from the external environment.

(iii) Analytic Hierarchy Process (AHP) for land-use ranking: The Analytic Hierarchy Process (AHP) method [56] was selected in order to determine the weight of the criteria used for land-use selection in quarries and metal and lignite mines after closure. The pairwise comparative evaluation of the criteria required by the method was conducted by an interdisciplinary group of ten experts, including professionals specialized in Mineral Resources Engineering (2), Environmental Engineering (2), Spatial Planning and Development, Mechanical Engineering, Civil Engineering, Architecture, Surveying Engineering, and Geotechnology. The number of participants was considered adequate for an AHP application, where the emphasis is placed on the expertise and relevance of respondents rather than on large sample sizes. In addition, as with all expert-based multicriteria methods, the weighting process may be influenced by subjective judgment and potential biases related to the experts' professional backgrounds, experiences, and institutional perspectives. To mitigate this limitation, the expert panel was composed of participants from diverse fields, allowing multiple perspectives to be incorporated into the weighting process. Although this approach enhances the robustness of the analysis, the resulting weights should still be interpreted as informed expert judgments rather than objective values. This limitation does not undermine the usefulness of the AHP framework as a transparent and systematic tool for prioritizing land-use criteria. Nevertheless, to ensure consistency, the individual judgments were checked through the consensus index before aggregation.

(iv) The Analytic Hierarchy Process (AHP) was employed to evaluate and prioritize the selected criteria and sub-criteria for post-mining land-use selection. The assessment was performed through pairwise comparisons conducted by a working group and a panel of experts, who compared the criteria according to their relative importance [56]. In each comparison, preferences were quantified using Saaty's fundamental 1–9 numerical scale, ranging from 1 (equal importance) to 9 (extreme importance). The consolidated criteria weights representing the entire panel were calculated using the weighted geometric mean of the individual responses. Due to the large size of the resulting matrix and the increased consistency requirements (45 pairwise comparisons), a standard algorithmic optimization method was applied to minimally adjust the values. This mathematical refinement ensured that the final Consistency Ratio (CR) fell strictly below the acceptable threshold of 0.10 without altering the qualitative direction of the experts' judgments. These finalized weights were subsequently utilized to calculate the performance scores of the alternative land-use options.

(v) Force Field Analysis (FFA) for land-use selection: Force Field Analysis (FFA) was employed to systematically examine the key factors that may facilitate or hinder the implementation of the proposed post-mining land-use alternatives. The method distinguishes between driving forces (supporting implementation) and restraining forces (limiting implementation), providing a clear overview of the main advantages and barriers associated with each alternative. In this study, FFA was applied to the seven (7) proposed land-use options considered for exhausted quarries and mines in Western Macedonia. For each land-use option, driving and restraining forces were identified, and stakeholder representatives evaluated their influence using a $-5 \rightarrow +5$ rating scale where 1 refers to minimum impact, and 5 represents maximum impact. For the evaluation of land uses through Force Field Analysis, a sample of 15 participants was selected to accurately capture local trends. The group consists of residents from four villages located near industrial activities (one near a quarry, one near a mine, and two near lignite mines), as well as six individuals from Kozani and five from Ptolemaida. Although these participants do not work in these industries, they experience their daily effects. To ensure a diversity of perspectives, the group includes individuals

from various educational backgrounds (secondary, technical, and higher education) and different professions, such as farmers, self-employed professionals, private sector employees, and scientists. Because of this profile, they are able to objectively evaluate which land uses will best support the future growth and development of their region. The results of the FFA supported the comparative interpretation of the alternatives by highlighting their practical feasibility and implementation challenges.

### *2.1. The IDEF0 Method*

IDEF0 is a process modelling method that provides a structured theoretical representation of real-world systems and decision-making processes. It enables rigorous and systematic modelling by describing each "process" through a diagrammatic framework in which functions and supporting mechanisms are explicitly defined. A "process" is defined as a set of activities that transforms a set of input data into output data for another process, using human resources, technology, and other supporting assets.

An IDEF0 model is developed through a series of hierarchical diagrams, where information is graphically represented using boxes and arrows. Boxes represent functions (i.e., actions, processes, or transformations), whereas arrows represent the information or objects involved in the process, referred to as ICOM (Input, Control, Output, Mechanism) (Figure 1). The arrows do not indicate a sequence of operations, but rather the flow and exchange of information. Specifically, inputs represent the data entering the function, while outputs represent the results generated through the transformation performed by the function. This transformation is governed by controls, which define the constraints and conditions under which the inputs are processed. Controls are depicted as arrows entering the top side of the box. Finally, mechanisms represent the enabling resources that support the execution of the function, such as software tools, technical infrastructure, or human expertise. Mechanisms are depicted as arrows entering the bottom side of the box [57].

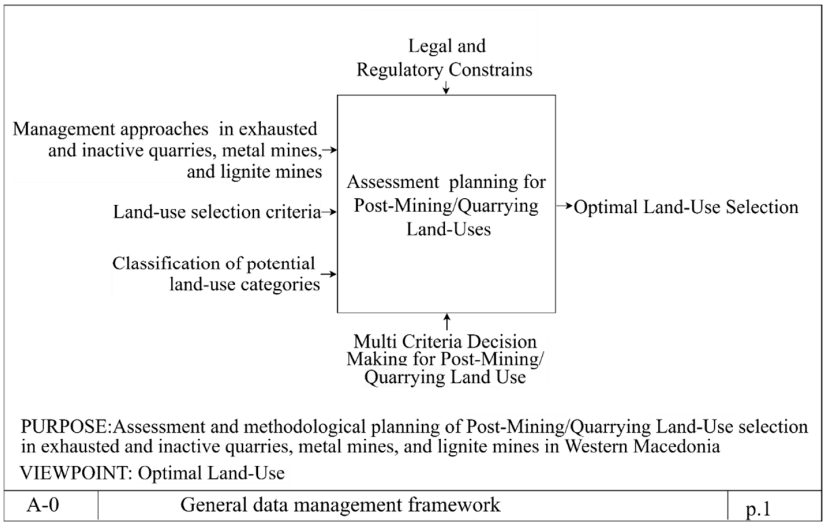


**Figure 1.** Diagram A-0: general data management framework of assessment planning for post-mining/quarrying land-uses.

Each IDEF0 model begins with a top-level diagram, known as **A-0**, which provides the overall context of the system under investigation. The A-0 diagram represents the highest hierarchical level and includes a single function box together with its associated arrows. It defines the scope, purpose, and focus of the process. The A-0 diagram can then be decomposed into lower-level diagrams that include additional function boxes, known as **parent boxes**, which provide a more detailed analysis. When further elaboration is

required, these diagrams may be further decomposed into **child diagrams**, offering an increasingly detailed representation of the process.

### *2.2. IDEF0 Modelling of the Optimal Land-Use Selection Process for Quarries and Mines*

In the present study, the IDEF0 method was employed both as a process-modelling tool and as a framework for structuring the methodology of the research in order to model and visualize the process of optimal post-mining and quarrying land-use selection. The model integrates the main stages of the decision-making process in a structured and hierarchical way, linking the evaluation criteria, regulatory requirements, and alternative land-use options within a unified framework. The inputs of the model include data derived from the management approaches applied to inactive quarries, metal mines, and lignite mines, the relevant land-use selection criteria, and the classification of potential land-use categories, while the outputs correspond to the optimal land-use options that can be allocated to post-mining sites. Through this approach, the IDEF0 representation provides a systematic overview of the factors and methodological stages involved in the decision-making process, supporting the development of a comprehensive framework for land-use planning in areas requiring rehabilitation.

The top-level A-0 diagram presents the general context of the "Optimal Land-Use Selection" process (Figure 2) and was developed to clarify the key tasks required for the assessment and methodological planning of land-use selection in exhausted and inactive quarries, metal mines, and lignite mines. In the present model, further decomposition into child diagrams was not considered necessary.

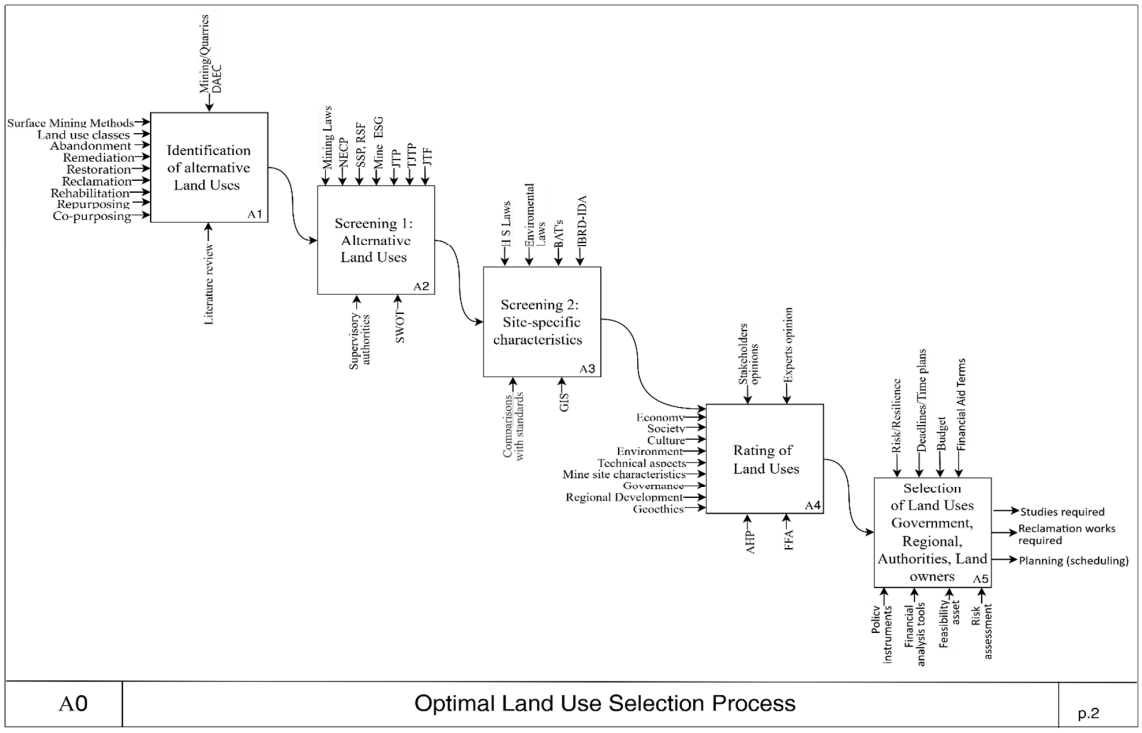


**Figure 2.** Diagram A0: Optimal Land-Use Selection Process.

More specifically, Figure 2 illustrates the overall data management structure of the process. The input flows were identified through an interdisciplinary approach and a systematic literature review conducted at the global level and include management approaches [58,59], land-use selection criteria [60,61], and land-use categories associated with inactive quarries and mines [16,17]. To ensure the reproducibility of our methodology, a structured Systematic Literature Review (SLR) protocol was established. The detailed pa-

rameters, including search strings, inclusion/exclusion criteria, and the selected databases, are comprehensively presented in Table S1 (Supplementary Materials). The transformation of inputs into outputs is regulated by control data, which mainly includes the Greek institutional and regulatory framework governing rehabilitation and restoration of surface mining activities. The implementation of the process is supported by mechanisms consisting of Multicriteria Decision-Making (MCDM) methods, which enable the evaluation and prioritization of alternative land-use options.

The A-0 diagram is decomposed into the five stages of A0 diagram. Each stage incorporates specific scientific research methods that support the methodological workflow. In stages A1 and A2, analysis is applied to identify alternative land uses and examine the regulatory and planning framework, while synthesis is used to combine the literature findings, planning constraints, and regional development priorities into feasible land-use alternatives. In stage A3, comparison is employed to assess the compatibility of alternatives with technical standards and spatial planning requirements. In stage A4, **deduction** supports the transformation of general sustainability principles into measurable evaluation criteria, while induction is used to interpret expert judgments and stakeholder assessments during the AHP and FFA evaluation process. Finally, stage A5 synthesizes the results of the previous stages to support the final land-use selection.

Specifically, the stages are illustrated through five parent boxes (A1–A5). Box A1 corresponds to the identification of alternative land-use options, using information related to surface mining methods, land-use group classifications, and post-mining management approaches, including Abandonment, Remediation, Restoration, Reclamation, Rehabilitation, Repurposing, and Co-purposing. This function is controlled by Environmental Impact Assessments (EIAs) and Decisions on the Approval of Environmental Terms available through the national environmental registry, which document land-use allocations in active, rehabilitated, and abandoned mining sites. The supporting mechanism of A1 is the literature review [1], which identified land-use applications and sub-groups of suitable land uses implemented internationally.

The outputs of A1 are used as inputs for A2, where alternative land-use options suitable for Western Macedonia are compiled and filtered through national and regional planning instruments, including the applicable mining and quarrying regulations, spatial planning frameworks, and transition-related strategic policies. These controls include, among others, the Mining and Quarrying Works Regulation (KMLE) [62], national legislation for extractive industries, the National Energy and Climate Plan (NECP) [63], the Special Spatial Planning Frameworks, the Just Transition Development Plan (JTP) [64], the Regional Just Transition Plan for Western Macedonia (TJTP) [65], the Just Transition Fund and associated financing tools, as well as ESG-related principles addressing environmental and social impacts and governance quality. This function is supported by competent supervisory authorities (e.g., the Ministry of Environment, regional and local authorities, and the transition governance structures), while SWOT analysis is applied as a supporting mechanism to identify strengths and weaknesses derived from the internal environment of the sites, as well as opportunities and threats originating from external conditions.

The outputs of A2 are then introduced into A3, where they are further refined using controls related to occupational health and safety legislation, environmental regulations, Best Available Techniques (BATs) for rehabilitation, and international planning guidelines for transition regions. Comparisons with standards and Geographic Information Systems (GIS) are the key mechanisms supporting this step. The outputs of A3 form the inputs of A4, which integrates the selected land-use alternatives with the evaluation criteria identified through the literature review. These criteria include economic, social, environmental, cultural, technical, locational, governance, regional development, and geoethical dimen-

sions. The transformation at this stage is supported by expert judgement and stakeholder participation, while the mechanisms applied include Force Field Analysis (FFA) and the Analytic Hierarchy Process (AHP). Finally, the outputs of A4 serve as inputs to A5, which corresponds to the final selection of the optimal land-use options.

### *2.3. Description of the Workflow Stages and Procedural Execution*

The stages are numbered, each encompassing the incremental transformations required to achieve, through the assessment and design of the methodology, the optimal selection of land uses. This selection is aligned with management procedures for open-pit, active, and inactive quarries, as well as metal and lignite mines.

### *2.4. Software Tools*

The following software tools were used in this study:

- draw.io: An open-source, web-based diagramming tool used for the development of flowcharts illustrating the land-use selection procedure, based on the IDEF0 methodology [66].
- Online Software Tool for the Analytic Hierarchy Process (AHP v.27.8.11): This tool was applied to perform pairwise comparisons, calculate criteria weights, and estimate the overall score of each alternative land-use option according to the selected evaluation criteria [56].
- Force Field Analysis (FFA) Excel Template (v.3.1): A Microsoft Excel-based template used to assess each land-use option individually, based on driving and restraining forces influencing land-use selection [67].
- Geographic Information System (GIS): QGIS (version 3.40.3) and ArcMap (version 10.0) software packages were utilized as the primary environments for spatial data modeling, baseline spatial analysis, and cartographic representation of active, inactive, and restored quarries, as well as metal and lignite mines. Instead of functioning merely as static mapping tools, the GIS environment was employed to execute the spatial join, harmonization, and topological validation of heterogeneous datasets retrieved from municipal archives within the Region of Western Macedonia, the National Cadastre (ktimatologio.gr), the official platform of the General Directorate of Mineral Raw Materials [68], and the Electronic Environmental Registry. The spatial attributes derived from this GIS-based status quo analysis served as the definitive data input layer for the decision-making framework. Subsequently, the Analytic Hierarchy Process (AHP) was executed externally using the specialized AHP-OS online software tool [56] to weigh, evaluate, and rank the target criteria, thereby establishing a rigorous, multicriteria spatial decision support workflow.

## 3. Description of the Study Area

The study area is the Region of Western Macedonia, located in the northwest part of the country, traditionally considered a "peripheral" location. Despite its peripheral location, it has a key position in the Western Balkans as it is a natural gateway to Greece's northwest neighbouring countries (North Macedonia, Albania). Administratively, it is divided into four Regional Units (RUs): Kozani, Florina, Kastoria, and Grevena (Figure 3). It is predominantly a mountainous area, with 83% of its territory covered by mountainous and semi-mountainous land, and it is the only region of the country with no outlet to the sea. It covers an area of 9451 km$^2$ and population is 254,595 inhabitants, according to the 2021 census. Approximately 50% of its population is concentrated in the RU of Kozani, where the main city and capital of the Region is located.

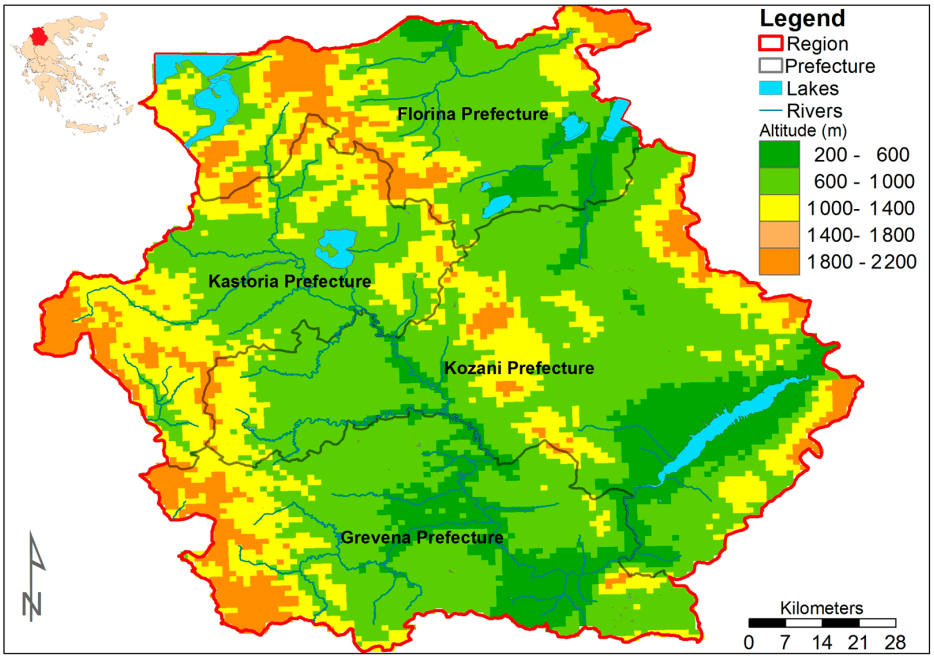


**Figure 3.** Map of Western Macedonia Region.

The Region of Western Macedonia is characterized by its abundant natural resources, which provide nationwide benefits. It has the largest lignite reserves in the country, the use of which contributes decisively to national electricity production, significant reserves of ores, industrial minerals, and marble, as well as several scattered gravel pits. The Region's mineral industry is an economic sector of national importance due to the fact that ores and other industrial minerals mined in its territory provide raw materials that make up a significant proportion of the country's exports. Quarries also have a clear export orientation, constituting a source of income for local socio-economic systems [69].

The Region of Western Macedonia is officially designated as a just transition region; due to de-lignification, the region is in a critical phase of moving from lignite dependence to a low-carbon economy.

The spatial distribution and operational status of mining and quarrying activities within the study region are illustrated in Figure 4. The extractive sector in the area comprises a mix of active quarries and mines, an extensive network of inactive sites—dominated primarily by idle quarries—as well as several successfully restored municipal and private quarries. For a more comprehensive spatial overview, detailed cartographic representations distinguishing between active and inactive sites are provided in Figures S1 and S2 (Supplementary Materials).

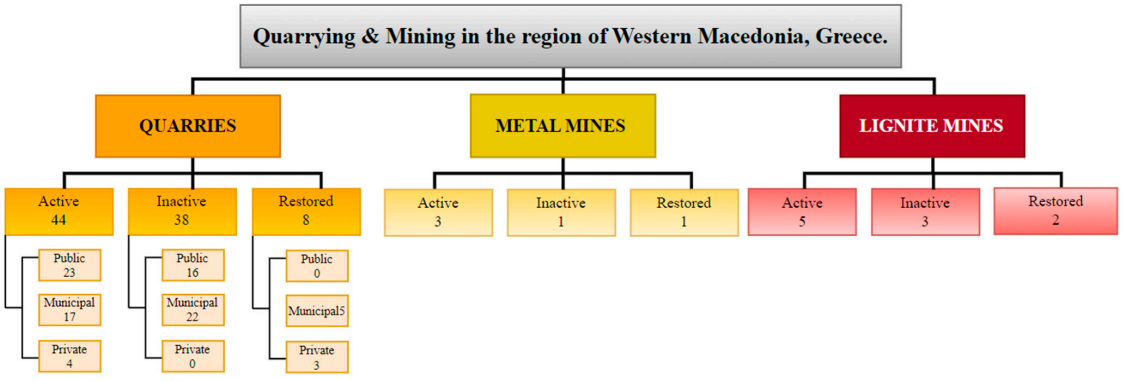


**Figure 4.** Quarries and Mines in the region of Western Macedonia, Greece.

## 4. Results

### *4.1. Alternative Land Uses Identification (Box A1)*

The literature review conducted by the authors of this article in [1] has shown that a diverse range of land-use options is pursued following the closure of surface mines and quarries. These land uses were categorized based on 12 general classes and 38 subclasses. Eleven classes are listed in [1] while apiculture has been added as a twelfth one due to particular interest in the acacia-restored deposits of lignite mines. The land uses implemented globally to date presented in Table S2 (Supplementary Materials).

Based on the above data, it is evident that a greater variety of land uses is found in the class of residential and commercial use. This can be attributed to the need to meet multiple stakeholders' demands while also utilizing an area's unique characteristics and the infrastructure left behind by mining activities.

The final selection of land uses is carried out based on criteria ensuring successful rehabilitation and a positive impact on the area's development. Globally, nine (9) general criteria have been used to date for land-use evaluation, which are further categorized into seventy-two (72) specialized sub-criteria, as illustrated in Figure S3 (Supplementary Materials) [1].

### *4.2. Screening 1: Land Uses That Follow the Regulatory Guidelines and Limitations (Box A2)*

Building on the land uses identified in the previous step, a systematic review of the current legal and planning framework was carried out in order to identify those that are consistent with the existing legislation, national and regional development plans, spatial planning regulations and frameworks, energy and transition plans, and environmental impact studies relevant to rehabilitation A schematic overview of the key documents examined is provided in Figure S4 (Supplementary Materials), while the subsequent sections summarize the main restrictions, obligations, and institutional directives guiding the selection of compatible land uses.

#### 4.2.1. European and National Legislation

Environmental legislation governing extractive projects in Greece has progressively established restoration and rehabilitation as core obligations, in line with the European Union environmental acquis. Law N.1650/1986 introduced, for the first time, the objective of environmental restoration [30]. Subsequently, Joint Ministerial Decision (JMD) 69269/1990 institutionalized the requirement for environmental permitting for activities involving the exploitation of natural resources [31].

Law 4014/2011 [70] further reinforced this framework, allowing quarry operations only after completion of the environmental licensing procedure. This law constitutes a key instrument for harmonizing Greek environmental permitting procedures with major EU environmental directives, particularly Directive 2011/92/EU [71] on environmental impact assessment, Directive 2001/42/EC [72] on strategic environmental assessment, and Directive 2004/35/EC [73] on environmental liability.

Law N.4030/2011 [74] permits the installation of waste treatment facilities for excavation, construction, and demolition waste (CDW) in inactive quarries, aiming at landscape and environmental restoration, regardless of land ownership status. This provision is aligned with Directive 2008/98/EC [75] on waste, which promotes waste recovery, material reuse, and the restoration of degraded land through the beneficial use of waste, thus supporting the objectives of circular economy policies within the EU.

Law N.4512/2018 [76] obliges quarry operators to rehabilitate exploited quarry sites and specifies the terms and conditions for completing the restoration process; in cases where quarry activities were carried out within forest areas, reforestation is mandatory.

These restoration obligations are closely linked to Directive 2006/21/EC [77] on the management of waste from extractive industries, which requires extractive operators to prepare waste management plans, ensure site rehabilitation after closure, and provide financial guarantees for restoration measures. Furthermore, the rehabilitation provisions are consistent with Directive 2004/35/EC [73] on environmental liability, as well as with Directives 92/43/EEC [78] and 2009/147/EC [79] concerning the protection of habitats and wild birds, particularly where quarrying activities affect environmentally sensitive areas.

Moreover, the Regulation of Mining and Quarrying Works (KMLE) [62] sets the rules for rational exploitation and defines the restoration requirements for mines and quarries upon termination of extraction activities. It explicitly states that the final restoration form should be harmonized with the broader environment. In cases involving public, municipal, or community-owned land, restoration planning should also consider local needs for specific land uses, in accordance with written recommendations from regional and local authorities.

#### 4.2.2. Spatial Planning Frameworks

According to Greek planning legislation, spatial planning at the national and regional levels is implemented through Special Spatial Planning Frameworks at the national level and Regional Spatial Planning Frameworks at the regional level. Mineral extraction projects must comply with national and regional spatial planning frameworks, ensuring that extractive activities and post-mining/quarrying land-use planning are aligned with broader development and environmental policy objectives.

At present, the adoption of a Special Spatial Planning Framework for Mineral Raw Materials remains pending, as it is still under preparation. This framework is expected to provide policy directions for the spatial organization of the sector in relation to existing land uses, based on sustainable development principles, the enhancement of national comparative advantages, and the protection of cultural and natural heritage.

The Special Spatial Planning Framework for Industry does not include specific provisions for raw material extraction activities and, consequently, does not explicitly address mine and quarry rehabilitation. It focuses primarily on auxiliary facilities of extractive operations, while emphasizing the need for integrated restoration interventions in areas affected by past industrial pollution, with responsibility assigned to the producer and the landholder. For the Regional Unit of Kozani, it highlights that the strong specialization in power generation and mining has resulted in significant environmental impacts (mainly air pollution and temporary alteration of land morphology), thus requiring targeted anti-pollution measures and nature protection actions [80].

The Special Spatial Planning Framework for Tourism, under consultation, promotes sustainable tourism development with emphasis on environmental protection, landscape restoration, and cultural heritage preservation. It supports the reuse of inactive quarries and former extractive sites for alternative tourism activities (e.g., theme parks or special-interest tourism), provided that environmental rehabilitation and visitor safety are ensured. In this context, inactive mines and quarries are also considered potential geosites within the geotourism category and may be integrated into thematic tourism networks [81].

The study for the revision of the Special Spatial Planning Framework for Renewable Energy Sources (RES), concerning the siting of solar energy exploitation facilities, defines Priority Areas and Acceleration Areas. These include ‘Areas that have changed character’, i.e., areas previously used for other purposes, to be restored, such as depleted quarries, former mining fields, depleted lignite fields, sites with high pollutant loads, degraded areas, and Uncontrolled Waste Disposal Sites (UDSs) [82].

The Regional Spatial Planning Framework of Western Macedonia sets priorities for protecting and enhancing natural heritage and landscape, while promoting productive use

and conservation of natural resources. Regarding mineral raw materials, it emphasizes integrated landscape restoration programs and the identification of alternative land uses for exhausted extraction sites, considering both natural and anthropogenic functions in surrounding areas. It also foresees the preparation of specialized studies supporting restoration programs and post-mining land-use planning.

In line with the Just Development Transition Plan (JDTP), the Regional Spatial Planning Framework identifies the strengthening of Kozani's business infrastructure as a priority, through the development of Business Parks, [83], logistics parks, and circular economy parks, particularly in degraded land and restored facilities within the Kozani's Zone of lignite mining, as well as in abandoned urban land and former industrial sites. In addition, the framework supports sustainable management of existing and abandoned land stocks, prioritizing industrial development in already-used areas and brownfields, promoting reuse policies, and avoiding the conversion of natural land into new built environments. It also enables the lifting of restrictions related to land-use changes through provisions embedded in the national planning system.

Within this context, ten categories of land-use selection criteria were identified for rehabilitation areas and existing infrastructures, along with twenty-four (24) recommended post-mining/quarrying land uses, including: Business Parks [83], logistics parks, circular economy parks, renewable energy systems and energy networks, productive activities compatible with soil conditions, reuse of buildings and unexcavated plots for production, technical infrastructure networks, ecosystem restoration, energy recovery from secondary fuels, biomass utilization, energy-related cultural infrastructure, photovoltaic systems prioritizing in Zone of lignite mining, pumped-storage projects, innovative energy storage applications, waste-to-energy units, industrial and wholesale storage zones, cultivation of energy crops, and designated mining development zones such as the Tranovalto marble extraction area [84].

Finally, the Spatial Urban Plans (SUP) for the Zone of lignite mining of Kozani—Eordaia—Florina, which are directly linked to the rehabilitation and reuse of these lands, were still incomplete at the time of writing of this article.

#### 4.2.3. Strategies

The National Energy and Climate Plan (NECP) set the objective that Greece's lignite phase-out by 2028 should be aligned with the European Union's ambition for climate neutrality and international energy developments. A key priority is ensuring that the post-lignite transition is socially fair for Western Macedonia and Megalopolis. The NECP also highlights the need to finance development actions in regions historically dependent on lignite extraction, supporting renewable energy projects, biomass/biogas initiatives linked to agricultural cooperatives, energy self-production schemes, and circular economy applications, including the reuse of secondary materials and ash valorisation, as well as the promotion of industrial heritage [63].

The Just Transition Plan (JTP) identifies the immediate launch of rehabilitation works in PPC S.A. lignite mines as a critical action for ensuring a smooth transition in Western Macedonia and Megalopolis. The plan emphasizes the reuse or decommissioning of extensive PPC building and mechanical infrastructure and highlights the role of circular economy practices in reducing environmental impacts while supporting employment. Within the clean energy pillar, photovoltaic plants are already being developed by PPC S.A. and Hellenic Petroleum S.A., while additional investments are proposed, including green hydrogen production, energy storage facilities, an e-mobility industrial park, a waste management facility, and a biomass processing centre. The JTP also includes the

preservation of Western Macedonia's industrial heritage as part of a broader diversification strategy for the region's tourism profile [64].

The Territorial Just Transition Plan Western Macedonia (TJTP) for Western Macedonia documents the necessity of environmental rehabilitation of lignite lands, the reuse of degraded sites and infrastructure, and the implementation of projects supporting a new productive model without generating additional environmental pressures. Land and infrastructure repurposing in lignite fields constitutes the third of the plan's five priorities, focusing on actions in Kozani and Florina, particularly for restored lands expected to be transferred to the Greek State after rehabilitation works financed through the Recovery Fund. Proposed interventions include green infrastructure (e.g., flood protection works, agricultural terraces, biodiversity restoration and monitoring, and water efficiency infrastructure) as well as technical works enabling land-use transformation (e.g., access infrastructure and public utility networks supporting business parks). Furthermore, under the fourth priority, the plan proposes restoration of archaeological and cultural sites within lignite mines to support alternative economic activities and sustainable mobility measures [65].

The World Bank Roadmap for the Transition to the Post-Lignite Era in Western Macedonia underlines the importance of establishing a regional innovation ecosystem, with a focus on green energy, information technologies, and agri-food systems. A dedicated pillar addresses the reuse and repurposing of restored lands and existing infrastructure, emphasizing legislative revision, proposals for the reuse of exhausted mines and related assets, and the development of a methodological framework for evaluating post-lignite land-use options. The proposed approach identifies five categories of land-use selection criteria and suggests indicative land-use scenarios, including: (i) energy production and storage/industrial production/waste processing, (ii) agriculture/horticulture/forestry, (iii) recreation/tourism, and (iv) offices/research facilities/technology parks [85].

The Strategic Environmental Impact Assessment (SEIA) for the development of a network of Waste-to-Energy units from MSW (Municipal Solid Waste) is currently under public consultation, with its finalization expected soon. The SEA integrates the environmental dimension into the establishment of a national network of six (6) energy recovery units by evaluating and assessing their potential environmental impacts. According to SEIA, one of these units is slated to be located in Western Macedonia, specifically within the Regional Unit of Kozani. This unit will process waste from the Regions of Central Macedonia, Western Macedonia, Epirus, Thessaly, and part of the Ionian Islands.

The Region of Western Macedonia, beyond its specialization in the energy sector, is a national pioneer in waste management, currently operating within the depleted lignite mines of Kozani. In addition to existing facilities, there is the potential to install WtE unit within already established infrastructure, such as decommissioned power plants (e.g., former lignite units) [86].

#### 4.2.4. Environmental Impact Assessment Studies (EIA) and Environmental Permits

A systematic search was conducted in the Electronic Environmental Register (EER) to identify Environmental Impact Assessment (EIA) studies and modification/renewal studies of Environmental Terms Approval Decisions (AEPO) concerning active, inactive, and rehabilitated lignite mines, metal mines, and quarries in the Region of Western Macedonia. As the EER provides available documentation from 2012 onwards, this process resulted in the identification of eight (8) EIAs and sixteen (16) AEPOs decisions that have already been presented [33–53]. Subsequently, additional targeted searches were carried out through online sources and relevant regional institutions, leading to the collection of two (2) revegetation/restoration (phytotechnical) studies [32,87], three (3) EIAs [88–91],

and two (2) AEPOs [92,93]. The collected documentation was analysed to examine land-use selection criteria categories, specific evaluation criteria, proposed post-mining land-use options, and implemented land uses applied in restoration planning.

Although EIA procedures are intended to identify mitigation measures and define restoration obligations incorporating stakeholder consultation during the project design stage, in practice, they do not always ensure the selection of optimal post-mining land uses. In many cases, restoration measures proposed in EIA studies and environmental permit decisions are limited to the minimum interventions required for project approval, focusing mainly on landscape stabilization and ecological rehabilitation through afforestation. While such measures may address environmental compliance requirements, they do not necessarily respond to the broader socio-economic needs of regions undergoing transition or deindustrialization, where the identification of productive and locally beneficial post-mining land uses is critical. Furthermore, although public consultation is formally integrated into EIA procedures, it often functions as a procedural requirement rather than as a substantive participatory planning process, with limited influence on the final restoration strategy. As a result, the post-mining land-use solutions approved during the licensing stage may prove environmentally acceptable but socio-economically suboptimal, thereby justifying the need for additional evaluation frameworks aimed at balancing environmental restoration goals with long-term regional development priorities.

#### 4.2.5. Land-Use Classes and Alternative Land Uses Proposed for Rehabilitation

Based on the above findings and particularly considering the Just Transition plans aiming to maintain social cohesion and mitigate the recession currently affecting the regional economy, the management approach of environmental restoration projects in closing quarries, metal mines, and lignite mines is undergoing a significant shift. Interventions focusing solely on soil and water decontamination and on the restoration of ecological balance are no longer sufficient. Local communities increasingly demand new productive activities capable of alleviating the social and economic impacts of mine closure. In this context, land-use proposals aligned with the concepts of repurposing and co-purposing are becoming widely accepted and actively promoted. Figure 5 presents a logical flowchart illustrating the management procedures for inactive quarries, metal mines, and lignite mines, reflecting this new approach and strategic orientation.

Considering the dual objective of the planned interventions, namely environmental protection and the revitalization of the regional economy, the Greek legislation, spatial planning frameworks, transition-related strategic plans, and associated reports propose thirty-four (34) post-mining/quarrying land uses for the rehabilitation of exhausted quarries and metal and lignite mines. The classification of these land uses into groups, along with the specific groups recommended by each reviewed development plan, is presented in Table S3 (Supplementary Materials).

Furthermore, the review of Environmental Impact Assessment (EIA) studies and Environmental Permits for extractive projects located in Western Macedonia resulted in the identification of eleven (11) land-use classes, comprising twenty-four (24) distinct land uses that have either been implemented or are planned to be adopted within the framework of soil restoration activities The land-use classes and subclasses extracted from the development plans, regulatory texts, reviewed EIA studies, and Environmental Permits, are comprehensively presented Table S4 (Supplementary Materials).

Overall, the initial screening phase reduced the number of land-use groups from 13 to 11 and the number of sub-groups from 38 to 24.

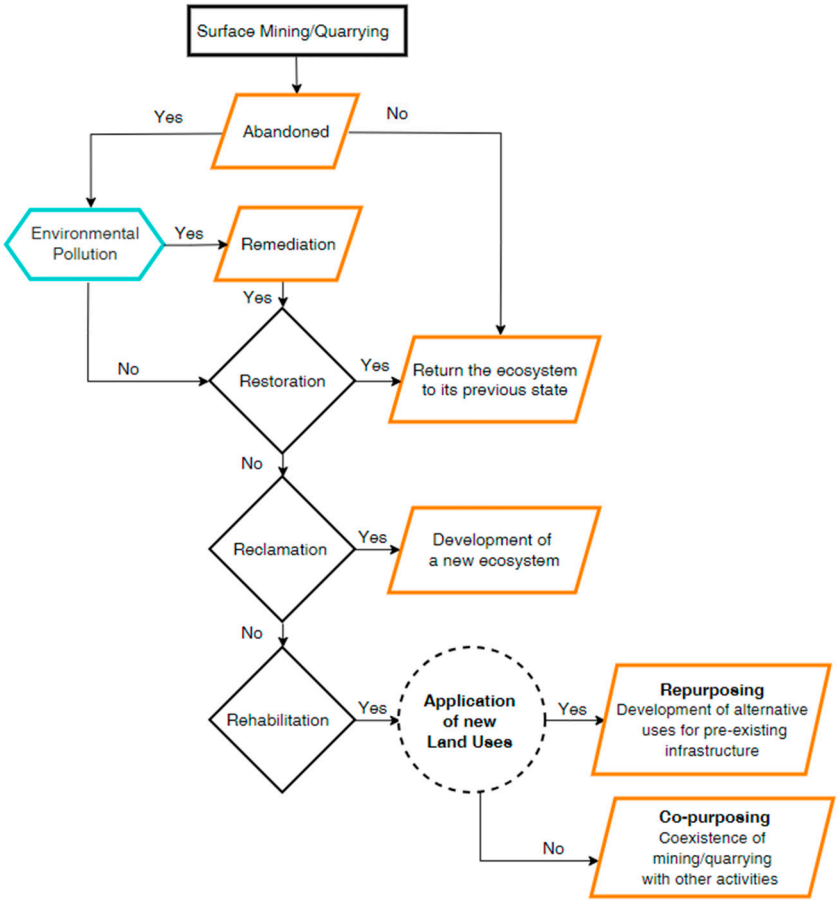


**Figure 5.** Post-Mining/Quarrying Land-Management Strategies.

### *4.3. Screening 2: Land Uses Compatible with Local Characteristics (Box A3)*

To further distinguish the land uses considered suitable for former quarry sites and metal and lignite mining areas in Western Macedonia, a SWOT analysis was conducted. This analysis aimed to identify the **strengths** and **weaknesses** associated with the internal environment of quarries and metal and lignite mines, as well as the **opportunities** and **threats** arising from their external environment. the identification of these factors considers all key environmental components in their broader sense, including society, economy, and employment, and the natural environment and quality of life.

Based on the information presented in Table S5 (Supplementary Materials) significant differences were identified in terms of the strengths and weaknesses characterizing quarries compared to metal and lignite mines. For this reason, the proposed alternative land uses differ between quarries and mining sites. An exception is reforestation, which is proposed in both cases, as several quarries and mines are located within forest areas and are required to be reforested under national legislation.

Moreover, the identified threats suggest that the long-term viability of future land-use planning is critically dependent on the ability of stakeholders to achieve coordination and consensus. Conflicts over land-use are intensified by the tendency of different actors to prioritize the interests of the groups they represent, often at the expense of wider regional development objectives. This weak consultation undermines the establishment of shared strategic priorities and contributes to institutional fragmentation. As a result, decision-making processes are often delayed reflecting both a reluctance to engage in substantive dialogue and the inherent difficulty of reconciling competing land-use options. These delays further exacerbate political uncertainty, as decision-makers may avoid taking responsibility for potentially controversial choices because of the perceived political cost. In the context of post-mining transition, such

dynamics can significantly impede timely investment planning and weaken the social and economic viability of redevelopment strategies.

Finally, after the SWOT analysis, the number of land-use classes that match the special characteristics of Western Macedonia is six (down from ten in the previous stage), while the number of sub-classes has been reduced to half, from 24 to 12. To facilitate the investigation that will follow, the subclasses were limited to 7 (Figure 6), considering that the subclasses related to agricultural uses and forests exhibit similar characteristics and can be unified (Figure S5).

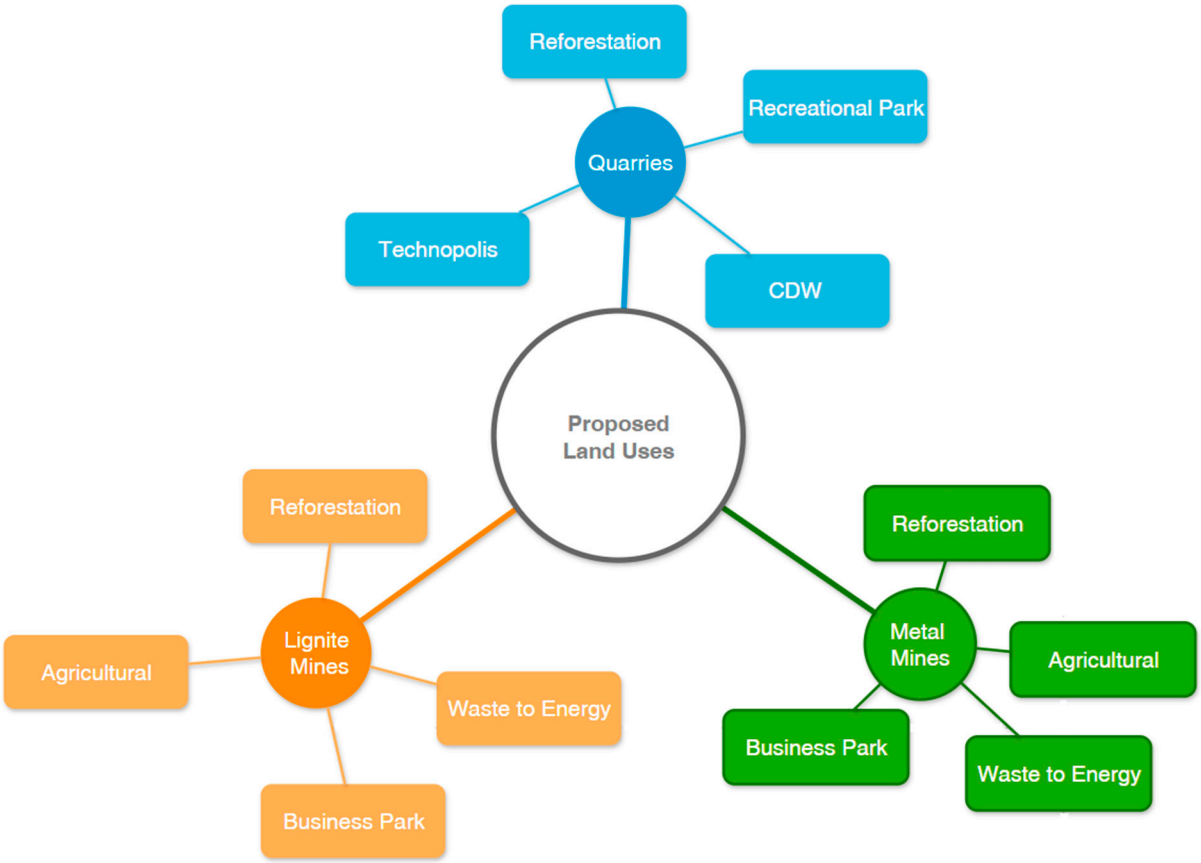


**Figure 6.** Proposed land uses for inactive quarries and metal and lignite mines.

Regarding quarries, in addition to reforestation, the following land uses are proposed:

(a) Construction and Demolition Waste (CDW) treatment facilities: According to national legislation, such facilities may be established in inactive quarries and metal and lignite mines for the purpose of rehabilitation the natural landscape and environmental conditions, regardless of the ownership status of the site.

(b) Recreational uses: Quarries are often located in proximity to settlements, which typically lack open public spaces. Moreover, the limited available areas within urban areas are usually reserved for residential development due to their high economic value. Quarries also occupy large areas and are commonly located near road networks, ensuring accessibility. In addition, the availability of existing utility infrastructure reduces the cost of construction and connection to public service networks.

(c) Technopolis (innovation and technology parks): These areas can host low-impact business activities, high-technology enterprises, research and educational functions, and service-sector facilities. Permitted activities include low-nuisance workshops and small-scale manufacturing, vehicle freight terminals, logistics facilities, business incubators, and technology support centres [83,93]. Therefore, quarries located near

settlements could be transformed into organized and officially designated zones accommodating low-impact economic activities.

Regarding metal and lignite mines, in addition to reforestation, the following land uses are proposed:

(a) Agricultural land uses (crop farming, livestock breeding, poultry farming, and apiculture): These are proposed because, in many cases, land expropriations took place in areas previously cultivated with cereals, sugar beets, and other crops. Furthermore, local communities request the return of mined land for cultivation or use as grazing areas.

(b) Waste-to-Energy (WtE) facilities with energy recovery: According to the Strategic Environmental Impact Assessment (SEIA) for the development of a national network of energy recovery units for waste-derived energy feedstock from Municipal Solid Waste (MSW), an energy recovery facility is proposed to be located in the Regional Unit of Kozani [85]. Western Macedonia has long-standing experience in the energy sector and has been a national frontrunner in waste management, implementing an Integrated Waste Management System since 1995. Since 2017, the Waste Treatment Plant (WTP) located in an exhausted lignite mining area of Kozani has been pre-treating mixed MSW, with residues disposed of in a sanitary landfill for residual waste. MSW pre-treatment constitutes a priority within EU waste policy under the Waste Framework Directive [94], which classifies waste incineration with energy recovery as an "other form of energy recovery", as it converts non-reusable and non-recyclable waste into energy and reduces reliance on landfilling, the least preferred option due to its high environmental impacts. Therefore, the development of a WtE facility in exhausted lignite mines would align with EU policy directions and the relevant SEIA recommendations, while further supporting advanced waste management practices at the national level [94–96].

(c) Business Parks: These constitute integrated clusters of infrastructure, services, and facilities supporting business activities, particularly in the context of the regional development transition driven by lignite phase-out. In Western Macedonia, several industrial zones and business parks already exist (e.g., in Florina, Kastoria, and Kozani, including the Kozani Wood Industrial Park); however, many remain inactive or host a limited number of enterprises [97]. Additionally, several Regional Units include Informal Industrial Concentrations, characterized by high densities of enterprises but inadequate infrastructure, planning deficiencies, and environmental issues, requiring operational and environmental upgrading (e.g., two such areas have been identified in Kozani). The Central Union of Chambers of Greece, representing small and medium-sized enterprises, supports the development of Business Parks [97]. Moreover, the Spatial Planning Framework of Western Macedonia promotes their establishment in each Regional Unit to strengthen the productive base and stimulate investment. Business Parks may host a wide range of secondary and tertiary sector activities, excluding commercial malls, including manufacturing and related activities, mechanical service installations, logistics operations, research centres and laboratories linked to applied industrial, energy and mining research, technology support centres, high-technology service laboratories, technical training schools and university branches, as well as electricity and heat production from renewable energy sources and natural gas, electricity storage, agricultural and livestock activities, and other supporting functions necessary for the operation of the park [98].

### *4.4. Land-Use Ranking (Box A4)*

The national legislation currently in force, the spatial planning frameworks, the World Bank Roadmap for Western Macedonia, the JTP, the TJTP, and the reviewed EIA/DAEC documentation take into account eight out of the nine categories of land-use selection criteria identified in [1] (Table 1. Criteria related to the economic category were identified in five out of the seven examined documents, indicating a clear shift towards land uses that may revitalize the regional economy and address social challenges such as population decline and increasing unemployment. Environmental criteria follow, incorporated in three out of the seven documents, whereas social criteria are not explicitly mentioned in any of the reviewed texts. This may be attributed to the assumption that social problems will be mitigated once economic issues are resolved. Nevertheless, in the rating process of the seven selected land uses, all nine groups of selection criteria will be applied, as this does not affect the implementation of the Analytic Hierarchy Process.

**Table 1.** Categories of criteria derived from institutionalized planning directions.

| Categories of Criteria | Regulatory Framework | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Regulation Mining/ Quarrying 2011 | SSPF Tourism | SSPF RES | World Bank | NECP | SEIA WtE | JTP | TJTP W. Macedonia | RSPF W. Macedonia |
| 1. Economy | | • | | • | • | | • | | • |
| 2. Society | | | | | | | | | |
| 3. Culture | | | | | | | | • | • |
| 4. Environment | • | • | • | | | | | • | • |
| 5. Technical Aspects | | | | • | | • | | • | |
| 6. Mine Site Characteristics | | | | • | | • | | | |
| 7. Governance | • | | | | • | | | | |
| 8. Regional Development | | | | | • | | | | |
| 9. Geoethics | | | | | | | | | • |

Note: The black dots (•) indicate which criteria are addressed or included in the institutionalized planning directions of each regulatory framework document.

### *4.5. The Comparison Concerned the Nine Categories of Criteria Presented in Detail in Table S6*

Although the 26 sub-criteria presented in Table S6 (Supplementary Materials) could not be directly integrated due to AHP methodological constraints, they were shared with the experts to provide essential context during the pairwise comparison of the primary criteria categories.

The evaluation was conducted using the AHP 1–9 scale, which constitutes a fundamental numerical scale applied in pairwise comparisons between criteria or alternatives. It allows decision-makers to quantify subjective preferences by scoring how much more important one element is compared to another, ranging from 1 (equal importance) to 9 (extreme importance). The values of the consolidated criteria table (including all participants) were calculated as the weighted geometric mean of the individual responses of all participants. The results of the evaluation are presented in Table S7 (Supplementary Materials).

Specifically, the environmental criterion exhibited the highest weight among all criteria, with a value of 15.90%, implying that terrain morphology before and after extraction, as

well as visual disturbance, strongly determine land-use selection in quarries and metal and lignite mines under restoration.

The governance criterion followed with a weight of 15.50%, highlighting that governmental policy, national policy, and the legislative framework represent highly significant factors, as they establish boundaries and restrictions, obligate operators to restore extraction sites, ensure completion of restoration in cases where the operator is unable to do so, and, through monitoring mechanisms, guarantee the reduction in the environmental footprint of mining activities.

Closely following, with a similar weight of 15.00%, the economic criterion indicates that financial aspects (e.g., funding instruments), the ability to attract investments, employment, and local income constitute critical factors for regional development. This reflects the necessity for the selected land uses to act as a driving force for the restart of economic activity in the affected areas.

A relatively high weight was also recorded for the regional development criterion (13.10%), demonstrating that regional and local development policy is considered important. This is because the planning directions provided for each area largely determine whether the proposed land uses will conflict with existing land uses, which could ultimately compromise the success of the transition process.

Due to the large size of the matrix (10 × 10) and the increased consistency requirements (45 pairwise comparisons), a standard algorithmic optimization method was applied to minimally adjust the values. This ensured that the Consistency Ratio (CR) fell below the acceptable threshold of 0.10, without altering the qualitative direction of the experts' judgments. The reliability of the outcomes is further validated by the exceptionally low Consistency Ratio (**CR = 0.7%**), which rests well below the standard 10% threshold to confirm the mathematical stability of the judgments, as well as by the high consensus rate (**67.8%**) that demonstrates a strong alignment among the participants despite minimal individual deviations.

The next phase of the procedure involved the rating of the seven selected land uses by a second expert group. This group included representatives of the Technical Chamber of Greece, executives from quarries, metal mines, and lignite mines, as well as two economists representing local government and the local development agency, respectively. The second expert group comprised five members, including a mining company representative whose background varied according to whether quarries, metal mines, or lignite mines were under evaluation. This specialized panel was tasked with evaluating alternative land uses, leveraging their technical expertise to determine sustainability and compatibility with the specific mining environments. Ultimately, the representatives assessed the impact of each land use on the respective criteria using a 1-to-7 rating scale, ranging from 1 (Highly positive) to 7 (Highly negative). Table 2 presents the weighting coefficients of each criterion, which were applied in this phase of the process, along with their confidence intervals. Table 3 presents the individual scores for each proposed land use across all evaluation criteria, alongside the overall score calculated from the average of the experts' assessments.

As shown, for quarries, the development of recreational activities was the alternative that achieved the highest overall score, followed by reforestation with a relatively small difference. In many cases, reforestation constitutes the only feasible option, largely due to the fact that several areas before quarrying activities were forested land. In such cases, mandatory reforestation is required by national legislation.

Regarding metal mines and lignite mines, the preferred alternative land use was the establishment of a waste-to-energy (WtE) facility, although it presented only a slight advantage compared to agricultural land uses and reforestation. This may be attributed to the location and large spatial extent of the mines, combined with the significant environmental

degradation that has occurred in the extraction areas, which potentially creates favorable conditions for siting a WtE facility without generating increased nuisance impacts on adjacent communities.

**Table 2.** Determination of criteria weights using the AHP method.

| | Criterion | Comment | Weights | +/− |
|---|---|---|---|---|
| 1 | ECONOMY | | 15.0% | 2.0% |
| 2 | SOCIETY | | 9.9% | 1.3% |
| 3 | CULTURE | | 5.2% | 0.9% |
| 4 | ENVIRONMENT | | 15.9% | 2.1% |
| 5 | TECHNICAL ASPECTS | | 7.9% | 1.1% |
| 6 | MINE SITE CHARACTERISTICS | | 8.2% | 1.5% |
| 7 | GOVERNANCE | | 15.5% | 1.8% |
| 8 | REGIONAL DEVELOPMENT | | 13.1% | 1.0% |
| 9 | GEOETHICS | | 9.3% | 1.7% |
| | | | 100.0% | |

**Table 3.** Evaluation of proposed land uses.

| | | Quarries | | | | Metal Mines | | | | Lignite Mines | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Criteria** | **Weights** | **Reforestation** | **Recreational Park** | **Waste Treatment Facilities** | **SME Hub** | **Reforestation** | **Agricultural** | **Waste to Energy** | **Business Parks** | **Reforestation** | **Agricultural** | **Waste to Energy** | **Business Parks** |
| Economy | 0.1497 | 5 | 5 | 1 | 5 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| Society | 0.0993 | 7 | 7 | 3 | 5 | 4 | 3 | 2 | 1 | 3 | 2 | 4 | 4 |
| Culture | 0.0521 | 3 | 7 | 1 | 3 | 4 | 4 | 6 | 2 | 5 | 4 | 4 | 4 |
| Environment | 0.1586 | 7 | 7 | 1 | 1 | 2 | 6 | 3 | 3 | 1 | 1 | 1 | 1 |
| Technical Aspects | 0.0792 | 3 | 3 | 1 | 1 | 4 | 4 | 3 | 4 | 4 | 4 | 1 | 2 |
| Mine Site Characteristics | 0.0817 | 5 | 5 | 3 | 5 | 4 | 3 | 4 | 3 | 2 | 3 | 4 | 3 |
| Governance | 0.1553 | 3 | 3 | 1 | 1 | 2 | 2 | 4 | 2 | 1 | 3 | 3 | 2 |
| Regional Development | 0.1309 | 5 | 5 | 1 | 1 | 3 | 2 | 2 | 2 | 1 | 2 | 2 | 1 |
| Geoethics | 0.0933 | 5 | 5 | 3 | 3 | 4 | 3 | 6 | 4 | 1 | 1 | 4 | 3 |
| | 1.000 | 4.94 | 5.15 | 1.55 | 2.61 | 2.94 | 3.17 | 3.29 | 2.49 | 1.73 | 2.10 | 2.42 | 2.04 |

### *4.6. Land-Use Selection (Box A5)*

Force Field Analysis (FFA) was applied to evaluate the factors influencing the feasibility of implementing each proposed land-use option. The method enables systematic identification and graphical representation of the driving (supporting) and restraining (opposing) forces associated with each alternative, thus highlighting its main advantages and limitations.

The assessment was conducted for seven (7) alternative land uses that could potentially be implemented in abandoned quarries and metal and lignite mines in the Region of Western Macedonia, namely: reforestation, recreation park, construction and demolition waste (CDW) treatment facility, Technopolis, agricultural land uses, business park, and waste-to-energy (WtE) facility. Each option was examined through the identification of positive and negative forces affecting its siting and implementation.

The FFA template provided by CIToolkit.com [66] was used. The template consists of a Microsoft Excel worksheet allowing the separate scoring of driving and restraining

forces. For each land-use option, a dedicated table was completed, in which supporting forces were recorded on the left side and opposing forces on the right side.

As detailed in the Methodology (Section 2, iv), 15 stakeholders evaluated the driving and restraining forces for each land-use option using a –5 to +5 scale. The average scores and algebraic sums were calculated to reflect implementation feasibility.

Subsequently, all recorded forces, even those reported by only one stakeholder, were brought to the attention of all stakeholders to assign them a score using the scale mentioned above. Finally, for each force, the authors determined the average score, and the algebraic sum of all forces' scores was used to compare land uses which is illustrated in Figure S4 (Supplementary Materials), and to determine whether supporting or opposing forces prevail.

While Figure S5 illustrates the cumulative volume of arguments (algebraic sums) raised by the stakeholders, Table 2 provides a normalized comparison to account for the unequal number of forces identified across the alternatives. By dividing the raw algebraic sum by the total number of forces, the Normalized Net Score reflects the true mean intensity of stakeholder perceptions. As shown in Table S8 (Supplementary Materials), the normalized ranking strongly corroborates the graphical findings of Figure S5 (Supplementary Materials). Recreational Parks maintain the highest positive consensus (+0.57), whereas Technopolis presents the highest net negative intensity (−0.40), confirming that the unequal number of forces did not skew the core directional outcomes of the FFA.

(a) Reforestation

Reforestation constitutes a complex restoration approach aiming at the re-establishment of the original ecosystem or, where necessary, its replacement. Its main benefits include landscape improvement, soil erosion prevention in steep excavation faces, enhancement of local biodiversity, and improved hydrological balance through increased infiltration and groundwater recharge. It also creates temporary employment during slope reshaping and planting works, while enabling mild recreational activities and nature-based tourism (e.g., hiking, wildlife observation). Moreover, legislation supports its application, as reforestation is mandatory when extraction took place within forest land.

However, implementation may be constrained by limited accessibility of remote quarry and mining sites, reducing visitation and eco-tourism potential. Reforestation also entails high construction and maintenance costs (e.g., backfilling, slope stabilization, topsoil placement, irrigation, and monitoring). Employment demand declines after restoration, as monitoring can be conducted remotely (drones, satellite imagery, sensors, and GIS-based analysis). Additionally, the risk of failure or slow ecosystem recovery remains significant due to climatic conditions, technical deficiencies, and inadequate maintenance.

Overall, supporting forces were found to outweigh opposing forces, indicating that reforestation is generally a favorable land-use option, as presented in Table S9 (Supplementary Materials).

(b) Recreation Park

In many cases, restoring the original ecosystem is either infeasible or not desirable. Consequently, abandoned extraction sites may be converted into new stable and beneficial land uses, contributing to broader regional rehabilitation. The transformation of post-mining landscapes into recreation parks represents an increasingly applied circular economy practice, combining nature, leisure, and education. Such projects may improve environmental quality and aesthetics, enhance quality of life, support tourism and hospitality services, and generate employment during both construction and operation.

Nevertheless, recreation parks require high initial investment and continuous maintenance funding. Additionally, distance from major urban centres and limited accessibility

may reduce visitor numbers, potentially compromising financial viability and resulting in negative economic outcomes.

Based on the FFA results, supporting forces strongly prevail, suggesting that recreation parks represent a highly promising option, as presented in Table S10 (Supplementary Materials).

(c) Construction and Demolition Waste (CDW) Treatment Facility

In several quarries and mines, existing infrastructure (excavation fronts, stockpiles, storage areas) may be reused after closure, allowing repurposing of the site and supporting economic transition through the utilization of existing facilities.

CDW includes solid waste generated from building construction, demolition, renovation, excavation works, technical infrastructure projects, and natural disasters. CDW treatment facilities are considered a suitable repurposing option for inactive or even active extraction sites and have recently gained attention in Greece. Such facilities promote recycling and material recovery, reduce demand for primary raw materials, support circular economy objectives, and contribute to compliance with national and EU targets, which require at least 70% reuse, recycling, and recovery of CDW by weight [96]. Furthermore, they may partially absorb the specialized workforce available due to the transition process.

However, potential environmental impacts include risks of uncontrolled waste accumulation and improper disposal. Proximity to settlements may increase nuisance impacts such as noise and dust from transport operations. There is also the risk of limited market absorption of the recycled materials produced. Finally, investment costs may be substantial, depending on facility scale and applied technology.

The analysis indicated that supporting forces slightly exceed restraining forces, suggesting moderate feasibility, as presented in Table S11 (Supplementary Materials).

(d) Technopolis

A Technopolis is defined as an organized area hosting low-nuisance business activities, including workshops, light industry, renewable energy installations, vehicle freight stations, logistics facilities, business incubators, and technology support centers. Quarry sites located near urban centers may be converted into Technopolises, attracting enterprises and potentially coexisting with related activities. Financial support may also be facilitated through the Just Transition Fund, which aims to enhance entrepreneurship in transition regions.

However, many businesses have already relocated outside urban areas, mainly to informal industrial clusters, making further relocation potentially unattractive. In addition, declining SME activity in recent years raises concerns about demand, while infrastructure development costs remain high.

The FFA results showed that restraining forces prevail, indicating limited attractiveness of this option under current conditions, as presented in Table S12 (Supplementary Materials).

(e) Agricultural Land Uses

Agricultural land uses in restored quarry and mining sites represent a complex restoration approach, often aiming to re-establish pre-existing land functions, as many extraction areas were previously used for crop production, livestock grazing, or beekeeping. Agricultural restoration is among the most common reclamation practices, since land return is a consistent demand of local communities, particularly in lignite mining areas where land was frequently expropriated.

Land restitution may strengthen the primary sector and support diversification towards new crops, provided that soil decontamination and slope reshaping are completed. Nevertheless, agricultural policies do not sufficiently incentivize younger generations to engage in farming. Moreover, the increasing tendency to allocate restored or undisturbed mining land to photovoltaic parks constitutes a major competing land use, aiming to preserve the energy profile of the region.

According to the analysis, restraining forces outweigh supporting forces, suggesting relatively low feasibility conditions, as presented in Table S13 (Supplementary Materials).

(f) Waste-to-Energy (WtE) Facility

Waste-to-energy plants are supplied with municipal solid waste and other residual waste streams that cannot be reused or recycled. These facilities produce energy in the form of steam, electricity, or hot water, which may be injected into the power grid or supplied to district heating systems and industrial consumers.

WtE plants can be designed at different scales, allowing siting in both small quarries and large mining areas. They may also coexist with other waste management activities. In Western Macedonia, such a facility could potentially be located in the exhausted Kardia mine field, where waste disposal and treatment infrastructure already exists (landfill, integrated management facilities, and mechanical–biological treatment unit). The plant could process residual waste from the existing Waste Treatment Plant, reducing landfill disposal. The region also benefits from a skilled workforce in energy and waste management. Furthermore, legislation and strategic environmental planning frameworks support the development of energy recovery facilities, with siting proposals already included in relevant SEA documents for the Kozani regional unit.

Economic benefits may arise through the sale of thermal and electrical energy and the recovery of secondary materials (e.g., ash, aluminum, aggregates). A key advantage is the flexibility in both plant capacity and siting.

However, WtE facilities involve high capital and operational costs and generate relatively limited employment. Environmental risks may be significant in cases of poor operation, technical failures, or excessive waste accumulation. Moreover, public opposition and criticism from environmental organizations remain common, largely driven by limited public awareness regarding the benefits and risks of the technology.

Overall, restraining forces exceeded supporting forces, indicating limited social and environmental acceptance, as presented in Table S14 (Supplementary Materials).

(g) Business Parks

Business Parks (BPs) host a wide range of secondary and tertiary sector activities. Large-scale metal and lignite mines, typically located far from urban centres and covering extensive land areas, may be rehabilitated into business parks capable of attracting major investments and potentially coexisting with other compatible activities.

Western Macedonia presents favourable conditions, including strong energy infrastructure suitable for energy-intensive industries and an upgraded road network supported by the Egnatia Motorway and its vertical axes connecting Greece with Albania and North Macedonia. These transport corridors facilitate regional connectivity and commercial flows. The new spatial planning framework also designates zones for broader development of secondary and tertiary sector activities, while the Just Transition Fund may enhance investment potential.

Nevertheless, the lack of railway connections to Balkan markets and major ports (Thessaloniki and Igoumenitsa) limits competitiveness in freight transport. Additionally, existing organized industrial areas in the region are inactive or underutilized, whereas informal industrial clustering dominates. Local communities often prioritize land restitution for agriculture and express scepticism regarding the benefits of large business parks. Furthermore, apart from road and energy networks, most required infrastructure would need to be developed from scratch, leading to very high costs. Finally, the failure of previously announced major investments has reduced public trust due to unrealized job creation.

FFA results indicated that restraining forces prevail, suggesting that business parks face significant barriers to implementation as presented in Table S15 (Supplementary Materials).

## 5. Discussion

### *5.1. Methodological Assessment*

The evaluation methodology presented above offers a structured approach to decision-making in an inherently complex field. The results are assessed through the combined application of different tools that examine both the optimization of land-use selection based on predefined technocratic criteria and the practical feasibility of the proposed land uses within a framework of the broadest possible stakeholder consensus.

It should be emphasized that the proposed methodology aims to enhance, rather than replace, the formal decision-making process related to land-use selection in post-mining areas. It does not seek to conflict with existing administrative procedures, as such an approach would render it inapplicable. Instead, it attempts to operate within the current legislative framework while simultaneously enabling stakeholder participation, acknowledging that many actors traditionally retain significant influence over final policy decisions.

The proposed methodological framework, combining IDEF0, SWOT, AHP, and FFA, reduces subjectivity by providing a transparent and structured process that limits personal bias in spatial planning. Furthermore, it enhances clarity and comprehensibility by allowing the complex process of land-use selection to be presented in a simple and illustrative manner. Finally, it strengthens participatory planning by facilitating stakeholder engagement and supporting policymakers in prioritizing socially acceptable solutions.

The SWOT analyses are time-dependent; changes in external factors, such as financial instruments or regulatory frameworks (e.g., future spatial planning for mineral raw materials and renewable energy sources), can significantly alter sustainable land-use decisions.

The results of the optimal land-use selection process for inactive quarries, metal mines, and lignite mines are not treated as a simple ranking list. Instead, they are evaluated through the comparison of two distinct approaches: the Analytic Hierarchy Process (AHP) and the Force Field Analysis (FFA).

The AHP method constitutes the core evaluation tool, enabling the assessment and ranking of land-use alternatives according to a range of environmental, economic, governance, and other criteria, as defined by expert groups for quarries, metal mines, and lignite mines.

The FFA method systematically examines the driving forces that support the implementation of each land-use option against the restraining forces that hinder it. Ultimately, decision-makers—while informed by the expert-driven AHP ranking—must carefully weigh these conflicting stakeholder perspectives and may adjust the final selection accordingly. At this stage, socio-economic filters such as social acceptance, high capital or operational costs, and the availability (or absence) of viable financing mechanisms often prove decisive. Crucially, the introduction of the normalization check confirmed the robustness of the initial ranking. By accounting for the varying volume of identified arguments across alternatives, the normalized net scores demonstrated that recreational parks command the strongest positive consensus among stakeholders (+0.57), reinforcing this option's viability from a social perspective. The evaluation demonstrates that a land use may be technically "optimal" (based on AHP results) yet practically "non-implementable" or "socially unacceptable" (based on FFA findings). This dual evaluation approach enhances the reliability and robustness of the methodological framework for transition planning in regions such as Western Macedonia.

The weighting results further indicate that environmental criteria exert the strongest influence on the initial prioritization of alternative land uses, followed by governance, economic, and regional development criteria. The predominance of environmental considerations confirms that terrain morphology, restoration requirements, and visual impacts remain the primary determinants in post-mining land-use assessment. At the same time, the high weighting assigned to governance criteria demonstrates that regulatory obliga-

tions, policy direction, and institutional oversight are regarded by experts as fundamental preconditions for successful rehabilitation planning. The strong contribution of economic and regional development criteria further reflects the expectation that post-mining land uses should not only restore environmental conditions but also generate investment opportunities, employment, and compatibility with broader regional development objectives. These findings suggest that technically optimal land-use prioritization is driven by an integrated balance between environmental restoration goals and socio-economic transition needs, rather than by purely technical or environmental considerations alone.

Despite its methodological robustness, the effectiveness of the proposed framework depends on the institutional and participatory conditions under which it is applied. While the framework enhances transparency and supports structured decision-making, its outcomes may be compromised when stakeholder participation is not undertaken in good faith or when institutional actors prioritize strategic or sector-specific interests that are not fully aligned with the broader objectives of sustainable regional development. Under such conditions, the evaluation process may formally retain its participatory character while substantively reproducing pre-determined preferences, thereby reducing the practical value of the methodology. Consequently, the successful application of the framework requires not only technical rigor but also a governance environment capable of ensuring balanced representation, transparent decision-making, and genuine consideration of evaluation outcomes in the final land-use selection process.

An additional advantage of the proposed framework is its capacity to support long-term monitoring and adaptive land-use management. The methodology is designed in a way that allows its repeated application either entirely, for instance, when significant regulatory, economic, or planning conditions change, or partially through the re-evaluation of the later stages when new land-use alternatives are proposed by public authorities or potential investors. This iterative character enables the framework to function not only as a one-off decision-support tool but also as a flexible mechanism for periodically reassessing land-use priorities, ensuring that post-mining transition planning remains responsive to evolving environmental conditions, stakeholder expectations, and development opportunities over time.

### *5.2. Land-Use Selection in Post-Mining Areas of Western Macedonia*

The challenges of transition in Western Macedonia, the case under study, particularly in the context of land-use allocation in quarries, metal mines, and lignite mines, are highly complex and multidimensional. The region is at a critical juncture due to the accelerated energy transition and lignite phase-out, making the identification of realistic and economically viable alternatives imperative.

The main challenges identified can be summarised as follows:

Methodological and Strategic Gaps: Despite the emphasis on lignite mine closure, systematic methodological evaluation of alternative land uses across different extractive activities (lignite, metals, quarries) remains limited. Decisions are often based on fragmented criteria, focusing primarily on environmental or technical parameters, while social acceptance, cultural identity, and long-term economic resilience are not consistently integrated.

Institutional and Spatial Planning Barriers: A major challenge is the absence of a Special Spatial Framework for Mineral Raw Materials, which would provide fundamental and nation-wide spatial planning guidelines for the sector in relation to existing land uses. In addition, Local Urban Plans and Special Urban Plans for lignite phase-out zones remain under preparation or are incomplete.

Economic and Social Viability: The transition requires the preservation of social cohesion and mitigation of economic decline. New productive activities must compensate

for lost income and employment, such as Business Parks or Waste-to-Energy (WtE) facilities. However, high restoration costs, limited cooperation culture, and bureaucratic barriers pose significant obstacles.

Land-Use Conflicts: Conflicts emerge between traditional land uses (e.g., agriculture) and new investments such as large-scale photovoltaic parks aimed at maintaining the region's energy profile. Moreover, social resistance and lack of trust, due to unfulfilled promises regarding job creation, complicate the implementation of major projects, including Business Parks.

The scoring of the four alternative land uses proposed for each of the three cases (quarries, metal mines, and lignite mines) highlights a challenging reality: stakeholders maintain high expectations for the post-lignite era. In the case of metal mines, Waste-to-Energy and Agricultural land uses barely reached the minimum scoring threshold. In contrast, none of the four alternatives achieved a satisfactory score if lignite mines are considered. Only in the case of quarries did Forests and Recreation Parks achieve a score significantly above the scale's midpoint.

A particularly important finding concerns the divergence observed between expert-based prioritization and stakeholder assessments. While expert evaluations assigned high importance to governance and regional development criteria, stakeholder responses revealed that implementation feasibility depends not only on technical suitability but also on institutional credibility and social acceptance. In Western Macedonia, stakeholder attitudes appear to reflect accumulated distrust arising from previous governance failures, including controversies over settlement relocations, perceived non-compliance with environmental regulations, contested waste facility siting decisions, and the prioritization of large-scale renewable energy investments over community-based initiatives. Repeated announcements and subsequent cancellations of major transition projects, such as green hydrogen and battery production investments, have further weakened confidence in regional planning. As a result, even technically well-ranked alternatives may be perceived as inadequate to offset the economic losses associated with lignite mine closure.

This finding suggests that improving implementation feasibility requires targeted strategies to rebuild trust and strengthen stakeholder acceptance. Previous studies indicate that social acceptance of contested land uses can be enhanced through transparent decision-making, early stakeholder involvement, and the fair distribution of local benefits. For example, Segreto et al. [98] emphasize that renewable and infrastructure projects gain greater legitimacy when local communities are engaged from the planning phase and when economic benefits, such as employment opportunities or community revenue-sharing mechanisms, are made visible. Similarly, Liu et al. [99] show that public acceptance of waste-to-energy projects can be significantly improved through participatory planning, transparent environmental communication, and compensation measures tailored to local concerns. Therefore, the feasibility of post-mining land-use strategies depends not only on their technical merits but also on the capacity of institutions to foster trust, ensure procedural fairness, and demonstrate tangible local benefits [100,101].

Notably, for lignite mines, all four proposed land uses received the lowest environmental score. This finding reflects a generalized negative predisposition toward any planned intervention, likely attributable to:

(a) High expectations fostered regarding future industrial investments in the post-lignite era;
(b) Delays in activating financial support mechanisms for the regional economy;
(c) The emergence of a new, mono-dimensional development model centred on the construction and operation of large-scale photovoltaic and wind parks by major energy corporations.

Information Gaps: Access to historical environmental data (before 2012) through the Electronic Environmental Registry remains difficult, hindering comprehensive restoration planning. Furthermore, many abandoned and unregistered quarries require systematic management.

The above findings demonstrate that the transition requires a shift from simple ecological restoration toward strategic repurposing and co-purposing approaches. The literature supports the application of multicriteria decision-making methods (such as AHP and FFA) to reduce subjectivity and enhance transparency in spatial planning, thereby contributing to a just and sustainable transition.

Beyond the case of Western Macedonia, the proposed framework offers theoretical insights that may be applicable to other extractive regions undergoing socio-economic transition. Its integrated structure can be adapted to different territorial contexts through the adjustment of evaluation criteria, weighting priorities, and stakeholder inputs according to local environmental, economic, and institutional conditions. This adaptability makes the framework particularly relevant for former mining regions facing similar challenges of economic restructuring, environmental rehabilitation, and social acceptance, such as those in Germany, Poland, and the Czech Republic. However, the transferability of the framework depends on the institutional capacity of each region to support participatory planning processes and to integrate evidence-based evaluation into formal land-use decision-making. Therefore, while the methodological structure is broadly transferable, its effectiveness remains context-dependent and closely linked to the governance capacity of the planning environment in which it is applied.

### *5.3. Methodological Limitations and Future Work*

While the proposed framework offers a structured spatial decision-support tool, certain methodological limitations must be acknowledged. First, the evaluation relies on a specific panel of experts and stakeholders; although highly qualified, their judgments introduce a degree of inherent subjectivity. Second, the aggregation of these individual preferences was performed using the geometric mean method, which, despite being a standard AHP practice, may smooth out extreme but potentially valid individual consensus variations. Third, as previously justified, the 26 sub-criteria were excluded from direct pairwise comparisons to eliminate cognitive overload and maintain mathematical consistency, restricting their role to qualitative contextual guidelines. Finally, the validation and transferability of the framework are currently bounded by the distinct legislative, environmental, and spatial characteristics of the Region of Western Macedonia. Future research will focus on expanding the stakeholder sample size, utilizing fuzzy-AHP variants to better handle epistemic uncertainty, and testing the framework's transferability in different geographical regions facing post-mining transition challenges.

## 6. Conclusions

The main conclusions of this study highlight the potential utility of the proposed methodological framework and indicate a noticeable divergence between institutional planning and business practice:

- Divergence between institutional framework and practice: The land uses and selection criteria proposed by Greek legislation, special spatial frameworks, and transition plans (e.g., the Just Development Transition Plan) do not fully coincide with those ultimately selected and implemented by mining and quarrying enterprises.
- Land uses proposed by the experts (AHP Results): Application of the AHP multicriteria method identified Recreation Parks as the optimal solution for quarries and Waste-to-Energy (WtE) facilities for mines.

- Divergence of experts and stakeholders' opinions (AHP vs. FFA): The results of AHP do not always align with those of FFA. While convergence was observed for recreational parks development in post-quarrying lands, in the case of metal and lignite mines, the WtE option was not considered appropriate under FFA, as restraining forces (e.g., limited social acceptance and high cost) outweighed the driving forces.
- Methodological contribution: The adopted methodological framework (IDEF0, AHP, FFA) proved to be a highly structured approach, as it clearly and systematically presents the complex process of land-use selection, producing practical and policy-relevant insights.

An important policy implication of this study lies in highlighting the gap between the availability of structured decision-support methodologies and the limited institutional capacity of existing governance frameworks to formally incorporate their outcomes into binding land-use decisions. The methodological framework proposed in this study enables the qualitative and quantitative evaluation, ranking, and selection of post-mining land-use alternatives through a transparent and systematic process that combines expert judgment with stakeholder participation. In this respect, it provides a practical mechanism that has the potential to enhance the perceived legitimacy and foster broader social acceptance of post-mining planning decisions, although these conceptual benefits require further empirical validation in future field implementation.

However, a significant limitation remains at the institutional level. Although public consultation mechanisms exist within legislative, environmental, and spatial planning procedures, the outcomes of these processes are generally advisory rather than binding, and public authorities are not formally required to adopt structured participatory evaluation methods in final decision-making. As a result, scientifically robust and socially supported land-use alternatives may not necessarily be reflected in the decisions ultimately implemented. This institutional weakness limits the practical effectiveness of integrated planning approaches and could potentially undermine stakeholder trust in the planning process.

Nevertheless, the framework developed in this study represents an important step towards more participatory and evidence-based land-use governance. By incorporating not only expert assessments but also, in a distinct evaluation phase, the views of stakeholders who will ultimately experience the long-term impacts of post-mining land-use decisions, the methodology seeks to strengthen the democratic framework of planning outcomes. In this sense, stakeholder participation extends beyond consultation, as the degree to which local preferences are acknowledged may structurally influence the broader social and political viability of administrative decisions. This need for stronger integration between technical evaluation, stakeholder engagement, and institutional decision-making is also highlighted in other coal transition regions. Evidence from Germany shows that successful coal phase-out policies relied not only on economic compensation measures but also on long-term institutional coordination and the active involvement of regional actors in shaping transition pathways, while comparative analysis across multiple coal regions demonstrates that socially accepted post-mining transitions depend on governance frameworks capable of balancing environmental restoration objectives with local employment and development priorities. These findings suggest that the success of post-mining transitions in regions such as Western Macedonia increasingly depends on governance models that effectively align environmental rehabilitation goals with local socio-economic expectations.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182111014/s1, Table S1: Systematic Literature Review (SLR) Protocol; Table S2: International Land Use Classification (12 categories and 38 subcategories); Table S3: Land use classes proposed by institutional and strategic planning directions for Western

Macedonia; Table S4: Summary of land-use classes and subclasses identified in planning frameworks and environmental licensing documentation; Table S5: SWOT analysis for inactive mines and quarries in Western Macedonia needing rehabilitation; Table S6: Land use selection criteria for post-mining areas; Table S7: Pairwise comparison of criteria using the AHP method; Table S8: Raw cumulative scores, number of forces, and normalized net scores for the evaluated land-use alternatives; Tables S9–S15: Detailed Force Field Analysis (FFA) Matrices and Stakeholder Scores for the 7 Alternative Land Uses (Reforestation, Recreation Park, CDW, Technopolis, Agriculture, WtE, Business Park); Figure S1: Analytical Map of Active and Inactive Quarries; Figure S2: Analytical Map of Active and Inactive Mines; Figure S3: Groups of Criteria for Post-Mining/Quarrying Land Use Classification; Figure S4: Regulatory framework for Post-Mining/Quarrying Land Use; Figure S5: Algebraic sums of scores assigned to forces act for and against the proposed land uses.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| EIA | Environmental Impact Assessment |
| ESIA | Environmental and Social Impact Assessment |
| SEIA | Strategic Environmental Impact Assessment |
| DAEC | Decision Approving Environmental Conditions |
| NECP | National Energy and Climate Plan |
| SSPF | Special Spatial Planning Framework |
| RSPF | Regional Spatial Planning Frameworks of Western Macedonia |
| SUP | Spatial Urban Planning |
| ESG | Environmental, Social, and Governance |
| JTP | Just Transition Plan Greece |
| TJTP | Territorial Just Transition Plan Western Macedonia |
| JTF | Just Transition Fund |
| JMD | Joint Ministry Decision |
| S.W.O.T. | Strengths, Weaknesses, Opportunities, Threats Analysis |
| HS Laws | Health Safety Law |
| BAT's | Best Available Techniques |
| IBRD | International Bank for Reconstruction and Development |
| IDA | International Development Association |
| GIS | Geographical Information Systems |
| AHP | Analytical Hierarchy Process |
| FFA | Forcefield Analysis |
| WtE | Waste to Energy |
| CDW | Construction and Demolition Waste |

| | |
|---|---|
| WTP | Waste Treatment Plant |
| MSW | Municipal Solid Waste |
| PMLU | Post-Mining Land Use |
| RES | Renewable Energy Sources |
| UDS | Uncontrolled Waste Disposal Sites |
| MCDM | Multicriteria Decision-Making |

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