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Sustainable Rehabilitation of Surface Coal Mining Areas: The Case of Greek Lignite Mines

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Received: 2 July 2020; Accepted: 31 July 2020; Published: 3 August 2020

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Abstract: Surface lignite mines of the Balkan Peninsula face growing pressure due to the CO_2 emissions reduction initiatives, rapidly increasing renewable-power capacity, and cheap natural gas. In this frame, the development of a modern mine land rehabilitation strategy is considered as a prerequisite for mitigating the social and economic impacts for the local communities. In the case of western Macedonia lignite mines, these prospects are investigated based on a PEST (political, economic, social, technological) analysis of seven alternative land uses. Urban (industrial) development, green houses, and industrial heritage parks are considered as the most appropriate land uses for mitigating the socioeconomic impacts due to the loss of employments. For the land uses occupying large areas (i.e., agriculture, forestry, livestock farming, and photovoltaic parks), an optimisation algorithm is proposed for determining the mix of land uses that maximise revenue, equity, and natural conservation and minimise investment. The algorithm was applied using the opinions of 10 experts, who were involved in mine land reclamation projects carried out in the western Macedonia region in the recent past. According to the results obtained, photovoltaic parks are rated as a more attractive investment than extensive agriculture, as regards the anticipation of revenues, while livestock farming and forests are necessary to safeguard the ecosystem's functions.

Keywords: coal; lignite; mines; reclamation; rehabilitation; land use; decision-making; optimisation; sustainability

1. Introduction

The European Green Deal is the response of the European Union (EU) to the climate and environmental-related challenges that are the defining task of this generation. It is a new development strategy that aims to transform the EU into a fair and prosperous society with a strong and competitive economy, where growth is decoupled from intensive resource use and there are no net emissions of greenhouse gases [1]. By signing the Paris Agreement, the EU made an official commitment to undertake certain measures for limiting global warming to "well below 2 °C" [1–3]. Then, in November 2018, the European Commission released a long-term strategic vision to reduce greenhouse gas emissions, between 80% and 100% compared to 1990. In fact, the ambitious goal of a 100% reduction of greenhouse gases represents a climate-neutral economy [4].

In order to achieve this goal, the EU will need to rapidly decarbonise its power sector. However, the implementation of this strategy poses significant technological, economic, and social challenges [4]. Coal infrastructures exist in 108 European regions. It is estimated that the coal sector currently employs about 237,000 people (185,000 work in coal/lignite mines). Poland employs about half of the workforce of coal/lignite mines and thermal power plants, followed by Germany, the Czech Republic, Romania, Bulgaria, Greece, and Spain [2].

Coal and lignite-fired thermal power plants face overwhelming regulatory pressures to lower greenhouse gas emissions. Power plants also face increasing competition from growing renewable-power capacity and from lower natural gas prices, trends that are developing against a backdrop of stagnating demand. While European year-ahead (2019) coal prices have dropped to about $66 per ton from more than $100 a year ago, EU carbon permits have escalated fivefold since 2017. As a consequence, the current cost of burning coal is significantly higher [5] and coal-fired power plants are becoming unprofitable as they have experienced losses worth €6.6 billion in 2019, according to a new study by the British think tank "Carbon Tracker" [6]. The most exposed utilities are the German RWE, the Czech EPH, and the Greek Public Power Corporation SA (PPC) who could haemorrhage about €2 billion in 2019 [2,7].

The above-described situation is particularly true for the lignite-intensive regions of the Balkan countries that have to be prepared for the reduction or phasing-out of mining and lignite power generation activities [7]. The dependency of these regions on the lignite exploitation resulted in limited growth of other economic sectors. This is related to a socioeconomic phenomenon known as "lock-in": A tendency for incumbent industries to actively resist the diversification of the local economy in order to avoid competition for economic resources [8]. This fact, combined with indirect impacts of mining on the quality of environment, properties' value, and health, leads to a vicious cycle, whereby the deteriorating attractiveness of the regions for new investments makes them ever more reliant on the lignite exploitation [8]. However, many coal dependent regions perceive decarbonisation driven by environmental considerations only as a process with adverse socioeconomic impacts, which expose local communities to unnecessary turbulence with unpredictable flow-on effects [7].

Despite the aforementioned obstacles, the reduction or phasing-out of mining and coal power generation activities is considered as one of the most cost-effective methods to achieve emissions reduction due to both market-driven and regulatory trends [6]. Under these circumstances, the economic importance of coal mining has decreased. Coal mining regions have lost a considerable part of their economic base and are facing structural changes [3]. Wuppertal Institute has published an analysis of common characteristics and site-specific differences of four coal-dependant European regions: Silesia PL, western Macedonia EL, Aragon ES, and Lusatia DE [9]. The analysis is focused on the distinction between the hard coal-producing region of Silesia and the lignite-producing regions. Silesia exhibits a high level of urbanisation. It is also strongly industrialised, with many sectors having considerable shares in regional GDP. On the contrary, lignite-producing regions remain rural areas with low population densities, where mines and thermal power plants are the main providers of jobs [9].

In this context, the Greek government announced the abolition of lignite-based electricity generation by 2028 and the increase in electricity generation via RES to 35% by 2030. Under the new strategy, there will be an ambitious program to accelerate the reduction of lignite-based power generation over the next decade [10]. Given the fact that 69% (2019) of Greece's lignite production takes place in the region of western Macedonia, this area will be at the heart of the energy transition, with all the threats but also opportunities that this entails [7,10].

Taking into account the fact that the climate mitigation is a collective effort in Europe, it seems fair that coal/lignite mining regions should receive support to master the challenges of this transition [2,3]. The Greek government is currently preparing a new comprehensive action plan for this purpose [10]. An essential part of this plan are the contributions granted via various European resources, such as the Fair Transition Fund and other financial mechanisms. However, the success of this plan relies on the decisions made by local and regional authorities regarding the development of new sustainable economic activities in the post-mining era [11]. Although actions aiming at the diversification from existing economic activities depending on lignite are necessary, first and foremost, the development of the optimum mix of land uses on the reclaimed mining areas is critical for achieving sustainability targets at the local and regional level.

The main objectives of this contribution are the determination of a series of sustainability criteria and indicators and, to a next stage, the development of an evaluation process for various land rehabilitation scenarios. This process is validated in the case of the western Macedonia lignite centre, a complex of surface mines that was the main pillar of the energy sector of Greece for more than six decades. More specifically, the paper is organized as follows: The second section provides background information on the evolution of the lignite industry in the western Macedonia region, the current situation and the perspectives of the local economy during and after the transition to a zero-lignite era, and the results of the mine land reclamation works carried out so far. The third section proposes a series of land uses that are considered to fit better in the examined case for amortising decarbonisation stresses, based on the circular economy principles and the founding tools available in the frame of the European Just Transition Mechanism. The fourth section describes a procedure for the evaluation of various land rehabilitation scenarios based on a PEST analysis and an optimisation algorithm that takes into account the criteria of revenues, investment cost, conservation of nature, and equity. In addition, the third section and the initial paragraphs of the fourth section provide references supplementary to these presented in the introduction, which strengthen the author's claims and suggestions. Finally, the last two sections provide a short discussion and conclusions.

2. Background

2.1. The Lignite Mines of Western Macedonia

Starting in the early 1950s, the lignite industry has critically shaped the development of western Macedonia. The decision to intensify the exploitation of domestic lignite deposits has been a central political option, supported by all Greek governments over the years. Up to now, 1.7 billion tons of lignite have been produced and more than 8.5 billion cubic metres of rocks have been excavated from four surface mines (Figure 1). The remaining exploitable reserves in the lignite field under exploitation by Public Power Corporation SA are estimated to be 820 million tons, while private mines reserves are 120 million tons. Public Power Corporation SA also has the rights to exploit 460 million tons of lignite located in areas where mining activities have not been developed so far [12].

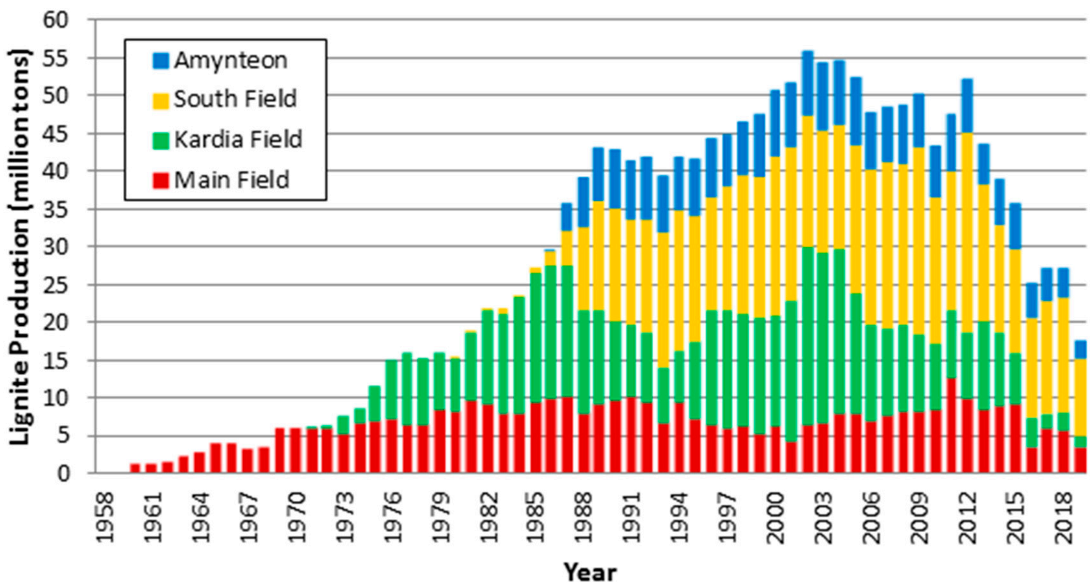

Figure 1. Lignite production of the western Macedonia Lignite Centre [12].

The lignite deposits of western Macedonia belong to an elongated sedimentary basin with a length of 250 km, which extends to NW into the SW territories of north Macedonia (Figure 2) [13]. The basin is divided into two elongated grabens with different stratigraphic evolution and subsurface morphology.

The basin formation occurred at the end of the Tertiary era and its creation is considered to be a consequence of subsidence in large NW–SE fault zones [14,15]. The different sedimentation rates of the basin resulted in frequent intercalation between the lignite layers and the sterile, which consist, mainly, of marls and subsequently from clay and sand. As a consequence, the lignite deposits are characterised by a multiple-layered form, which deteriorated considerably the quality characteristics of excavated lignite compared to these of geological lignite due to the unavoidable co-excavation of sterile. The basement underlying the sedimentary basin includes Paleozoic schists, ophiolites, and granites. Above the basement lays the Pelagonian Structural Zone, which consists from Mesozoic dolomitic limestones, interlaying with volcanic sediments with ophiotic blocks, and flysch. The basin itself consists from Tertiary and Quaternary sediments with a maximum thickness of 1000 m. The upper part of the basin is filled with Miocene to Pliocene sand, sandy clay, lignite, and marl, mainly of fluvial to lacustrine origin. More specifically, in the surface lies the Quaternary sediments, then the Plio-Pleistocene unit that has a thickness of 20–100 m and consists of sand and clay, which intercalate with marls and conglomerates. Below this sequence lies the Plio-Miocene deposits consisting of layers of lignite and sand. These sediments are rich in $CaCO_3$ since it can be found in all the sediments of the sequence, including the lignite [14].

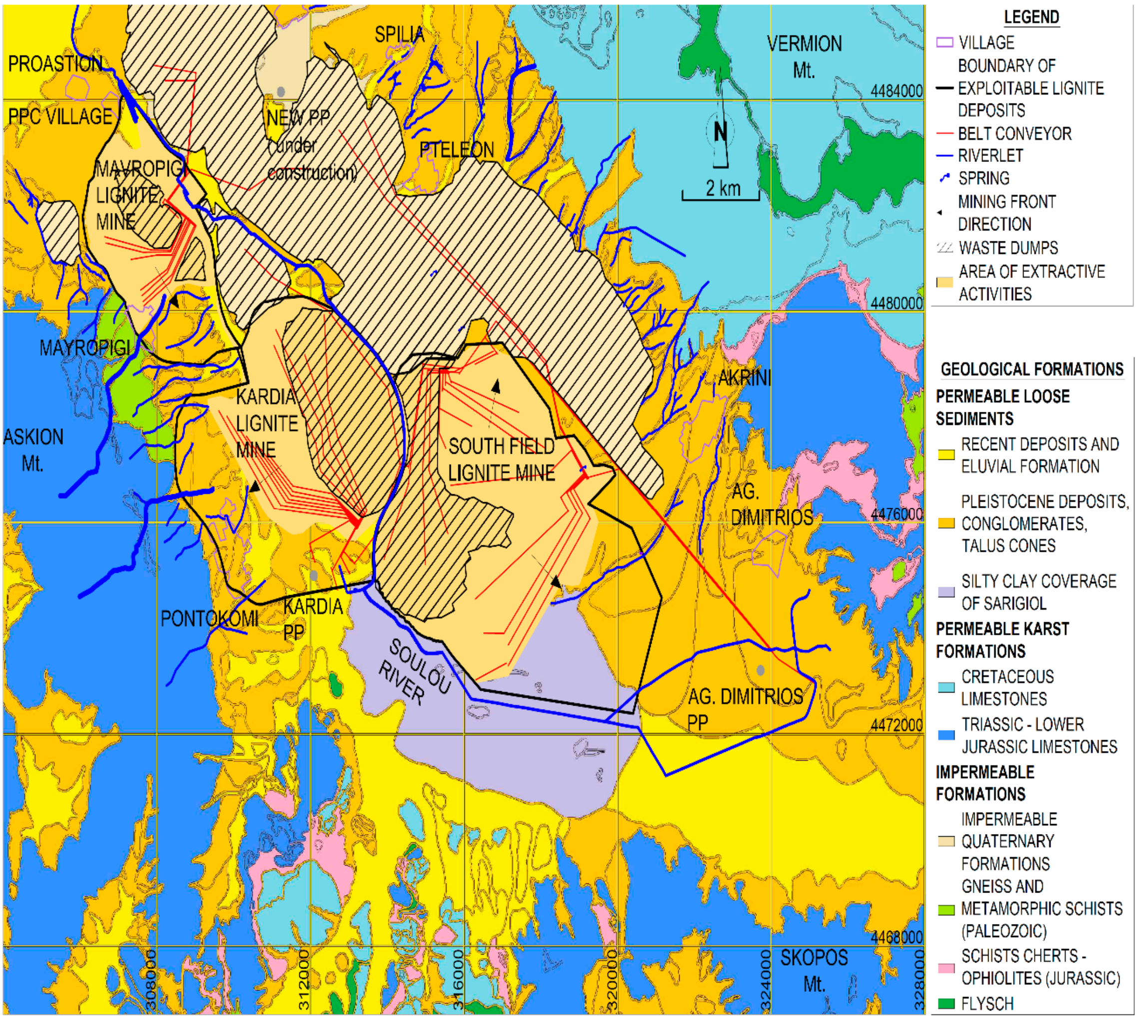

Figure 2. Geological map of the western Macedonia Lignite Centre (Ptolemaida mines) [13].

Nowadays, the mines occupy 17,000 ha (Figure 3). The area that was gradually expropriated for mine development purposes was mainly agricultural. Forests covered limited areas, usually close to watercourses. Moreover, several villages that were located in close proximity to the mines have been resettled [12].

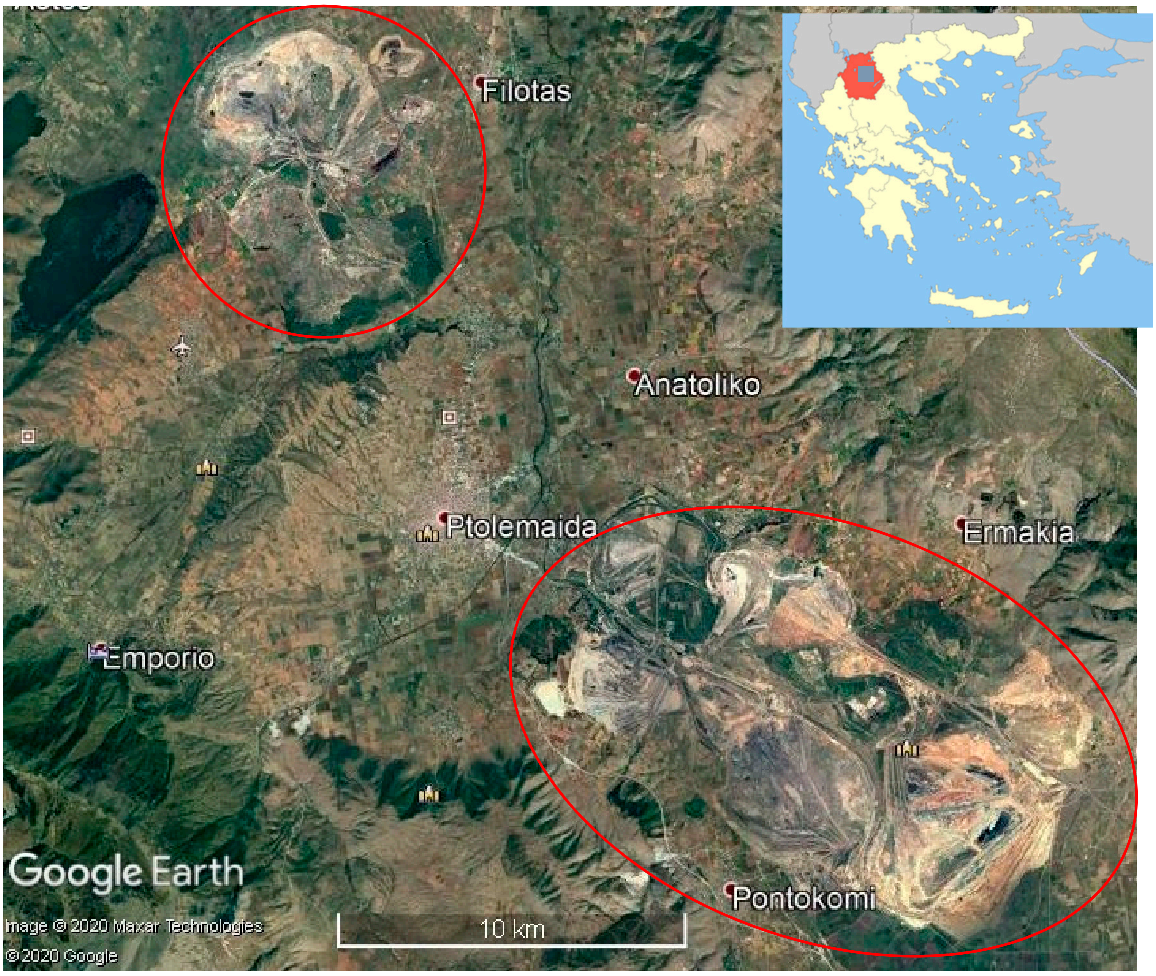

Figure 3. Satellite view of the western Macedonia Lignite Centre, with the red curves indicating the two mining areas: Amynteon (NW) and Ptolemaida (SE).

The mines have been equipped with 42 bucket wheel excavators, 250 km of belt conveyors and 17 spreaders, while shovels and trucks are used for the excavation and transportation of the hard rocks that are present in the overburden strata. These formations usually require blasting. In the last year (2019), 17.7 million tons of lignite and 130 million cubic metres of rocks were excavated from the four active open-cast lignite pits. This production rate is significantly lower than the record figures of 55.8 million tons of lignite (2002) and 332 million cubic metres of rocks (2005). The mines meet the fuel demand of 11 thermal power units with a total installed capacity of 3737 MW, which should be gradually reduced due to the EU decarbonisation targets that are fully adopted by the Greek government [12].

Regarding water management, this is a critical issue for the operation of the surface mines and the implementation of the environmental protection and land reclamation programme. For this reason, a complex system of seven pumping stations, which also serve as sedimentation ponds, and numerous wells, which are responsible for the drop of the groundwater table around the pits, have been developed [14]. A small river that flows into Lake Vegoritis receives surface water and groundwater discharges pumped from the mines. The river has already been relocated a few times for the needs of the expansion of the mine's exploitation. Under normal operating and weather conditions, the river receives annually more than 40 million cubic metres [14]. The quality characteristics of the water allow its use for dust depression in-pit, irrigation, or even for water supply purposes. Deviations from water quality standards usually refer to the concentrations of suspended solids and electric conductivity values. Problems with acidic drainages have never been detected due to the presence of minerals rich in CaO in the entire lignite-bearing basin [15].

2.2. Western Macedonia Decarbonisation Impacts

The lignite industry has critically shaped the development of western Macedonia. For many decades, more than 25% of the regional GDP (gross domestic product) and more than 22,000 direct and indirect jobs have been unilaterally supported by local lignite activity needs [16].

Based on Hellenic Statistical Authority data, the use of an input-output model methodology for the period 2000–2016 showed that there is a direct correlation between lignite production and jobs. For every million tons of lignite produced, 185 jobs are maintained in the mining-energy sector and 725 jobs are created in the local labour market; this is a ratio of 1:3.9. The correlation of annual lignite production rates and employment in the western Macedonia region is illustrated in Figure 4. Although the R^2 value of the linear regression line of total employment is not high, the number of jobs in western Macedonia in 2028, when the lignite output will be zero, is estimated to exceed marginally 70,000 (i.e., 24% compared to year 2014), unless strong impact mitigation interventions are implemented [17].

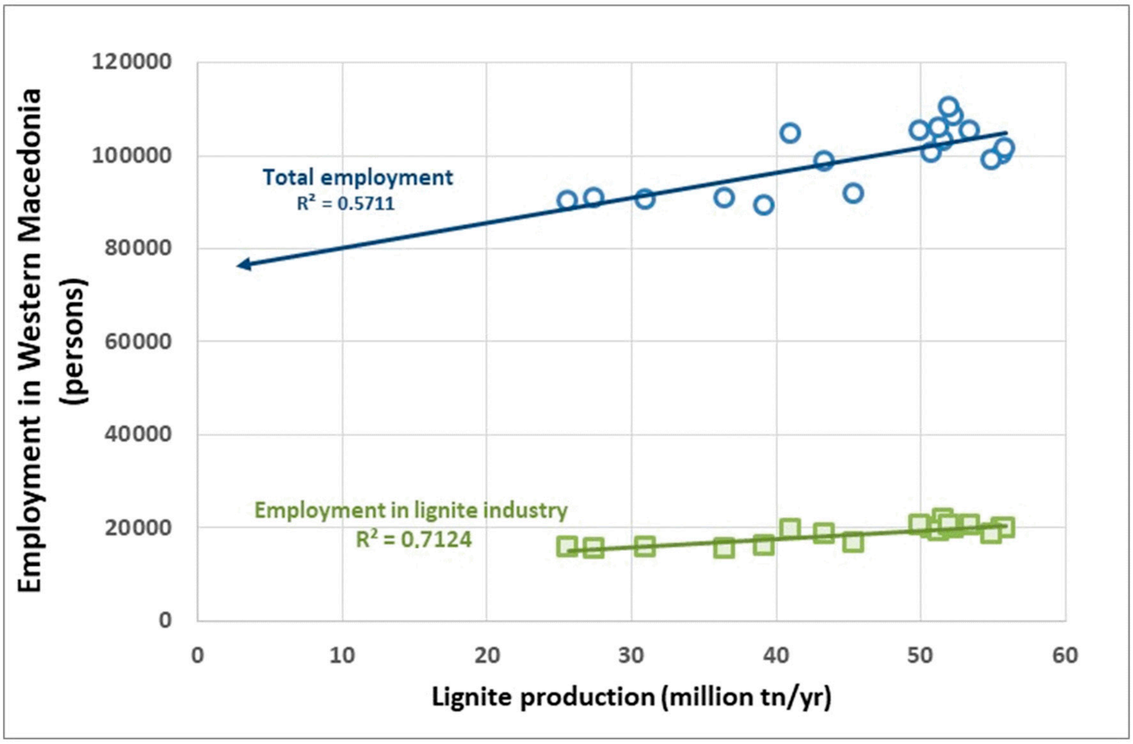

Figure 4. Lignite production and employment in western Macedonia.

Moreover, the regional GDP was very sensitive to the slight increase of lignite production during the period 2000–2005 (Figure 5). In the next years, when lignite production collapsed from 55.0 million tons in 2005 to 25.6 million tons in 2016, this correlation weakened (i.e., the slope of the blue regression line in Figure 5 is smaller than the one of the red line). This is probably due to deterioration of the stripping ratio, which kept the total rock excavations almost constant until 2013. The strong correlation of regional GDP with the excavated rock volumes is illustrated in Figure 6. In particular, this figure demonstrates how the regional economy is affected by the rock-moving works carried out by subcontractors of Public Power Corporation SA [16,17].

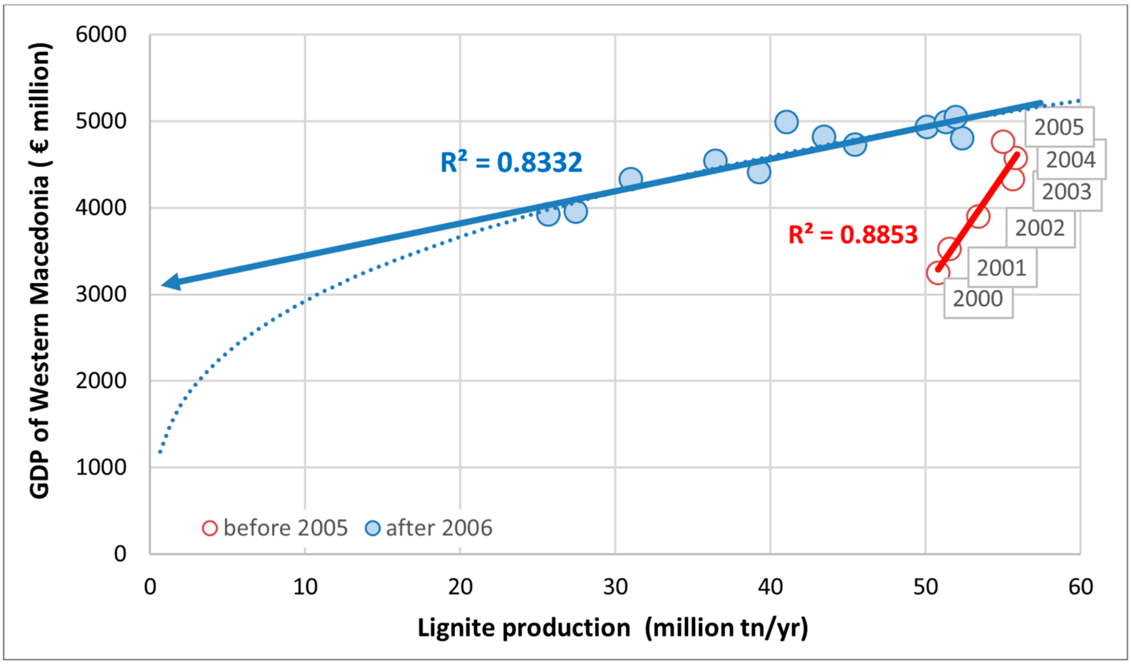

Figure 5. Correlation of GDP of the western Macedonia region and annual lignite production.

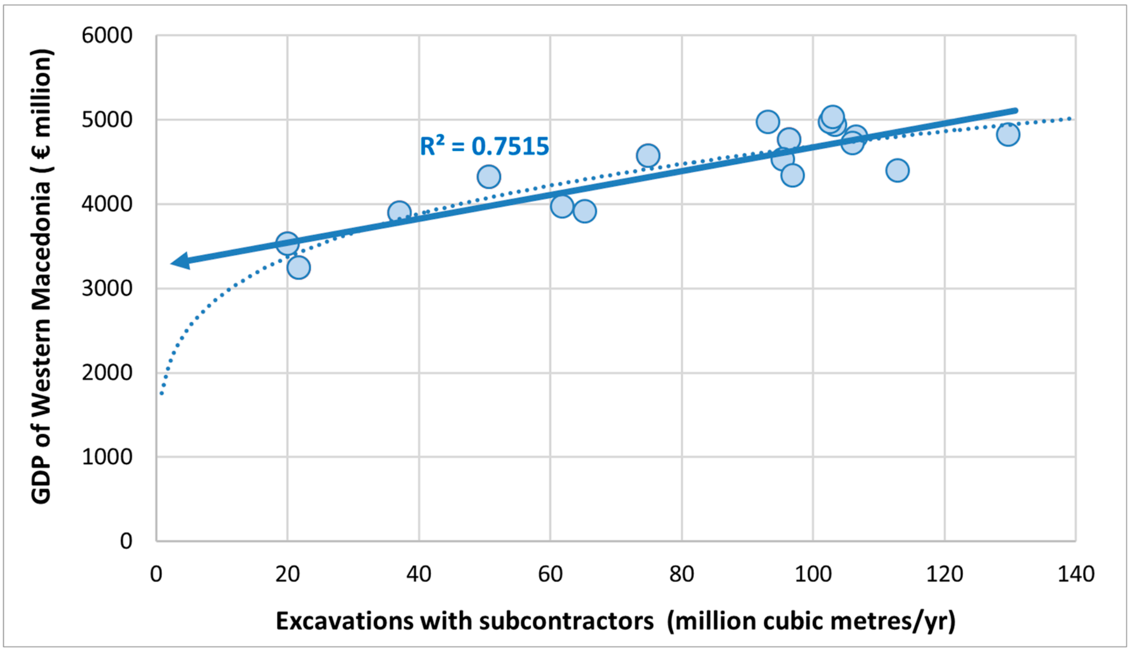

Figure 6. Correlation of GDP of the western Macedonia region and annual excavations carried out by subcontractors operating in lignite mines.

Based on the data presented in Figures 5 and 6, it can be predicted that, with zero lignite production and zero excavations in 2028, the GDP of west Macedonia will be moved between €3.2 billion (linear regression) and €1.5 billion (power regression). In the first case, if regional GDP is €3.2 billion, the wealth loss of the region of west Macedonia will reach 27%. In the second case, if regional GDP shrinks to €1.5 billion, urgent political intervention will be necessary to minimise demographic changes and to reduce economic and social impacts in the long term [17].

Summarising the effects of decarbonisation in the western Macedonia region and having as a reference the year 2013, the zero lignite production in 2028 is expected to bring the following consequences [11,16,17]:

– GDP decline by 26% and an annual loss of revenue of €1.2 billion.
– Loss of 21,000 jobs and an employment reduction in 24%.
– Total income loss for the period 2013 to 2028 of €9 billion.

Jobs loss and regional GDP reduction as a consequence of the withdrawal of lignite plants in the period 2009–2016 are presented in Figure 7, combined with a prediction for the year 2028, when lignite production is expected to be zero [17]. The above-presented Figures 4–7 make clear that western Macedonia's long-term dependence on the lignite cancelled every developmental effort, which was quantitatively reflected in low productivity diversification and low innovation rates. Moreover, it has created conditions that cannot be addressed by corrective interventions but require long-term productive restructuring policies, based on the competitive advantages of the wider region of west Macedonia. A key component of these policies should be the rehabilitation of the surface lignite mines.

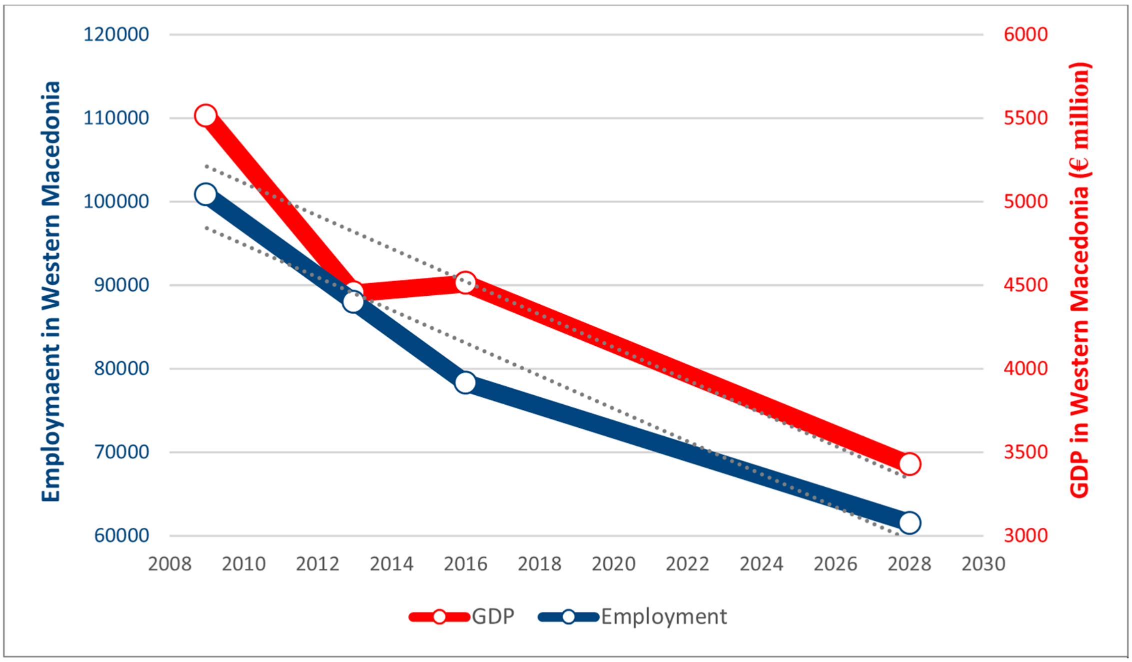

Figure 7. Forecast of GDP—employment progression in Western Macedonia.

2.3. Land Reclamation of Western Macedonia Lignite Mines

In Greece, all mining and quarrying activities operate according to the revised regulations determined in a ministerial decision amended in 2011. Moreover, mines and quarries have to meet quality standards and to apply preventive and mitigation measures that are described in numerous national laws and European directives [18].

Nevertheless, the main legal tool that regulates all environmental management decisions of a mining company is the environmental permit. The first permit referring to the mining activities at the western Macedonia lignite mining complex was signed in 2001, after a long period of negotiations with all the involved local and national authorities. Since then, additional permits have been signed for all mining operations, as well as for numerous auxiliary activities, such as the ash and asbestos cement disposal sites [18,19].

The main issue introduced by the permits is the implementation of a land reclamation programme according to specific guidelines dealing with waste heaps topography, landslides prevention, topsoil management, and reforestation [19]. Permits also refer to the costs of implementing the above-mentioned terms and conditions for the permitting period and until mine closure/rehabilitation (Table 1). This cost includes all the activities required for environmental management during mining operations and land reclamation according to the plans that have been approved by the authorities.

In addition, to compensate the adverse impacts of lignite mining on the environment and on other sectors of the local economy, the mine operator pays a revenue bond, which corresponds to 0.5% of its turnover. The total amount of money that has been paid from PPC so far (2018) is ca. €260 million and has been distributed to the prefectures, where lignite mining activities exist, accordingly to the produced lignite quantities. The regional authorities have taken full responsibility for selecting and implementing the development projects that are financed by this bond [18,19].

Table 1. Cost of implementing the terms and conditions of environmental permits [19].

Mine Complex.	Total Area Occupied (ha)	Environmental Cost until Permit Expiration (€)	Environmental Cost until Mine Closure—Reclamation (€)
Ptolemaida	14,792	25,000,000	90,000,000
Aminteo	5294	8,000,000	40,000,000

The development of a progressive land reclamation plan, which will be implemented throughout the entire life of the lignite mines, is a critical part of a successful land management strategy. Land reclamation ensures that the post-mining landscape is safe and is stable from physical, geochemical, and ecological perspectives; the water quality is protected; and a reliable environmental quality monitoring system has been installed [20]. Land reclamation is based on the map of land uses (Figure 8), which is contained in the Environmental Impact Assessment study that has been approved by the Ministry of Environment [20,21]. This map is subject to modifications when the permits are expired (usually every 10 years) and a new environmental impact assessment study is elaborated. The revised map of land uses may incorporate modifications relevant to the planning of the mines as well as changes of the type and spatial distribution of land uses.

Up to now, 3700 ha of mine land have been reclaimed. The usual reclamation practices include the development of farming lands in horizontal areas on the top of the waste heaps, and the reforestation of the sloped surfaces of the heaps' margins. The cultivated land is rented to local farmers and is seeded with wheat. The yields achieved vary considerably from site to site but, in general, are comparable to these reported for crops developed in the surrounding areas [22]. However, a study conducted by the Aristotle University of Thessaloniki showed that the development of agricultural activities in reclaimed mine lands cannot compensate for the job losses due to the mines' closure and power plants' decommissioning [23]. This situation does not change taking into account also the jobs related to honey and biomass production from reforested areas [24]. In this frame, for the near future, it is expected that PPC will continue the reforestation of sloped surfaces and the development of agricultural land in horizontal surfaces and, eventually, will start to construct photovoltaic parks in large horizontal plots of the waste heaps. Taking into account the topography of the pits and waste heaps and the hydrogeological conditions, it is estimated that 8% of the total area occupied by the mines will be covered by artificial lakes [21]. The remaining area can be used for livestock farming and reforestation, while 55% of this area is appropriate for agricultural activities and photovoltaic parks.

No matter what the development plans of PPC are and the commitments of the central government and regional authorities on the decarbonisation policies that will be applied in western Macedonia, the reclamation of the mine land is a legal obligation. In the following paragraphs, numerous arguments that prove the necessity of going with land reclamation one step further to land rehabilitation focused on the realisation of development programmes and innovative land uses that enhance the perspectives of the local economy are presented, among others.

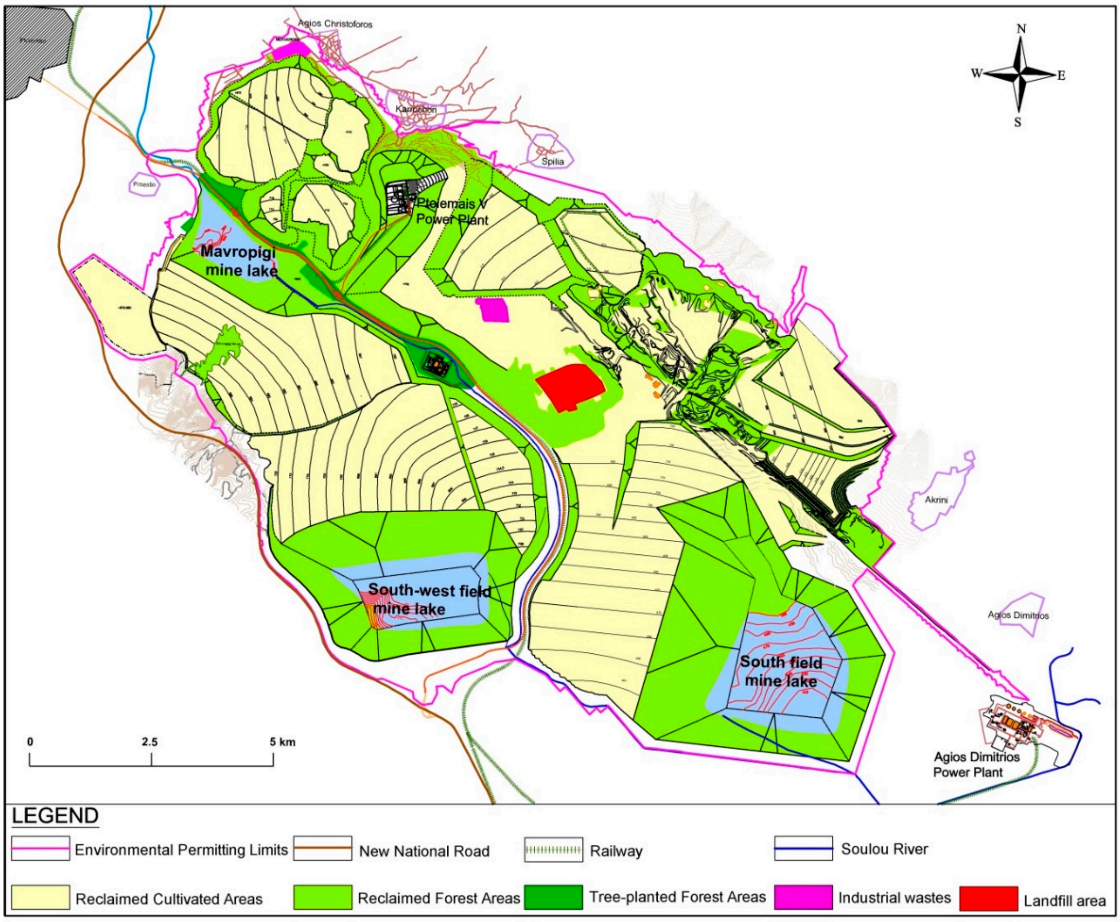

Figure 8. Land uses in the western Macedonia Lignite Centre after the mine closure and the completion of the land reclamation programme prescribed in the environmental permits [21].

3. Planning Rehabilitation for Amortising Decarbonisation Stresses

The mitigation of economic and social impacts of decarbonisation requires actions targeting beyond land reclamation. By adopting the terminology proposed by Lima et al. [25], from the 4R post-mining recovery practices (i.e., remediation, reclamation, restoration, rehabilitation), rehabilitation fits better in the case of western Macedonia lignite mines, where optimisation of land capacity for human use is a prerequisite for considering the socioeconomic prosperity of the region in the post-mining era, maintaining at the same time the ecosystem value. This is also in accordance with the society requirements, as these have been expressed by local and regional authorities and numerous stakeholders [26].

A fundamental target of rehabilitation is to create the best possible land capabilities that can enable a multitude of land uses in the future. In this frame, mine site rehabilitation should be planned to meet the following key objectives: (i) The long-term stability and sustainability of the landforms, soils and hydrological pattern of the site, (ii) the partial or full restore of ecosystem capacity to provide habitats for biota and services for people, and (iii) the prevention of pollution of the surrounding environment [26,27].

Particularly in the case of western Macedonia lignite mines, the vision of mine closure until 2028 urgently requires a rehabilitation strategy to guide all decisions and actions during the remaining mines life. These actions needs to take into account the following: (i) The public health and safety cannot be compromised; (ii) the natural resources are not subject to physical and chemical deterioration; (iii) the post-mining land uses may be sustainable in the long term; and (iv) the socioeconomic impacts need to be minimized; (v) opportunities, such as the maintenance of infrastructure, facilities, and services, need to be taken into account to maximise socioeconomic benefits [28].

Closure and rehabilitation planning must include the participation of community members, local and regional government, and development partners. In addition, mining companies must participate in local economic development initiatives to reduce the dependency of local communities on mines' operation before their closure [29,30].

It is worth noticing that unplanned closures create significant problems for the mining company, the community, and the regulator. In Australia, 70% of the mines have closed for reasons other than exhaustion of reserves, such as low commodity prices, high costs, safety or environmental breaches, policy changes, community pressures, closure of downstream markets, floods, and geotechnical failures [28]. This actually happens nowadays in western Macedonia, where the closure of lignite mines came 25 years earlier as a result of the high lignite extraction cost due to the EU regulations for CO_2 emission allowances.

3.1. The Circular Economy Concept

Considering the basic concept and priorities of the circular economy related to resource efficiency and material use, a circular economy analysis of post-mining land uses in surface mining operations could contribute significantly to investigating the long-term economic viability and sustainability of such projects. The enormous size and long duration of these operations allows the incorporation of several aspects of sustainability and circular economy flows to the land rehabilitation strategy, which has been applied for many decades in parallel to mines' exploitation as soon as some parts of the mine area are no longer needed for the development of pits and waste heaps (Figure 9). For instance, the conservation of topsoil cover, which is excavated separately in order to be spread to form a fertile reclaimed mine land, is a legal requirement that clearly affects the sustainable future of the greater mining area. Moreover, a series of measures for surface runoff and groundwater management, wastewater treatment, management, and disposal of solid and special waste shape the performance of every surface mine in terms of achieving the sustainability and circular economy goals [31].

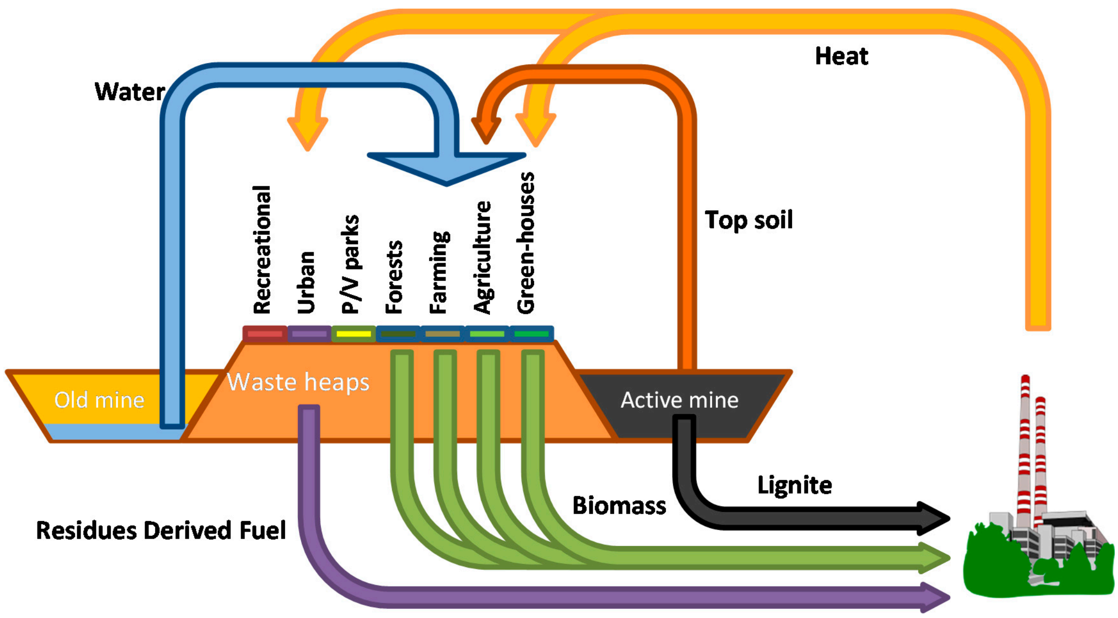

Figure 9. Schematic representation of circular economy practices applicable in surface lignite mines.

3.2. The Proposed Land Uses for the Rehabilitation of Western Macedonia Lignite Mines

Land resources are limited and finite. There is therefore a need to match land types and land uses in the most rational way possible so as to maximise sustainable production and satisfy the diverse needs of society [32]. Sustainable spatial development takes into consideration all environmental, social, economic, cultural, institutional, regulatory, and demographic aspects. Planning involves anticipation of the need for change as well as reactions to it [29].

If surface mine rehabilitation is planned, the scenarios of land uses must aim at outcomes that are climate smart, adaptable, and resilient. Successful rehabilitation is the state in which land is sustainable in the long term and can support agreed post-mining land uses, it can be effectively managed after the mine closure, and residual and latent risks are minimised. These risks usually imply the inability to maintain defined land capabilities due to loss of available soil, settlement, loss of surface water yield and loss of vegetation, lack of long-term water availability, and lack of maintenance of retained infrastructures by the new owners [26].

Kivinen [33] examined post-mining land uses in 51 metal mining sites in Finland. Forests cover 75% of the total post-mining area. An additional 17% is covered by water bodies (lakes, rivers, and wetlands). The agricultural land accounts for 8%, while sites relevant to commercial, recreational, or national heritage activities have been developed only in mines located in densely populated territories.

In the western Macedonia region, where lignite mining and electricity generation operations provide the only significant mainstream economic activity, post-mining repurposing scenarios and decisions about land use planning must refer to the greater mining area or even to the entire region. For instance, the development of certain crops in reclaimed waste heaps can be proved as a waste of money, when the same crops can be productive in neighbouring sites that were not affected by mining operations.

In this frame, the following land uses have been proposed by various stakeholders for the post-lignite era:

Agriculture (extensive farming): The crops of cereals are the typical agricultural activity in the greater lignite-bearing basin. Although farmers see mining land as inferior, they demand from the mine operator to rent large plots in order to extract benefits from them unsustainably, taking advantage of the financial support provided by the EU for certain cultivations. The development of modern farms based on the systematic agriculture principles is the ideal future, provided that water reservoirs and irrigation systems will be constructed.

Agriculture (green houses): It is the most promising type of agricultural activity, provided that cheap thermal energy produced by nearby located power plants should be supplied to farms.

Livestock farming: It is a traditional economic activity in a few of the communities located at the margins of the basin. It does not attract the interest of young farmers although Greece's import–export balance for meat and dairy products is negative.

Forests: Taking into consideration that the woodland areas destroyed due to the mines' development were very limited and in accordance to the rehabilitation principles, which aim at the reinstatement of ecosystem functionality and land productivity, allowing a different species composition from the original ecosystem, the plantation of various coniferous and deciduous trees is evaluated based on criteria related to aesthetics, slope stability, and revenue (e.g., biomass production for fuelling nearby located thermal plants, honey production). The new ecosystem may be simpler in structure than the original but more productive [27].

Recreational activities: They can be developed in reforested areas and around water bodies (final mine pits) located in the proximity of towns and villages, provided that appropriate infrastructures of a relatively low cost should be constructed. However, it is difficult to attract visitors from other regions or from abroad due to the competition from sites that have a reputation of providing high-quality tourist services. Nevertheless, an issue that probably requires special attention is the development of activities relevant to the industrial heritage.

Photovoltaic parks: Their development is considered by the lignite mine's operator as a feasible option for switching from a carbon-intensive electricity generation portfolio to a 'green' future. The availability of land and infrastructures relevant to the connection with the electricity transport network far outweigh the increased operating costs due to the longer distance from consumers.

Urban: Taking into account the willingness of local people to relocate to the major cities of the region, the development of residential areas seems to have limited interest. On the contrary, the location of industries and/or public sector activities, such as universities, research institutes, and hospitals, is considered historically as a measure for mitigating demographic decline and supporting the development of new sectors of strategic importance. In addition, the 'success story' of the construction of a landfill and waste management plant with a capacity of 120,000 t/year, which processes all the solid waste of the western Macedonia region, should act as a pilot project for the development of other waste-processing activities.

Taking into consideration that, after the phase out of the last thermal power plant in 2028 the remaining exploitable lignite reserves are estimated to be 500 Mt, surface mining can be another land use. The produced lignite can be used to non-energy related markets (e.g., activated carbon) or can be co-combusted in thermal power plants that use biomass or residues-derived fuel as basic fuels. It is worth noticing that in Finland, the re-opening of metal mines that have been closed in the period 1924–2016 was planned or under development in five cases (ca. 10%) and exploration permits were applied or admitted for half of the post-mining areas [33].

3.3. A Just Transition Mechanism

The required restructuring policies for revising the plan of land uses and restructuring the economy of the western Macedonia region can be part of the Sustainable Europe Investment Plan, which will mobilize more than €1 trillion of private and public investments over the next decade. This plan will support climate-neutral investments related to environmental protection and social cohesion [34].

This transition to a new economic development model will require large investment and a decisive policy response at all levels. Although all regions will need funding, the transition will imply a significant challenge to some of them, which have to adopt radical restructuring of their economies and to develop new economic activities and workforce skills. Regions highly dependent on coal/lignite utilisation for electricity generation purposes will need to ensure that business innovation and activities diversified from the mining and thermal power generation can maintain the social cohesion and provide an adequate number of new jobs.

To address the site-specific challenges encountered by the most impacted regions, the European Commission proposes a Just Transition Mechanism that provides dedicated support to generate the necessary investments. This mechanism will consist of three pillars, which will offer different grant and financing tools in order to cover the various types of support required by the public and private sectors of the impacted regions. These pillars are:

- The Just Transition Fund, which will provide primarily grants;
- The InvestEU, which will manage private investments; and
- A new public sector loan facility for supplementary investments to be leveraged by the European Investment Bank.

All programmes that will be applied in the frame of the Just Transition Mechanism will be accompanied by dedicated advisory and technical assistance [34].

4. Evaluation of Mine Rehabilitation Scenarios

Land management must explicitly consider what are the optimum land uses for a particular mine site and, at the same time, what are the optimal sites in an area or region for developing particular land uses. The proposed suitability criteria include site environmental characteristics, infrastructures, environmental hazards, development impacts, and institutional concerns [35].

Rehabilitation implies a decision-making process, which assesses the impacts of various land uses on the living environment and ecosystem and, to a next stage, the potential of these land uses to boost economic development. Land use planning, in turn, is a systematic evaluation of the land and water potential, in both qualitative and quantitative terms, and the economic and social conditions in order to select and implement the best land use options that meet the needs of people while safeguarding natural resources for the future and diminishing environmental risks [32,36].

As far as the conservation of nature is of concern, the Society for Ecological Restoration recommends the use of nine ecosystem attributes for measuring mine rehabilitation success: (i) Similar ecosystem diversity and community structure to those of reference sites, (ii) presence of indigenous species, (iii) presence of a functional group of species that are necessary for long-term stability, (iv) capacity of the environment to sustain reproducing populations, (v) normal functioning, (vi) integration within the topography, (vii) elimination of probable threats, (viii) quick recovery in cases of natural disturbances, and (ix) self-sustainability [37].

Furthermore, mining industry interferes in many ways in the social affairs. This implies a commitment to minimise the adverse impacts of mining on communities located in close proximity to the mines, and also introduces the issue of how to maintain the prosperity and sustainability of the society, which is closely related to the developing of processes and structures that support the potential of current and future generations to create healthy and liveable communities [38].

Rehabilitation planning usually includes comprehensive spatial analysis of the mining area, including the already reclaimed mine land. Thus, the literature abounds with papers proposing methods and techniques that support decision-making for the spatial distribution of alternative land uses based on a series of criteria, most of them by incorporating GIS-based applications.

For the lignite mines of western Macedonia, Pavloudakis et al. developed a methodology in order to match the land characteristics and repurposing scenarios of mine land rehabilitation based on the following broader categories of criteria [39]: (i) Location: Proximity to lakes, archaeological sites, and residential areas; (ii) geotechnical stability; (iii) topography; (iv) soil fertility: pH, acidity, alkalinity, concentration of nutrients, mechanical properties, and access to irrigation systems; and (v) environmental risks: Metal concentrations in soil and water. Palogos et al. [40] proposed an alternative approach by adding evolutionary algorithms to the land use evaluation process. Furthermore, Wang et al. [41] proposed a reclamation strategy for a mining site in Liaoning Province, China, combining land suitability analysis and ecosystem service evaluation methods. Forest, agriculture, and developed land were examined as alternative land uses using land suitability criteria related to topography, climate and socioeconomic factors, and targeted ecosystem services material production (e.g., timber), water conservation, soil protection, carbon sequestration, oxygen release, and air purification.

In this context, in order to emphasise the social and economic issues that must be taken into consideration in decision-making processes relevant to mine land rehabilitation, in Table 2, a comparative PEST (i.e., political, economic, social, technological) analysis is presented considering seven alternative land uses that are possible to be developed after the closure of the surface lignite mines of western Macedonia.

From the land uses analysed in the previous paragraph and in Table 2, green houses, and recreational and urban/industrial areas will occupy a relatively small percentage of the 17,000 ha of reclaimed mine land that will be available after the mines' closure. Thus, the development of these land uses does not jeopardise other uses and, to the extent that they help the achievement of the objectives of the land rehabilitation strategy, they must be politically and financially supported.

Furthermore, in order to optimise the total area to be covered by each of the four remaining land uses: Extensive agriculture, livestock farming, forests, and photovoltaic parks, an optimisation algorithm was developed. The algorithm differs from the decision-making methodology presented by the authors of this paper in previous studies [39,40] since it is focused on the selection of the optimum mix of land uses that meets certain environmental, economic, and social targets relevant to the rehabilitation of the mines without paying attention to the spatial distribution of land uses. In other words, this approach is driven by the goal to be achieved, which is the long-term prosperity of the society, and not by the restrictions associated with a specific set of criteria, assuming that financial resources are available for complete or even partial lifting of these restrictions.

Table 2. PEST analysis of the major macro-environment factors that affect decisions regarding post-mining land uses [11,23,27–29].

Land Use	P Political	E Economic	S Social	T Technological
Agriculture	Some crops are regulated by state or EU directives; establishment of cooperatives, etc.	Low productivity land; low investment cost; expensive irrigation	Traditional economic activities in the greater mining area; moderate number of new jobs	Topsoil management and soil remediation are required
Green houses	Lack of regulatory framework for heat supply to agro-sector; investment support mechanisms are required	Moderate investment cost; highly competitive market; considerable reduction of minimum viable acreage compared to extensive farming	The large number of agronomists working in the area makes easier the know-how transfer	Some techniques (e.g., hydroponics) do not require soil remediation; need to develop a marketing strategy to grab a big market share
Livestock Farming	Establishment of cooperatives	Ideal for low productivity lands; moderate to high investment cost for vertical growth of production (from forage to dairy products)	Limited number of new jobs; traditional activity for some villages in the greater area	Soil remediation is required
Forests	Limitations arising from the forest law and State planning	Possibility of forest exploitation for timber, biomass and honey production; careful calculation of the logistics costs is required	Moderate number of new jobs; upgrading of living conditions	Limited number of tree species can grow under the certain weather and soil conditions
Recreational activities	Limitations concerning safety of visitors (e.g., access to lakes)	Local population is not enough to guarantee economic viability; investments required for development of attractions	Most of them create limited number of new jobs; upgrading of living conditions; connected with industrial heritage	Regular monitoring of soil and water quality and slope stability is required
P/V Parks	Pending approval of permits	Availability of low-cost land and infrastructures for connection to electricity network	Have already been criticised for the limited number of new jobs during operation; limited argues for degradation of landscape, etc.	Opportunities for know-how development and creation of new businesses related to the construction of P/V parks, panels, etc.
Urban (industrial)	Establishment of industrial area; investments support decisions are required; construction works must follow technical specs.	Large investment cost; insufficient transportation networks (railways, airports)	Large number of new jobs; training—education of personnel is required	Need for know-how transfer; opportunity for development of new supporting activities

The proposed optimisation algorithm is based on the following broader categories of criteria [32]:

Revenues: Land use must be economically viable. The basic objective of land use planning is the efficient and productive use of the land by matching different land uses with the areas that will yield the greatest benefits at the minimum cost.

Investment: Although significant preparatory actions are underway to develop financial tools to support the transition of the regional economy, the minimisation of the required investment is still assessed positively.

Conservation of nature: In order to ensure continued production in the future, the conservation of the natural resources on which that production depends on is beyond any negotiation.

Equity: Land uses must be diverse and socially acceptable. People with different education and skills must have equal opportunities of employment. Poverty and social exclusion must be eliminated.

For each one of the four categories of criteria (or just criteria, for simplification reasons) j and for each land use i, a rate R_{ij} is given (using a 1–10 scale) Each of these rates is calculated as the average of the rates given by 10 experts (mining engineers, agronomists, and surveyors), who are or were involved in land reclamation projects carried out by PPC in the surface mines of western Macedonia region (Table 3).

Table 3. Rating of land uses for each of the four examined criteria.

Criteria (j):	Land Uses (i):			
	1. Agriculture	2. Farming	3. Forests	4. P/V Parks
1.Revenues (max)	6	6	3	10
2. Investment (min)	6	10	8	2
3. Conservation of nature (max)	5	7	10	5
4. Equity (max)	8	4	4	6

Then, the team of experts and the stakeholders involved in the land use planning process decide about the threshold of the rates that must have the combination of land uses regarding each one of the four criteria. In the examined case of the lignite mines of the western Macedonia region, the threshold values that were determined by the group of PPC experts are given in Table 4.

Table 4. Threshold values for each one of the examined criteria of land use planning.

Criteria (j):	Threshold Values TVj
1.Revenues (max)	7
2. Investment (min)	5
3. Conservation of nature (max)	7
4. Equity (max)	6

Then, the scores (average rates) of 286 combinations $[\sum_{n=1}^{11} n(12-n)]$ of land uses were calculated assuming that these four uses will cover 100% of the available land. For each land use i, the land coverage Pi ranged from 0% to 100% with a step of 10%. The optimum combination of land uses (i.e., the optimum percentage of area coverage for each one) is determined based on the sum of deviations (D) of the average rates from the determined threshold values for all the four criteria. The modelling equation has the following form (Equation (1)):

$$\mathrm{D} = \sum_{j=1}^{4}\left(if \ \sum_{i=1}^{4}(Rij.Pi) - TVj < 0 \ \ then \ \sum_{i=1}^{4}(Rij.Pi) - TVj \ \ else \ 0\right), \tag{1}$$

where:

D, the deviation of a certain combination of land uses coverages from the optimum score;

i, the land uses;
j, the land uses assessment criteria;
R_{ij}, the rate given to the land use i based on the criterion j;
P_i, the land coverage of the land use i, expressed as percentage % of the total mine area available for rehabilitation planning
TV_j, the threshold value for the criterion j.

For instance, if the land coverages of agriculture, farming, forests, and P/V parks have the percentages 10%, 20%, 40%, and 30%, respectively, and using the threshold values of Table 3, the above formula has the following form:

$$
\begin{aligned}
D = \; & 6\times 10\% + 6\times 20\% + 3\times 40\% + 10\times 30\% - 7 = 6.0 - 7 = -1.0 < 0 \rightarrow -1 \\
& 6\times 10\% + 10\times 20\% + 8\times 40\% + 2\times 30\% - 5 = 6.4 - 5 = +1.4 > 0 \rightarrow 0 \\
& 5\times 10\% + 7\times 20\% + 10\times 40\% + 5\times 30\% - 7 = 7.4 - 7 = +0.4 > \rightarrow 0 \\
& 8\times 10\% + 4\times 20\% + 4\times 40\% + 6\times 30\% - 6 = 5.0 - 6 = -1.0 < 0 \rightarrow -1 \\
\hline
D = \; & -2
\end{aligned}
$$

The above-described approach identifies the combinations of land uses that achieve a more balanced development, trying to meet at the same time the standards that have been set for economic prosperity, rational use of funds, nature conservation, and equity. Therefore, it ignores how much above the threshold values are the rates of the criteria for a certain combination of land uses and takes only into account the rates that are below the threshold. For instance, the D value decreases considerably, taking the value −3, if the rate for a certain combination of criterion and land use is 4 and the threshold is 7, but it does not increase at all (i.e., it has a zero value) if the rate for another criterion and for the same land use is 9 and the threshold is 6.

The optimum percentage ranges for the examined land uses in the case of the threshold values presented in Table 4 is shown in Figure 10a. The combination of land uses with the best score (rate) is indicated by the red dots and the percentage ranges correspond to the upper 5% of the scores. According to these results, it seems that the opinions of PPC experts regarding the selection criteria of land uses favour P/V parks (40%) instead of agriculture (30%) as a high revenue activity, although it requires a higher cost of investment. Forests (20%) and livestock farming (10%) hold smaller shares that are necessary for the preservation of natural features and the biotic environment. Taking into account the fact that 55% of the available area is appropriate for agricultural activities and P/V parks, as it has already been mentioned in paragraph 2, the percentage of 70% for these two land uses can be achieved only if the plantations targeted for biomass or biofuel production will be extended to sloped surfaces located in the perimeter of waste heaps.

In Figure 10b–d, the results achieved by using three different sets of threshold values are illustrated. By increasing the threshold value for revenues from 7 to 9 and keeping all the other thresholds constant, the percentages of P/V park areas and farming land increase and those of forest and agricultural land decrease. If the conservation of nature is the predominant target of the land reclamation strategy, receiving a threshold value of 10, the land coverage of P/V parks increases further and the forest land percentage increases at the expense of farming land. Finally, if the stakeholders favour not only the conservation of nature but also the cost reduction, even if the potential for higher revenues is deteriorated, the forest coverage increases dramatically, and all the other land uses are reduced.

The optimum land uses based on the rates of Table 3 and assuming equal weighing factors for all the criteria (j) are shown in Figure 11. This case implies that threshold values are neglected or, alternatively, the proposed algorithm is applied using the threshold value of 10 for all the criteria. As it was expected, the maximum score corresponds to 100% of land coverage by the land use that exhibits the higher average score for the four criteria (i.e., farming with average score 6.75/10). This approach does not favour diversification of land uses and this did not change if different weighing factors were used for the examined criteria. Moreover, in order to check further the sensitivity of the proposed criterion for land use coverage, in Figure 11, the results are shown, which correspond to a set of threshold values equal to the average score of each one of the examined land uses. This approach must also be avoided because it obviously has the tendency to distribute equally the land coverage percentages. Finally, in the last two sets of columns of Figure 11, the land coverage results are presented, using the threshold values of 6 and 7, respectively, keeping them constant for all the four examined criteria. The remarkable difference resulting from this comparison indicates that the higher the threshold values used, the higher the influence of the high scores achieved for certain combinations of land uses criteria, and the lower the threshold values, the higher the influence of the low scores (in fact, the scores above the threshold value are neglected).

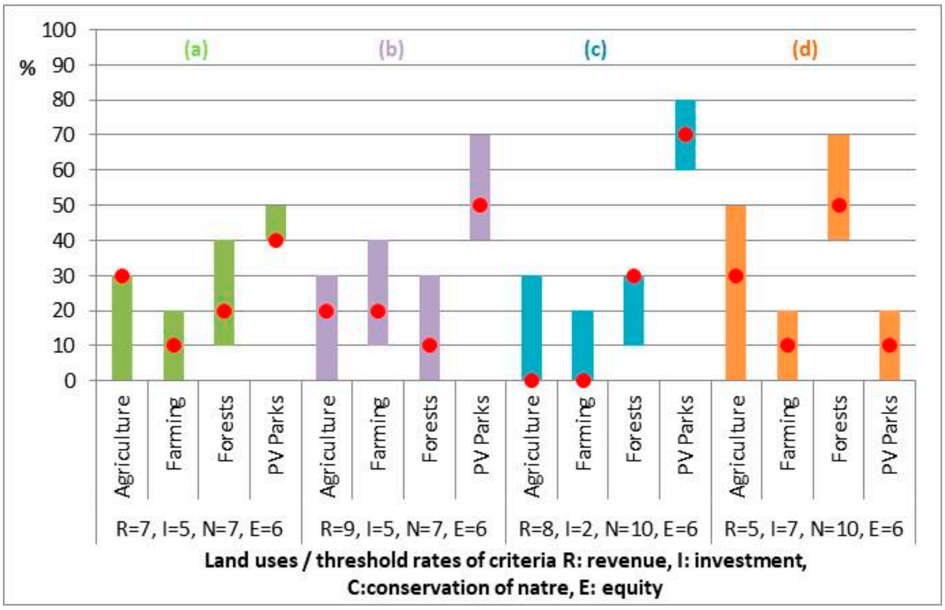

Figure 10. Ranges of land uses' percentages for different sets of threshold values for the examined optimisation criteria.

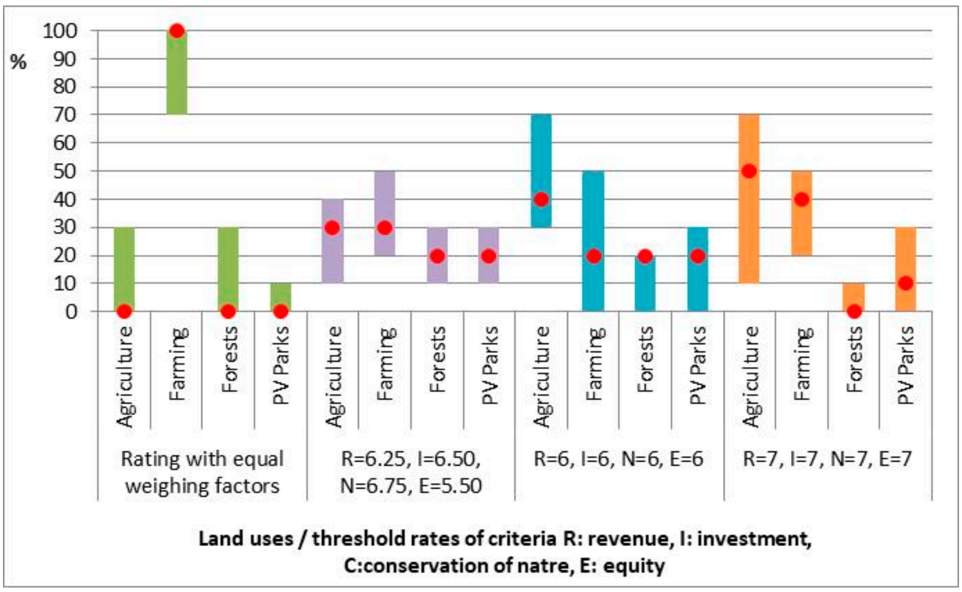

Figure 11. Sensitivity analysis of land uses' percentages in relation to various sets of threshold values for the examined optimisation criteria.

5. Discussion

In order to amortise decarbonisation stresses, the western Macedonia region needs, among others, an innovative mine land rehabilitation strategy. Taking into consideration the basic concept and the priorities of the circular economy, the present paper proposes seven land uses: Agriculture (extensive), green houses, livestock farming, forests, recreational areas, photovoltaic parks, and urban (industrial). All of them support the circular economy concept and each one complements the others in order to achieve sustainability targets. Urban development, which includes in a broader sense industrial and institutional development, is called for mitigating the economic and social impacts caused due to the loss of employment. Other uses, such as agriculture, livestock farming, and forests, can contribute to the energy economy cycle in numerous ways: Supplying an alternative fuel, which can co-combusted with lignite in thermal power plants; utilizing waste heat produced from thermal power plants; and utilizing water stored in the artificial lakes that will be developed in the final mine pits.

- The PEST analysis and the basic scenario that was examined with the decision-making algorithm clarified the expectations of the society from the different land uses.
- Extensive agriculture is an option that concerns only a few professional farmers while green houses are a promising investment, provided that the current regulatory framework will change and heat wasted by the thermal power plants will be available for uses other than district heating.
- Further to the conservation of the nature, reforestation can contribute to the local economy only if it is targeted to biomass production.
- Recreational activities that have been proposed so far by numerous stakeholders vary from mountain biking and fishing to industrial heritage parks and car racing circuits. Of course, the outputs expected from each of those activities differ considerably and must be evaluated accordingly.
- Photovoltaic parks are a realistic alternative for the creation of a new high-revenue activity, taking into account that PPC has decided to diversify its energy sources portfolio and is willing to pay the cost of investment and to take the relevant risks.
- Urban (industrial) development is the only land use that can create a large number of new jobs.

As far as the proposed optimisation algorithms is of concern, it was developed having in mind that the long-lasting prosperity of the society is closely related to the development of a strategy that balances effectively between conservation of nature and economic growth. The rates and the threshold values that were given by the experts contacted by the authors reflect a tendency, which has been gradually developed in the last years in the face of the shrinkage of lignite exploitation activities, to treat equally both environmental protection and economic development objectives.

Furthermore, the threshold values that were set by the experts for the three of the criteria (7 for revenues, 7 for conservation of nature, and 6 for equity) were higher than the average rates given from them to the four land uses for each of those criteria (6.25 for revenues, 6.75 for conservation of nature, and 5.50 for equity). Only for the cost of investment the threshold value (5) was less than the average rate (6.50). This fact is probably related to the large expectations of the local authorities and people involved in land rehabilitation projects regarding a generous financial support through the Just Transition Mechanism.

6. Conclusions

From the perspective of the new growth strategy of the EU and the ongoing changes in the world energy market, the reduction or phasing-out of lignite mining and power generation activities is considered as one of the most cost-effective methods to achieve CO_2 emissions reduction.

In this context, the Greek government announced the abolition of lignite-based electricity generation by 2028. For the region of western Macedonia, where in the recent past the installed capacity of lignite-fired power plants exceeded 4300 MW, the transition to a sustainable low-carbon economy entails threats but opportunities. The required restructuring policies can be part of the Sustainable Europe Investment Plan, which will mobilize at least €1 trillion of private and public investments over the upcoming decade. The supported actions must aim at the diversification from existing lignite-depended economic activities as well as at the revision of the spatial plan of the entire region so as to exploit the productive potential of all economic sectors.

Focusing on the rehabilitation of the surface lignite mines, the selected land uses should create new jobs and revenue without compromising on the objectives of protecting the living environment and ecosystem. At the same time, land uses should be self-sustaining, which means they will be able to generate profits when funding from European or national sources will cease. Considering the basic concept and priorities of the circular economy related to resource efficiency and material use, it could offer a reliable methodology for assessing the long-term economic viability and sustainability of numerous projects.

The application of a PEST analysis in the examined case study of the surface lignite mines of western Macedonia show that a series of economic activities that are expected to create many jobs combine the advantage of small land requirements.

Examples of this type of land use, which should be supported both politically and financially, are:

- The construction of industrial complexes. For instance, it has already been proposed the construction of factories that produce photovoltaic panels and batteries for electric cars.
- The construction of industrial heritage parks, utilizing part of the building infrastructures of the mines and power plants.
- The development of greenhouses that will use cheap heat supplied by the nearby located power stations.

For the land uses occupying large areas, i.e., agriculture, forestry, livestock farming, and photovoltaic parks, an optimisation algorithm is proposed for determining the mix of land uses that maximise the revenue, equity, and natural conservation and minimise the cost of investment. According to the results obtained based on the set of rates and threshold values determined by a group of PPC's land reclamation experts, photovoltaic parks seem to be a more attractive option than extensive agriculture, as regards land uses that are worth investing in, while livestock farming and forests are considered necessary to safeguard the ecosystem functions.

These results would be probably different if representatives of public and local authorities and other stakeholders were taking part in the group of experts that decided about the rates and the threshold values that were fed to the proposed algorithm. Nevertheless, the proposed algorithm can be used to support decision-making procedures that will take place in the near future in the western Macedonia region concerning the development of land rehabilitation plants and the rational distribution of funds coming from the Just Transition Mechanism.

The algorithm is also applicable to various decision-making problems, not necessarily related to surface mine rehabilitation, in cases that a group of experts and/or stakeholders have to determine the optimum mix of land uses, development project proposals, etc., each of which claims from the rest a share of a limited resource, in terms of space, funding, etc. To this extent, the algorithm can be used by every surface mine operator in order to develop an effective land rehabilitation plan.

Author Contributions: Conceptualization, F.P., C.R. E.K. and N.K.; methodology, F.P., C.R. E.K. and N.K.; validation, F.P., C.R. and E.K.; formal analysis, F.P., C.R., E.K. and N.K.; data curation, F.P., C.R. and E.K.; writing—original draft preparation, F.P., C.R. and E.K.; writing—review and editing, F.P., C.R., E.K. and N.K.; visualization, F.P., C.R. and E.K.; supervision, F.P., C.R. and E.K.; project administration, F.P. and C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

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