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ORIGINAL PAPER

Planning the Closure of Surface Coal Mines Based on Circular Economy Principles

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Abstract

The ongoing energy transition is expected to lead to the closure of many coal and lignite mines in the coming years, jeopardizing economic growth and social cohesion. The closure of a mine is a complex process that must be completed in accordance with the legislation and the environmental permit. The scope of this study is to prove that circular economy principles can contribute to the successful completion of a mine closure project, moving things beyond the narrow margins of legislation in two ways: (i) maximizing the recovery of materials with residual value and reducing the volume of discarded waste and (ii) by preparing rehabilitated mine land to be suitable for new uses that will assist in mitigating the economic and social impact and supporting sustainable development at the local and regional level. In this frame, based on the authors' experience in mine planning and land reclamation projects, a series of new Rs are added to the three basics (Reduce, Reuse, Recycle) in order to enhance materials and land management during mine closure. Furthermore, the closure of the lignite mines in the Greek Region of Western Macedonia is investigated. In this case, land reclamation projects and land uses were redesigned based on the principles of the circular economy and sustainable development goals, incorporating interventions such as the construction of photovoltaic parks and pumped storage systems and industrial areas. Based on these facts, the study concludes that the proposed approach for mine closure contributes to the achievement of the objectives of both the mining enterprises and the local governments that are seeking a new development model based on the inherent advantages of their region.

Keywords Lignite · Sustainability · Energy transition · Western Macedonia · Land reclamation · Repurposing

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Introduction

The mining sector is represented mainly by linear activities, being the major supplier of resources to modern society. The typical one-way operating mode consists of mineral exploration, mine exploitation, ore processing, fine product manufacturing, consumption and waste dumping [1]. Traditionally, mine closure was a complex and multidisciplinary part of this linear process, which required several years of planning and a coordinated effort from central and local governments and various stakeholders, ideally right from the start of mine planning.

At the same time, the mining industry is perhaps one of the most challenging areas for a circular economy because of the need for "purity" in the extracted materials [2]. This demand results in the production of various by-products and waste streams with insufficient quality characteristics, which provide many opportunities for further research into reprocessing and recovery of valuable raw materials, while several papers propose circular economy models and materials management plans applicable in mining projects [3, 4].

Considering coal and lignite mining, the European Green Deal 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 [5]. In order to achieve this goal, the EU will need to rapidly decarbonize its power sector. However, the implementation of this strategy poses significant socioeconomic impacts [6]. Coal infrastructures exist in 108 European regions. It is estimated that the coal sector currently employs about 237,000 people, 185,000 of them work in coal and lignite mines [7].

Nevertheless, under these circumstances, the economic importance of coal and lignite mining has decreased. Many EU countries have already announced plans to phase out the coal-fired power plants and the mines that supply them with fuel. To eliminate the impacts of decarbonization, measures to strengthen social cohesion, retain the population, provide decent work and develop new economic activities need to be planned and implemented in a timely manner. These measures are closely related to the repurposing of mine lands and the development of new land uses [8].

According to the legal framework in force in most countries, the land that is no more used for mining activities must be reclaimed. Based on the environmental permit of most mines, works such as contouring of final waste heaps surfaces, topsoil spreading and forestation, mainly to improve the landscape aesthetics, are described, costed and implemented by the mining companies. Alternatively, the development of land suitable for cultivation or livestock farming may be another option of moderate cost [9]. However, these mandatory interventions are not able to compensate for the reduction in economic activity due to the energy transition and decarbonization, especially in regions with a long history of coal exploitation [10]. Instead, additional measures and new land uses are necessary, the development of which will rely on financial support from mechanisms such as the EU Just Transition Mechanism [11]. As will be explained in the following paragraphs, the success of any intervention in this direction depends on the extent to which the strategy implemented is based on sustainable development goals and circular economy principles.

The scope of the present study is to demonstrate a path that leads from the phase-out of a mineral extraction project to the sustainable development of the affected area through an action plan that is based on the principles of the circular economy. In this frame, an action plan for mine closure is proposed, which adds many Rs to the already known circular loop for "reduce, reuse, and recycle", in order to optimize both the management of materials and equipment, having as the ultimate target the reduction of generated waste volumes, and the rehabilitation and repurposing of mine land. In this way, it will be proper to facilitate new land uses, capable of minimizing the economic and social impacts caused by the closure of mining activity. This proposed action plan is based on the authors' knowledge about laws, jurisdictions and best practices disseminated through organizations and the literature, as well as on successful stories and failures that occurred in mine operation and closure projects implemented in the complex of lignite mines in the Greek Region of Western Macedonia, which serve as the case study of this paper.

Background

The rational exploitation of mineral resources is the main target of the extractive industry. However, the long life span of mines combined with the inherent instability of mining projects contributes significantly to irreversible mineral losses. In this context, circular economy strategies can contribute to the identification of practices which either anticipate the use of equipment and materials beyond the closure of a mine or, even better, make mining projects economically viable, without interruptions of production, until the depletion of the exploitable reserves. The transition toward more sustainable mining practices may also include changes in business models and management culture. For instance, remining of rocks dumped in waste heaps is a possible connection between the primary resource sector and the waste management sector, which creates a larger loop in the economic cycle. In addition, extractive technologies can be applied downstream to waste recycling, notably metal scrap and electronic waste, which suggests the mining industry could be developed into a wide scope of circular economy principles [12]. This issue can be further highlighted by examining two recycling rates of iron: *end-of-life recycling rate* gives the percentage of iron that is recovered and recycled at the end of its life. According to UNEP data [13], this rate varies between 52 and 90%. *The recycled content rate* refers to how much-recycled iron occurs in new products, which means that if all of the new products come from recycled iron (a fully closed-loop system), then this rate would be 100% and if all iron in new products comes from mines the rates would be 0%. This rate varies between 28 and 52% [13]. This data proves two key features of the current recycling industry [2]:

– End-of-life recycling rates vary widely across different uses for metals. This is because different products are recycled at different levels of efficiency and rates across the world and also because the nature and structure of some products mean that it is infeasible to recycle the metals in them.
– The recycled content rates are dramatically lower than end-of-life rates due to increases in demand for final products, which outstrips the availability of scrap material. Even if end-of-life recycling rates go to 100%, if demand rates keep increasing, there would still be demand for materials extraction in mines.

Regarding mining products, many metals are, for the most part, infinitely recyclable. Their inherent characteristics, such as durability, strength and anti-corrosive properties, improve the sustainability of the products in which they are used: enhancing longevity, lowering maintenance requirements and providing higher functionality. Furthermore, their value enhances their recovery rates, and there is already considerable infrastructure in place to facilitate their reuse, remanufacture and recycling [14]. The so-called urban mining, the process of reclaiming compounds and elements from any kind of anthropogenic emissions, is an interesting concept which is emerging nowadays and should be incorporated within a circular economy model. Urban mining has generally arisen in developed countries, such as Japan and understanding its potential and any barriers and challenges in emerging economies is an interesting area for future research [2].

In practice, the circular economy offers mining companies opportunities to decrease operating costs and increase efficiency through optimizing resources. Since mining companies are constantly looking for ways to decrease costs and increase efficiency to maximize profits, adapting circular economy principles is beneficial to mining companies [15]. In addition, the emerging concern for global warming, phasing out of coal-based power generation and internal combustion engines and the lack of landfill availability may lead to potential changes in legislation for the mining industry. In this frame, the circular economy prepares mining companies to embrace the change in environmental standards set by global initiatives.

The aforementioned three principles of circular economy in the case of mining companies can be modified as follows [15]:

- Ensure that waste production during mining and ore processing is the minimum possible based on the best available technologies.
- Keep equipment and materials in use as long as possible, decreasing demand for new products and resources and deviating material flow from landfills.
- Enhance natural capital and create conditions to restore natural systems avoiding the use of non-renewable resources.

According to Kinnunen et al. [16], there is great potential for turning mining waste into valuable products. The tailings deposits contain metals in Finland worth hundreds of millions of euros. The economic valorization of these materials depends on processing costs. Various technologies are already exploited to recover metals from the tailings and use mineral residues in high- or low-value products. The economics of tailings mining is determined by the institutional framework (i.e. taxation and regulations) and by the quantities and prices of the targeted metals, which must be high enough to support the costs associated with processing.

Mining waste can also be used as backfill, aggregate in road construction and raw material for cement and concrete production. Manganese tailings are used in agroforestry, buildings and construction materials, coatings, resin, glass and glazes. Clay-rich tailings are used for making bricks and floor tiles. Bauxite red mud, a solid alkaline waste produced in aluminium refineries, is used as a soil amender, in wastewater treatment and as a raw material for glass, ceramics and bricks [14]. Regarding specifically coal mining waste rich in thermal content, produced due to the absence of selective mining methods and coal beneficiation, they can be reused in co-firing processes for energy production after being treated, minimizing at the same time the size of mining dumps [17]. In this frame, Pinchuk et al. [18] propose the development of eco-industrial parks, using a sector-clustered approach, to allow related industries to work in symbiosis, where mining waste can be involved as secondary raw materials in recycling, remanufacturing, recovery and regeneration processes.

Furthermore, the mines, particularly the surface ones, must reclaim effectively and in a sustainable way the land they have temporarily occupied for the development of the mining operations. For this reason, managing the soil and land of mines is another important research field on which the circular economy should focus. The circular economy aims to use resources derived from natural capital more efficiently. Soil and land play important roles in the circular economy, for instance, providing space for societal activities to take place and for producing biobased resources [19]. Their role in the biogeochemical cycles is very important for closing the water, nutrients and land purification cycles once the resources have entered the soil as waste. As the formation of top soil and the recovery of land and soil quality are extremely slow processes, they can essentially be viewed as non-renewable resources. Therefore, the restoration of mine land and soil is necessary to secure the future provision of natural resources and services on a local and regional scale. The circular economy can stimulate land reclamation through the provision of resources for food and livelihood, contributing in this way to the achievement of many sustainable development goals, such as zero hunger, clean water and energy, decent work and economic growth and life on land [20]. Pactwa et al. [17] claim that reclaimed waste heaps can be used as areas for investment projects of both social and environmental benefit. Their use may contribute to the economic development of the region, social activation of inhabitants, creation of new jobs and landscape changes while maintaining care for the natural environment. Therefore, even in waste storage areas, the contamination is not an obstacle to considering the highest and best land uses for such properties (e.g. housing developments).

It is worth noticing that the final stage of the mining operations' life cycle is to return the disturbed land to a productive, self-sustaining ecosystem where flora and fauna can flourish. This is proposed in nearly all environmental impact assessment studies and is required by the relevant permits [21]. Nevertheless, circular economy principles provide opportunities to regenerate disturbed land to create productive agricultural, forestry and/or fisheries sites to support the local economies. There are many cases in which mining companies have supported the development of farming operations and facilitated the training and upskilling of local community members to manage such operations. Mine sites have energy and water infrastructure that can be used for boosting new productive activities instead of being decommissioned. Closed mining sites can be transformed into tourist attractions, where seasonal sports, camping, fishing and hunting, hiking and nature observation activities take place, or into industrial or even residential areas [21, 22]. Biomass production by means of short-rotation energy crops can also be a highly significant component in a circular economy model applicable in reclaimed mine lands in terms of both material and energy production [23, 24].

Finally, focusing on underground mining, for the post-closure management of mining sites, several methods, which will act as a base for achieving sustainable development and circular economy goals, are investigated. The commonly used methods of mine filling with water and wastes may be successfully replaced by more economically justified projects, which may support local communities in terms of both income generation and workplace maintenance [22]. Mine water from flooded mines could be used as a geothermal energy source to supply thermal energy in buildings located in surrounding areas, while coal mining tunnels could be used as an underground water reservoir of pumped storage hydropower plants [24]. Moreover, there is a high possibility that novel approaches to mine reclamation, such as underground farming and research centres for physical and astrophysical measurements or the development of new mining technologies, will gather social acceptance due to clearly visible profits for the local community [22].

The Mine Closure Process

The closure of a surface mine is a dynamic and iterative process, which must be considered an integral part of every mining operation plan, requiring significant financial provisions and being associated with several safety, environmental and social risks. Taking into account that the lifespan of any mine is limited but usually several decades long, mine closure must begin at an early stage of mine exploitation and develop throughout the mine's life. Its effectiveness is critically determined by the implementation of measures for eliminating soil and water pollution and protecting ecosystems in a way that allows optimization of post-closure land use opportunities and social transition. Nevertheless, the legislation governing the operation of the mines obliges mine operators to prepare from the outset of a mining project mining and environmental studies, which describe the progress of the land reclamation works at regular intervals, as well as a final map of land use after the closure of the mine. Also, 45% of the countries that responded to a relevant survey of the International Council of Mining & Metals have laws or regulations in force that oblige mining companies to have adequate financial assurance to enable agreed closure and post-closure commitments to be realized [25]. The amount that must be covered by a financial assurance mechanism (which might include insurance, guarantee and bond) is equal to the estimated by the supervising authority cost of mine closure. Without financial assurance regulations, there is a considerable risk that governments will have to bear the significant costs of closing abandoned mine sites. After all, both governments and mining operators should not forget that the legacy of abandoned mines that accompanies the extraction industry has been a reason to suspend numerous significant mineral exploitation projects around the world.

Documents with international best practices and guidelines produced by governments and organizations can help mining companies benchmark their current mine closure strategies and improve their state of practice [25–30]. Traditionally, a mine closure plan described in the permit of a mining project includes measures that aim for the following (Fig. 1) [26, 27, 31]:

Physical stability: The physical stability of the mine site after its closure is the most fundamental requirement, which is closely related to safety. In this context, the risk of waste rock dumps collapse or slopes landslides must be minimized, while entry to mining areas that have not been stabilized yet must be prohibited.

Chemical stability: Reactive mine waste may cause surface water and groundwater pollution and may reduce the ability of soil to support vegetation. For instance, the problem of acid mine drainage arises when runoff water from precipitation contacts reactive mine waste and generates acidic discharges that can adversely impact the environment. However, several methods are available to prevent or treat in-situ the reactive mine wastes and their discharges.

Improvement of landscape aesthetics: The alteration of land during mining operations causes permanent changes to the topography and loss of unique landscape features of the disturbed area. Thus, the implementation of measures, namely forestation, is necessary to improve the aesthetics.

Restoration of ecosystem functions: The conservation of biodiversity and the attainment of a self-sustaining ecosystem may be a reasonable mine closure strategy in cases of large surface mines located in sparsely populated areas where local communities' prosperity is not connected with the beneficial use of land. This is usually achieved by planting endemic species.

Beneficial use of land: In order to partly amortize the socioeconomic impacts related to the mine closure, land reclamation projects aim at developing some other beneficial uses of the land, which are probably related to the economic activities of the pre-mining era, such as agriculture and livestock farming. Nevertheless, the cost of these interventions is comparable to that of forestation and differs considerably from the cost of repurposing the disturbed mine land introducing new land uses with high productive potential.

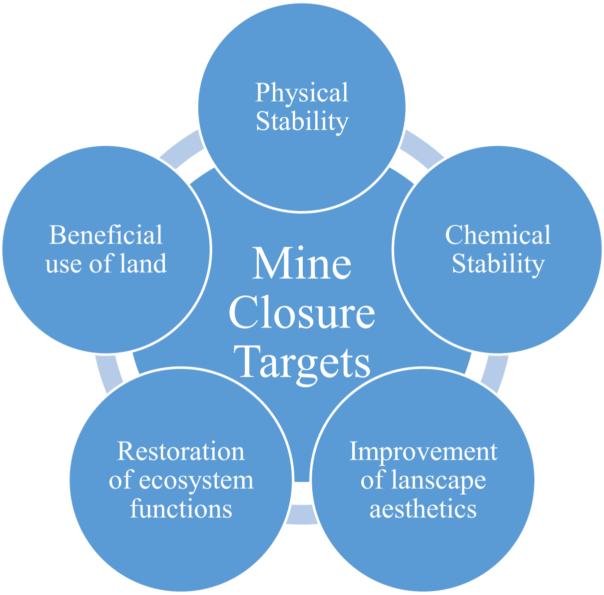


Fig. 1 Main targets of mine closure projects according to the more stringent national jurisdictions that are in force

Furthermore, the aforementioned targets will be achieved by applying a series of measures, which must be relevant to the site-specific conditions, realistic, measurable based on objective criteria and indices, and with a duration that allows being monitored over an appropriate time frame to ensure the results are robust for ultimate closure completion.

At this point, it is necessary to distinguish two cases: the first concerns the closure of a mine that has mined all the exploitable reserves of a deposit. In this case, the aim of the restoration works is twofold: to mitigate the impacts caused to the environment in a way that restores, to a satisfactory degree, the functions of the ecosystem and to develop land uses that compensate for the loss caused by the closure of the mine. These compensatory benefits need not only be valued in economic terms but also on the basis of a number of other criteria that have as a common denominator the quality of life of the inhabitants of the wider area.

The second case concerns mines that did not go as far as the depletion of the deposit's reserves and were forced to cease their operation earlier. The reasons that usually lead to such a development are related to changes in the external environment of the mining enterprise, which affect its economic results, or, more rarely, to technical failures involving its interior. One such case is that of the lignite mines of the Western Macedonia region (the case study that will be investigated in a following paragraph), as well as many other coal mines around the world that are leaving huge deposits unexploited due to the implementation of the carbon dioxide emissions trading system, which removed the competitive advantage of the low cost they had over other energy sources.

Whatever the reasons for the early closure of a mine, the process of closure must take into account the possibility of its reopening, either because there are again favourable terms for the exploitation of the useful mineral or rock in the use that existed in the past or because conditions have now been developed for its penetration into new markets and different uses than before.

No matter the place, size and other inherent characteristics of a mining project, responsible mine closure involves planning in consultation with all involved authorities and stakeholders. In the past, the process has relied on the mining company's ability to outsource the design of land reclamation projects and to carry out the relevant works either by utilizing its expertise in earthworks or by assigning the most specialized works to subcontractors. In modern practice, communities and regional governments play a key role in creating successful closure outcomes. Mining companies have much to learn from all the involved parties and need to capture and balance the views, concerns, aspirations, efforts, knowledge and capacity of all the people that will be affected by the upcoming mine closure [32].

The Proposed Circular Mode of Mine Closure

Nowadays, numerous institutions and companies have adopted sustainability principles for establishing a commitment to resource development in a socially and environmentally responsible manner. In this context, the International Council on Mining and Metals proposes ten sustainable development principles, which are in line with the conceptual framework of circular economy [33].

The concept of circular economy can help mining companies to plan and carry out projects in a more sustainable and efficient way, both in environmental and economic terms. Various approaches have emerged with an aim to include circular economy aspects across the mining life cycle. In the broader frame of resource management, most scholars agree that the circular economy should follow the "3R" principle, which is "Reduce, Reuse, Recycle" [3]. The European Union has at the core of its waste management policy a fourth "R" for "Recover" [34], while many other scholars propose up to "9Rs", which can be classified in a scale of increasing circularity as follows: Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Reduce, Rethink and Refuse [35, 36].

Since the circular economy is driven by design [5], the closure of a mine must be designed from the outset in such a way as to ensure that the following objectives are achieved:

- To maximize the reuse and recycling of equipment and materials as a priority (a) in production processes related to mining and (b) in areas adjacent to the mine
- To minimize the impact on the environment to such an extent that the possibilities for exploiting the reclaimed areas of the mine in other productive and recreational activities are not jeopardized
- To share a common vision for the post-mining era with local communities, regional authorities and other stakeholders, based on a consultation process that will last as long as the mine planning and operation, allowing adaptations that will be unavoidable, considering the duration of the mining projects and the emergence of new ideas and business opportunities that may occur within such a long period
- To select and implement measures of reasonable cost, which act supplementary in the frame of a rigorous action plan, aiming at re-establishing beneficial land uses and developing innovative economic activities agreed with all involved parties
- To immediately create new jobs for the mine personnel, which will require skills similar to those of the mining industry or even new skills, for which an education and training programme will have already been implemented

– To provide adequate financial resources so that closure plans can be completed even if the mining company abandons the site due to bankruptcy or any other reason or, alternatively, to relinquish the mining site to the government or third parties if this is necessary to achieve the objectives mentioned above sooner and to a greater extent

Furthermore, the two cycles presented in Fig. 2, each consisting of "8Rs", describe the application of circular economy principles to surface mining projects. The upper cycle of successive actions corresponds to the operation of the mines, while the lower one corresponds to the closure process. Common action to the mine operation and closure cycles is the "Rethink" action. Regarding mine operation, "Rethink" implies the need to thoroughly examine whether a new mining project should be launched, taking into consideration, on the one hand, the expected economic benefits and, on the other, the expected impact on society and the environment. Regarding mine closure, when this does not occur due to the depletion of reserves, "Rethink" means the review of this decision, taking into account on a life-cycle basis all the technical, economic, environmental and social parameters linked not only to the activity under closure but also the activity that is going to be the new source of mineral or the new technology that meets the customers' needs.

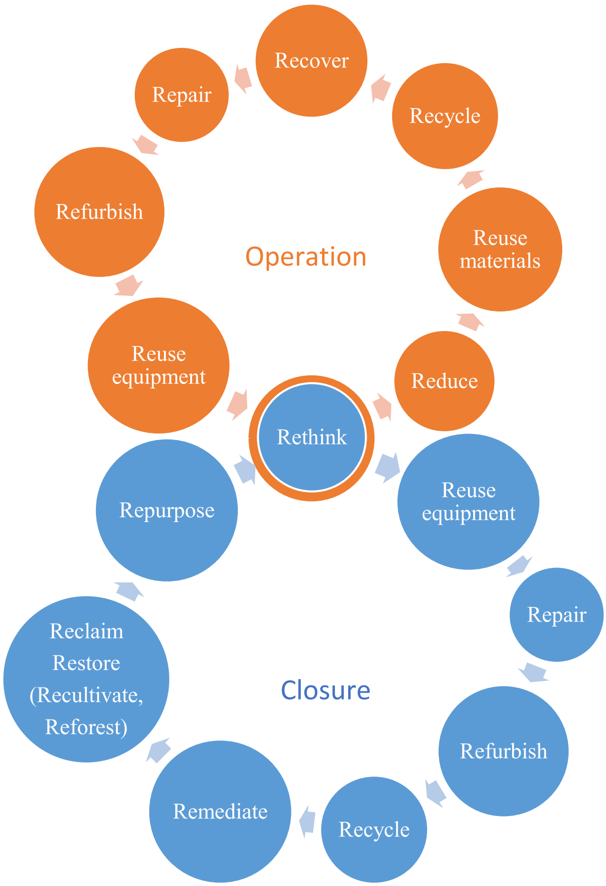


Fig. 2 The two cycles of "R-actions" constituting the circular economy model for the operation (orange) and closure (blue) of a surface mine

As far as the upper cycle is concerned, as mentioned earlier, the successful completion of a mine closure programme requires timely planning and implementation of specific measures when the production of the mine is still at the highest levels, which facilitates and dramatically reduces the cost of the land reclamation and mine closure works during the final phase of mine life. Among these measures, it is worth mentioning the following:

- Ore sorting and selective ore processing: Better in situ separation of ore from extractive waste means reduced ore concentration in waste and reduced waste concentration in the ore. This in turn minimizes the potential of environmental damages at the greater area of waste heaps and creates opportunities to commercialize by-products. Furthermore, this practice prevents leaving unextracted ore on site.
- Usage of excavated materials: Dumping excavated materials back into mine pits contributes to the prevention/reduction of space needed for the disposal of extractive wastes and their harmfulness. At the same time, the extractive material dumping process contributes to topography remediation purposes. Furthermore, using excavated materials as construction minerals, as far as it is technically feasible and environmentally sound, leads to less extractive waste being generated and offsets the primary production of construction minerals elsewhere.
- Management of topsoil: All topsoil removed during mine development and operating phases should be stored at separate locations and put back in place after the gradual completion of mining activities in order to achieve fast revegetation with local plant species and avoid extraction and transport of topsoil from elsewhere.
- Disposal planning and management for later recovery: The utilization of historical waste as a raw material increases the long-term value obtained from the original extraction, offsets primary production elsewhere and simultaneously contributes to site rehabilitation.

Trying to analyze further the components of mine closure, the ultimate targets of every mine plan must be taken into consideration, which are (i) to optimize the total materials cycle, taking advantage of the inherent characteristics of the mineral extraction project as well as synergies that can be developed in the vicinity of the mine and (ii) to create favourable conditions for the utilization of the reclaimed land for purposes that can be proved beneficial for both the mining company and the local communities. Figure 3 presents a triangular diagram with all "R-actions" that are applicable in a surface mining project. The R-actions of the right side of the triangle concern mine land management, starting from the base with the three R-actions that are obligatory according to the legislation and the environmental permit of every mine and approaching the apex with land repurposing, which is necessary for sustaining the social and economic prosperity, and relinquish, which implies releasing the mining company from any liability. The R-actions of the left side of the triangle concern the use of materials, giving priority to actions that are closer to the triangle's base.

The synergetic character of circular economy principles applicable in mine closure projects is based on a concept already mentioned in the introductory section, which identifies three different levels that result from the scope of the activities: macro, micro and meso level [3, 37–39]. While the macro level examines mining circular economy as a part of overall societal circulation policies and the micro level is focused on the own internal loop of each mining enterprise, meso level activities of circular economy are a kind of industrial symbiosis, taking mining industry as the core, where the waste, energy and by-product that cannot be digested in the mining enterprise are transformed into raw material or power for another enterprise. Mining industry transverse coupling and resources sharing with different industries such as power generation, metallurgy, cement industry, chemical industry,

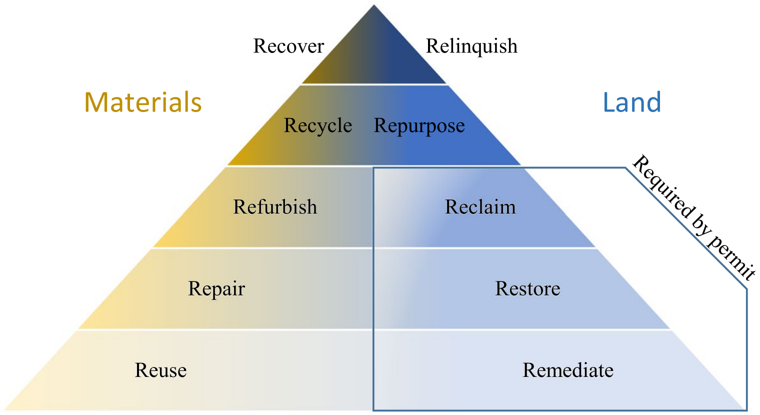


Fig. 3 Prioritization of all R-actions involved in surface mining closure projects for material cycle (left side) and land management (right side) enhancement

light industry and construction industry to form an enterprise network so that the material, energy and information can flow harmoniously in it.

Based on the above and adopting the vocabulary prepared by ISO [40] to facilitate effective communication within the field of mine closure and reclamation, the works that should be carried out under each one of the R-activities presented in Fig. 3 are described in the following paragraphs:

Remediation. Physical, chemical or biological treatment is often required to remove contaminants or pollutants from soil and groundwater, aiming at the preparation of the mine land to support the development of new land uses with minimum risks for the ecological functions and human health. Referring to abandoned mine sites, remediation aims to return sites to a physically and chemically stable state.
Restoration. A series of actions assist the recovery of the ecosystem structure and function to such as extent that natural flows and cultural values are restored to their prior state or to a state that replicates the desired reference ecosystem in a self-sustained manner.
Reclamation. A wide range of measures are planned and implemented based on a cost–benefit approach that tries to enhance mine land management options after the mine closure. The scope of reclamation differs from that of restoration, aiming at geotechnical stabilization of land and development of fertile soils so that recreational, agricultural and residential land uses are feasible alternatives after the mine closure. The ultimate target of reclamation is the return of disturbed land and infrastructure to a stable, productive and self-sustaining condition after taking into account beneficial uses of the site and surrounding land.

Specifically, a typical reclamation project should include the following activities:

- Elaboration of an action plan for developing new land uses in the restored mine lands, taking into account the legal framework, the obligations arising from the environmental permit, the plans of the mining company for further economic exploitation of the restored area and the opinion of the local community
- Configuration of safe slopes in the mine pit and the waste heaps

– Grading of the sloped final surfaces and construction of drainage ditches and other structures for controlling surface runoff, soil erosion and transfer of sediments to aquatic receivers
– Coverage of final surfaces that will be used for agricultural exploitation with fertile soil
– Planting of plants, preferably endemic, in the areas intended for afforestation or for recreation
– Configuration of the space around the lakes that will be formed in the final trench of the mine in order to ensure the safety of visitors and to create conditions for the utilization of the water body for recreation, irrigation, pumped storage, etc.

Moreover, it must be noticed that reclamation has a progressive character; thus, the determination of key tasks, key milestones and approximate duration for each task is required, as well as ensuring the availability and management of closure material sources, including adequate topsoil quantities.

Repurpose. The return of the mining landscape to the prior condition is often not possible. At the same time, parts of the mine land may be used for other purposes with relatively little intervention by creatively repurposing some of the existing mining infrastructure (i.e. roads, mine housing, operational buildings) and/or by reconfiguring aspects of the landscape (i.e. mine voids and mine features).

A mine land repurposing alternative is the construction of photovoltaic parks on reclaimed waste heap surfaces. It is an example of the regeneration of natural systems by replacing fossil fuels with renewable energy, an option that can be proven useful for energy-intensive mining enterprises, which try to decrease CO_2 emissions caused by using fossil fuels.

Relinquish. It occurs when ownership, residual liabilities and responsibility for a reclaimed mine site can be returned to the corresponding jurisdiction, the original owner or transferred to a third party. Relinquishment follows the completion of mine closure activities by satisfying the agreed criteria of success of the planned land reclamation activities.

Reuse. Using equipment and/or products with more care and longer, buying second-hand or finding a buyer for equipment that was not or hardly in use, and purchasing new products less frequently.

Repair. Large mining equipment repair, either in-house or in third-party workshops, can extend its operating life and reduce the cost of purchasing new machinery. Given the fact that the mine is in its ageing/closure phase, equipment repair is a critical procedure since the remaining life span of the mine is so short and does not allow the return of the relevant investment.

Refurbish. While the overall structure of large multi-component equipment remains intact, many components can be replaced or repaired, resulting in an overall "upgrade" of the machinery, which in turn allows considerable extension of its operating life and makes possible its sale after the mine closure. It is a procedure commonly applied in mine shovels, trucks, and continuous mining equipment.

Recycle. During mine closure, recycling is applicable in numerous ways, including various resources, such as waste rocks, chemicals, equipment (tires, machine parts), and construction materials and debris produced from the demolition of buildings and dismantling of infrastructure that is not expected to be utilized in the context of the new land uses that will be developed after the closure of the mine. These recycling opportunities are both feasible and high-impact because they have environmental and social benefits, such as reducing pollution and creating jobs.

Recover. The recovering principle means extracting resources from products that can no longer be used. Although the sale of equipment is considered the optimal management option after the closure of a mine, finding a buyer for used continuous mining machinery is a very difficult task since equipment selection is an integral part of mine planning and design [41]. Thus, dismantling and recovery of materials or controlled blasting demolition, dismantling and recovery of materials are two options for managing the metal scrap of heavy equipment and, at the same time, to eliminate in-pit pollution spots.

The Case of the Western Macedonia Lignite Centre

In the political and economic context of the EU energy transition strategies, Greek lignite mines are called upon to reduce their production activity and finally to cease their operation permanently within a short period of time before the exhaustion of their exploitable reserves. This exercise must be successful for several reasons relating to the social, economic, and environmental impacts that may arise at the local and regional levels. Lignite mining activities are hosted in areas with low population density, away from large urban centres and with a limited range of production activities usually related to the primary sector. This is also the case of the Western Macedonia region, where surface mines occupy a total area of 17,000 ha and are equipped with 42 bucket-wheel excavators and a large number of heavy machinery, both diesel and electric-driven. The annual lignite production currently is about 10 million tonnes, significantly lower than the record figure of 55.8 million tonnes achieved in 2004 [41]. The contraction of any component of this activity impacts the viability of the implemented economic model, which is measured as an increase in unemployment and a decrease in the population [8].

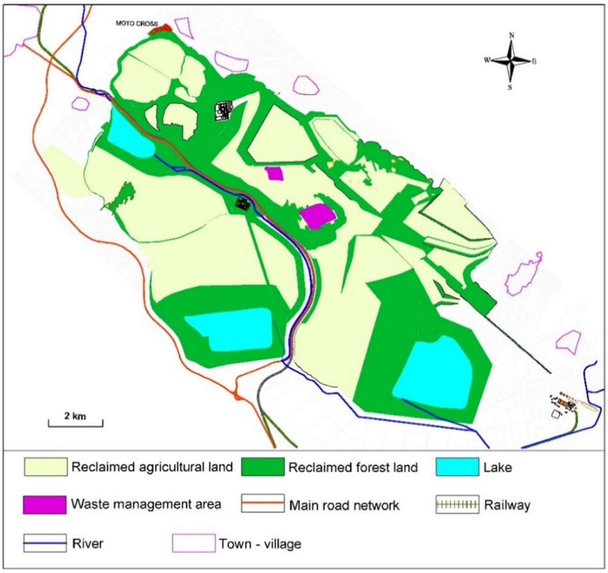
In this development, the lignite industry of the Western Macedonia region has entered a period of crisis. The large number of stakeholders involved in the strategy of lignite-fired power generation phase-out, as well as the urgent need to use efficiently the economic tools provided by the EU has led to the concession of a large part of the mining land by the lignite mining company to a public body established exclusively for managing just energy transition issues. The value of the expropriated land will be offset against the cost of land reclamation works that will be carried out. It is clear that this decision is a challenge for both the industry and government since this pathway to relinquish the lignite mining site is new and has not been tested yet.

Nevertheless, the adaptation of circular economy principles in a production system such as the lignite mines of Western Macedonia, which have been enforced to enter the closure phase of their operation, is a complicated procedure. As it has already been mentioned, the circular economy is based on a multi-step process anyway, starting from sustainable design, continuing with the selection of appropriate primary sources and operating procedures and finishing with the implementation of recycling and other practices that try to eliminate value leakages to any waste streams. However, lignite mines are productive systems that have operated for many decades and have been designed based on the traditional linear combination of processes applied in the extraction industry. To this extent, the implementation of circular economy practices is jeopardized by design, although some good recycling practices are implemented either for complying with an environmental permit or as a part of the corporate responsibility strategy. Therefore, the proposed circular economy mode of mine closure provides the mining company and local authorities with a managerial tool for the sustainable transformation of the region, eliminating the social, economic and environmental impacts. Some critical components of the proposed mode that have already been activated are discussed in the following paragraphs.

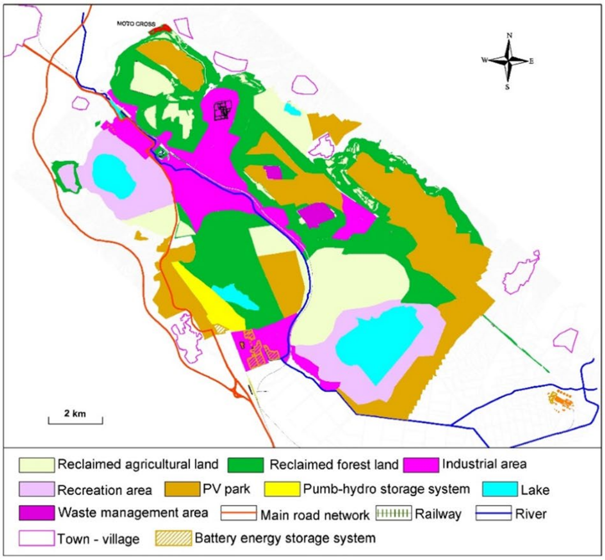
The efforts towards sustainable development are clearly reflected in the change in the planned land uses that will be developed in the mines' land after their closure. As it is presented in Fig. 4, the environmental impact assessment study of 2011 envisaged the creation of forests on the sloped surfaces of mine pits and waste dumps, arable land on the horizontal surfaces of waste dumps, and artificial lakes in the final voids of mine pits. Also, two existing solid waste disposal sites would remain after the closure of the mines: a municipal waste landfill along with a mechanical recycling plant and an asbestos cement landfill that has received materials dismantled from the cooling towers of local steam power stations. Although these land uses were fully in line with the existing legal framework that defines the reclamation of mine lands, they gave little prospect of developing the local economy. For instance, according to a study conducted by the School of Veterinary of Aristotle University of Thessaloniki [42], the types of crops that are considered suitable for reclaimed mine surfaces are vineyards, edible legumes, aromatic herbs and cereals (marginally), while the cultivation of energy crops, rye and oats is suggested only after improving the soil characteristics in areas where this is economically feasible. However, the viable size of crops (in hectares per farmer) limits the number of farmers that can cultivate this land to 22 and 100 per 1000 ha, for cereals and edible legumes, respectively. Taking into account that the total area of the mines that could be reclaimed as agricultural land is about 10,000 ha, the number of farmers working in them would vary from 220 to 1000 when the number of workers directly employed in the lignite mines and thermal power plant used to be 7500.

On the contrary, the revised, based on the circular economy principles, land-use planning adopts a completely different approach that goes beyond the provisions of the environmental permit and attempts to achieve multiple objectives at the same time: restoring the ecosystem, improving the residents' quality of life and repurposing the land developing new economic activities that create a sufficient number of decent jobs. The construction of photovoltaic parks with a total installed power of 230 MW [43], to the extent that it is not developed at the expense of other land uses, is consistent with the country's energy planning and contains important circularity elements since it utilizes the huge energy transmission infrastructure that exists in the area. It also addresses a major problem of restoration projects, which concerns the lack of topsoil to improve soil fertility and large amounts of water to create irrigated crops. At the same time, the development of industrial areas on 850 ha of land, which will be transferred to the jurisdiction of the just transition management body established by the Greek government, is expected to be the basis for attracting significant investments in the region. However, the number of jobs that will be created by the new investments is impossible to be predicted since it depends on incentives not yet specified and negotiations taking place at a high government level. The 1400 ha of areas around the lakes that will be formed in the final voids of the mine pits will be transformed into recreation areas, with the possibility of hosting sites of special purposes, such as open museums of mining equipment and sites of unique geological features. Artificial lakes are possible to be also used for creating pumped storage systems that will work in addition to the photovoltaic parks to normalize the flow of energy in the grid 24 h per day. Finally, the traditional land uses of agriculture, livestock farming, beekeeping and reforestation will

Fig. 4 Differences in land uses proposed in **a** the environmental impact assessment study of 2011 and **b** a revised post-closure land use planning of the Ptolemais mining complex, Western Macedonia Region



(a)



(b)

cover 6400 ha of the mining area in order to contribute to maintaining the balance of the ecosystem and the optimal integration of the mining area into the landscape of the wider area. To sum up, the revised land management plan of the lignite mines tries to satisfy simultaneously three objectives: (i) the restoration of ecological functions in disturbed land while improving the living standards of the local communities, (ii) the stay of power generation industry in the region and (iii) the support of agriculture, which is another traditional economic development pillar Western Macedonia region.

Regarding the materials cycle, the history of lignite mines has exhibited numerous cases of poor performance and good practices. Focusing on good management practices, it is worth noticing the reuse of bucket wheel excavators and spreaders of the Kardia mine in the neighbouring mines of South Field and Main Field that are still in operation. Moreover, all the diesel-engine equipment, conveyor belt heads and conveyor heads transport trucks, as well as a series of spare parts and equipment of buildings (e.g. air-conditioning and heating systems) of the Amynteo mine, which is located 20 km away from the complex of the other mines, were transferred to the South Field and Main Field mines.

In the framework of equipment refurbishment, a bucket-wheel excavator TAKRAF Srs2000 was reconstructed (refurbish) after the collapse of the bucket wheel and counterweight booms. Further to the restoration of the damage, improvements were made to the entire mechanical construction as well as a complete upgrade of the electrical equipment and automatic control systems of the Bucket-wheel excavator. The project began in 2017, and in 2023, the machine returned to normal operation on the 3rd bench of the South Field Mine. The total cost approached 10 million euros, and most of it is expected to be amortized until the mine closure (2028). Similarly, the booms of two back-hoe excavators CAT 6040 were repaired in-house within 100 days at a cost of 30,000 euros, when the cost of purchasing a new boom was 180,000 euros with a delivery time of 6 months.

Finally, an initial pilot demolition blasting of a bucket-wheel excavator TAKRAF Srs2000 in the Amynteo mine was carried out in order to decide further course of action regarding dismantling, recycling and materials recovery from heavy equipment. It is estimated that more than 1500 tonnes of metal scrap will be produced by this excavator, while the cost of controlled blasting was 10 times less than conventional dismantling with all safety and environmental issues to be under control.

The expected benefits from a circular economy mode of mine closure may be enhanced further following the transitional scheme described in Fig. 5. Essentially, this approach disconnects the closure of steam power stations enforced by the energy transition policies from the closure of all lignite mines located in the Western Macedonia region. Since the remaining exploitable lignite reserves are sufficient in several deposits and, in some cases, the overburden strata have already been removed, these deposits could be exploited on the basis of a new business model. To this extent, in accordance with the principle of rational exploitation of mineral resources, lignite would remain a significant resource to be exploited in smaller areas as it exhibits numerous uses in addition to this as a fuel. At the same time, other materials co-excavated with lignite in the same mines, such as clay and sand, and the ash that has been deposited in them could be exploited in the construction industry, while quantities of lignite could be supplied as a supplementary fuel (i.e. co-combustion with biomass and/or residues-derived fuel) to district heating units or industries. Moreover, the surface mine would change its operating method, abandoning high-productivity but inflexible continuous operating equipment, which would be sold to another mine or recycled as spare parts or scrap, while diesel equipment could be used (in some cases probably after refurbishment) becoming the main equipment of the mine. In this way, a new productive activity could be created, albeit on a smaller scale, which would have three important advantages: (i) it would create synergies with other activities in the mining areas, such as small district heating systems and the agricultural sector; (ii) it would maintain a large number of jobs that require knowledge and skills already possessed by the workforce of the area; and (iii) it would be in line with the principles of the circular economy and sustainable development since it would contribute to the further utilization of resources and the minimization of the generated waste.

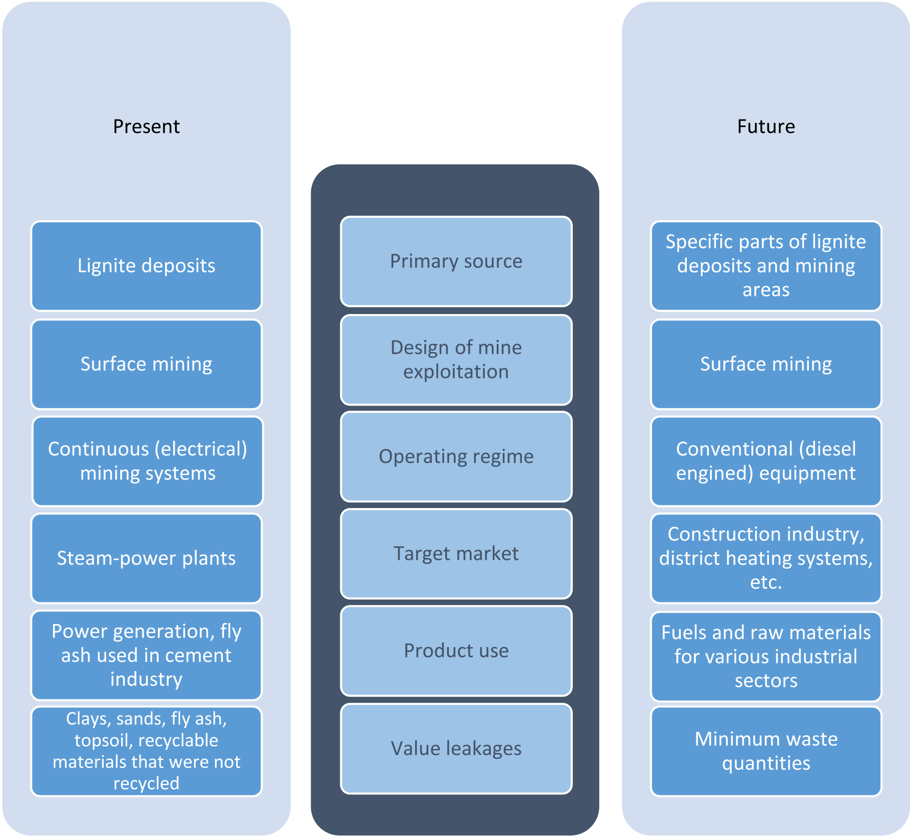


Fig. 5 The transition of a surface lignite mine from a large-scale activity that fuels thermal power plants to a small-sized operation that produces raw materials and fuels for various industries and utilities

Discussion

The adoption of the circular economy principles in a mine closure project is considered both feasible and imperative, even if the mine did not follow practices compatible with the sustainable development goals and the rational use of resources during its long period of operation.

Further to reuse, repair, refurbish and recycle strategies, which are possible to cover a large part of the mine closure cost, the restoration of the ecosystem is eventually a requirement, which, according to the legislation that is in force, must govern every mine closure project. Despite the knowledge gathered from the implementation of thousands of projects and the guidelines published by supervising authorities concerning land reclamation, topsoil management, geotechnical stability, management of water flow and water pollution, vegetation recovery, etc., there are only a few examples globally of mines that have received closure certificates acknowledging the land has been reclaimed to a level agreed by the governing body and where the site has been transferred to government or a third party. Both industries and governments are still building experience with mine closure, and many jurisdictions are still developing their understanding and policies that provide for the comprehensive closure of a mine operation.

In this context, the proposed methodology for the closure of a mine incorporates the principles of circular economy to initiate actions in two directions: (i) the effective management of materials and waste, the quantities of which during the dismantling and recycling phase of heavy mining equipment can be many tens of thousands of tons and (ii) the repurposing of mine land so that it can accommodate sustainable economic activities that will compensate for the loss from the phase-out of the energy industry. The proposed methodology is based on the experience from the 65 years of operation of the Western Macedonia lignite mines and, at the same time, transfers into action the global trends and changes in relation to the mine closure and development of new land use. The recent literature discusses the fundamental need for integration of mine closure and rehabilitation into wider regional planning towards being able to create opportunities for restoring and regenerating the mine disturbed lands [44]. Moreover, it is full of innovative projects that demonstrate specific measures for the economic development of areas that suffer from the mine closure impacts, such as the construction of photovoltaic parks on reclaimed mine surfaces [45] or even on the surface of mine pit lakes [46] or the creation of open, mining heritage parks that aim at boosting the industrial tourism [47]. Amirshenava and Osanloo [48] summarize the traditional options and modern trends for post-mining land uses in the following list: agriculture, forests, water bodies, industrial and commercial areas, residential areas, recreational and cultural services, renewable energy parks and landfill sites. In addition, for each one of these land uses, they carried out a SWOT analysis that provides basic information needed for land use strategic planning.

Nevertheless, the proposed circular economy-based methodology of mine closure exhibits numerous advantages but also faces some difficulties, as every methodology tries to introduce an innovation. More specifically, the advantages and limitations of the proposed methodology are the following:

Advantages:	Limitations:
- Rational use of resources	- Additional man-hours required for management and administration
- Reduction of waste volume	- Need for specialized personnel
- Incomes from equipment and materials sales	- The agreement of all stakeholders is usually necessary for further action
- Cost reduction due to equipment purchase delay or cancel	- Legal restriction for land use change
- Public acceptance	- Long-lasting bureaucratic procedures
- Availability of funding from just energy transition mechanisms	- Conflicts with established mindsets and perceptions inside and outside the mining company
- Self-sustained, synergetic productive activities	

Many of the above advantages and limitations can be quantified, in terms of expenses and incomes, to demonstrate that the proposed methodology is applicable to all mines facing the prospect of closure, whether in the context of the energy transition or for any other reason.

In any case, it should not be overlooked the fact that every mine is a production unit where large amounts of capital have been invested, and significant knowledge and experience have been accumulated in relation to the optimal exploitation of a specific mineral deposit. At the same time, the opening of every new mine that replaces an existing one is a difficult business decision that involves significant risks and uncertainties in the long run because of the need for large financing that was just mentioned and the inability to accurately predict critical parameters, such as the cost of production factors, the demand of products, safety issues, geopolitical stability and economic climate. For this reason, the closure of a mine should be considered a cessation of a specific business activity that was developed to exploit a mineral deposit and as an opportunity to look for new businesses, this time targeting different markets, based on the exploitation of the same mineral resource and/or other minerals that coexist and/or by-products of the previous period of operation. This approach is in line with both the circular economy's goal to minimize the waste quantities generated and disposed of, as well as the ethical principles of mining, which call for maximizing the recovered value from each exploitable deposit.

Conclusions

The closure of a surface mine is a complex process consisting of numerous projects described in legal and regulatory documents and reports of best practices. In cases of large-scale coal and lignite mines that are about to close with fast procedures due to the energy transition policies, the whole process becomes even more demanding. This is particularly true considering the limited potential of these areas to develop new economic activities, both in the reclaimed mining land and in the wider mining area, that will be capable of offering a comparable number of job positions with those provided by the mining and power generation industry.

The present study proposes a conceptual framework for the closure of a surface mine, which is based on circular economy principles and can achieve important goals on multiple levels. At the so-called micro level of mining companies, it can create internal loops of materials based on reuse, repair and maintenance and refurbishing practices that drastically reduce the cost of purchasing new equipment and materials and reduce the amount of waste generated. At the meso level of the local and regional economy, circulation practices can create the conditions for the development of synergies and industrial symbiosis. Having the area of reclaimed mines at the core of the economic activity, by selecting the appropriate land uses, resource sharing possibilities for steam and power generation, power storage, construction materials production, agricultural production, etc. can be maximized in a way that the material, energy and information can flow harmoniously. Finally, at the macro level, mine closure can be part of the overall societal circulation policies aiming at a self-sustained and balanced development based on the rational exploitation of mineral and other natural resources, utilizing the inherent advantages of each mining area and avoiding distortions caused by the dependence on a single productive activity of enormous size.

Some of the actions described in the proposed framework have already begun to be implemented in the lignite mines complex of Western Macedonia, either on a pilot or full-scale, and their positive results are already measurable in terms of reducing the maintenance cost of the mining equipment, reducing investments in the purchase of new mining equipment and increasing investments in energy production technologies of low carbon footprint.

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Data Availability The data presented in this study are available on request.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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