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REECOL Ecological rehabilitation and long term monitoring of post mining areas

Deliverable 4.5

Cost & Benefit Analyses of the new solutions for post-mining areas rehabilitation

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1. Introduction

The primary objective of this Report within the REECOL project is to perform a comprehensive Cost & Benefit Analysis (CBA) for the three innovative technologies for post-mining land reclamation developed under the WP4 of REECOL. This Report serves as a substantive synthesis of preceding research and development efforts, aiming to initially evaluate the economic and environmental viability of the proposed solutions.

This analysis is firmly embedded within the broader REECOL project agenda, which seeks to support the just transition of coal regions by implementing solutions that enhance the affordability and efficiency of reclamation processes. This Report builds directly upon the technical results delivered in the Project, using the specific frameworks established therein:

- Task 4.1: Development of directed succession methods for revegetation on post-mining terrains with a high redevelopment potential (GIG-PIB).
- Task 4.2: Development of a technology for non-contact rehabilitation and control of soil parameters with use of bio-waste (KOMAG).
- Task 4.3: Development of a technology for soil regeneration by composts of high biological activity (POLTEGOR).

These analyses also incorporate conditions defined in WP3, such as land degradation classifications and climate change adaptation scenarios, ensuring that business models are tailored to the actual conditions at the selected study sites. In this way, this Report bridges the theoretical foundations of the technologies with their practical implementation potential.

The analyses carried out under this task are intended to establish a foundation for the future industrial implementation of the technologies under development and to provide a preliminary assessment of their technical and economic feasibility. **Furthermore, the activities conducted within this task aim to create a basis for cooperation with industrial stakeholders interested in investing in the implementation and scaling-up of the proposed solutions.** The outcomes of this work may serve as a starting point for the preparation of joint demonstration and deployment projects, including initiatives supported by national and European funding programmes, such as the RFCS Big Tickets scheme.

The CBA aims not only to demonstrate financial profitability but, more importantly, to prove the value added by ecosystem benefits, such as soil organic carbon (SOC) sequestration, improved biodiversity, and the reduction of pollutant transfer, all of which align with the objectives of the European Green Deal.

1.1. Briefly on technologies developed in REECOL

Within the framework of the REECOL project, three complementary technologies were developed to enhance the efficiency, affordability, and ecological impact of post-mining land reclamation. These solutions address different stages and challenges of the post-mining land reclamation process:

- Steered succession of low-growing plants - this method focuses on accelerating and directing natural succession processes to quickly establish low herbaceous vegetation on waste heaps. It involves the use of low-cost soil additives (such as those based on sewage sludge ground mine waste rock and fly ash) to improve habitat conditions and the sowing of specific pioneer seed mixtures. The primary goal is to prevent the encroachment of invasive species and premature woody vegetation, thereby maintaining the redevelopment potential of the land.
- Non-contact soil rehabilitation technology - this innovative, integrated system enables the automated and precise application of reclamation materials without human intervention on the degraded site. It consists of three subsystems: a UAV-based vision system for analyzing vegetation indices (NDVI), a soil monitoring station, and an automated spraying unit. Guided by GPS-referenced treatment maps, the system can selectively apply water, fertilizers, mulch, or biowaste to specific zones based on their evolving needs.
- Soil regeneration by composts of high biological activity - adopting a circular economy approach, this technology transforms organic waste materials into a high-value resource for soil restoration. The developed product is a compost mixture consisting of 60% wheat straw, 20% waste chicken feathers, and 20% low-calorific lignite, inoculated with selected microbial strains to enhance biological activity. Produced using

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dynamic composting techniques, this bio-active compost enriches degraded soils with humic substances and nutrients, reducing reliance on synthetic fertilizers.

These technologies have been validated at the laboratory and semi-technical scales, with field-testing achieving Technology Readiness Level 6 (TRL 6).

1.2. Role of the developed technologies in reclamation processes

The selection and application of the developed technologies are strictly dictated by the specific characteristics of the post-mining site and the intended final land-use function. Within the REECOL Project, a clear distinction can be made between solutions optimized for:

- hard coal waste heaps and succession;
- lignite dumping grounds and potential agricultural restoration.

The reclamation of hard coal waste heaps is primarily based on the steered succession method (*see* ***Deliverable 4.1***), or may be complemented by the non-contact soil rehabilitation technology (*see* ***Deliverable 4.2***) for site-specific application of reclamation materials. These sites are characterized by difficult habitat conditions - a shortage of available phosphorus and nitrogen, poor water retention capacity, and a high content of hard coal that does not undergo decomposition. The primary goal here is often the temporary greening of areas with high redevelopment potential to prevent the spread of invasive species and the spontaneous development of dense woody vegetation, which can decrease the land's economic value. Steered Succession offers a low-cost method to quickly establish native low herbaceous communities that increase biodiversity and provide ecosystem services like pollination. The non-contact technology complements this by enabling the automated and precise application of seeds, mulch, and water on these often large and challenging surfaces, allowing for localized interventions based on real-time UAV monitoring.

On the other hand, the bio-active compost technology (*see* ***Deliverable 4.3***) was primarily developed for deep soil regeneration and rehabilitation, making it ideal for lignite dumping grounds (such as in the Konin Lignite Basin) and areas intended for agricultural use. Unlike the surface-level greening of heaps, this technology aims to rebuild soil functionality by enriching the environment with humic substances derived from the lignite fraction and selected microorganisms. Field trials on degraded lignite mine sites demonstrated that this compost acts as a powerful soil activator, resulting in a statistically significant 15% increase in plant growth (e.g., maize height). This approach aligns with circular economy goals and regenerative agriculture, providing a sustainable alternative to synthetic fertilizers for land operators who require long-term restoration of soil fertility and structure.

However, as during testing phase in REECOL WP4 and WP5 compost was also incorporated into hard coal heap rehabilitation by non-contact soil rehabilitation technology, as one of the reclamation materials to verify the compatibility of the developed spraying technology with compost application under field conditions.

In summary, while the succession and non-contact technologies focus on efficient, cost-effective stabilization of hard coal heaps to maintain their future utility, the bio-active compost is a specialized tool for restoring high-value biological productivity to lignite-based substrates and agricultural lands.

1.2.1. Integration of steered succession with non-contact soil rehabilitation

The steered succession method defines the biological concept of reclamation, including the revegetation strategy, by using low-cost soil additives, as well as determining the composition of the seed mixtures, and the target vegetation community. GIG-BIB technology also involves monitoring key performance indicators for land restoration activities, including the assessment of the soil's physico-chemical and biological parameters, as well as the characteristics and condition of the vegetation cover, based on in situ surveys and satellite data (remote sensing). The KOMAG technology complements this approach by providing an automated implementation platform based on UAV monitoring, GPS-guided treatment maps, and precision spraying of seed–mulch mixtures. In addition, continuous UAV monitoring enables verification of reclamation effectiveness and the implementation of supplementary treatments where required. Consequently, the KOMAG offers a precision, monitoring-based reclamation system.

1.2.2. Integration of compost technology with non-contact soil rehabilitation

Similarly, the compost technology provides the reclamation material, while KOMAG can provide the application platform in some site-specific scenarios (e.g. on steep slopes of the spoil heap). Specifically, POLTEGOR technology develops the high-biological-activity compost, produces the compost and provides the recommended application concept. On the other hand, KOMAG technology enables the application of compost-water suspensions, targets only areas identified through monitoring, optimizes compost consumption and enables repeated applications if monitoring indicates further intervention is needed.

Please note that within REECOL, the compost was incorporated into KOMAG's validation primarily to demonstrate that the automated spraying technology is compatible with the application of the developed compost under field conditions. Consequently, the non-contact soil rehabilitation technology extends the application potential of the compost technology by enabling precision, site-specific and demand-driven compost application on hard coal waste heaps, where localized treatment may be preferable to conventional spreading methods. Nevertheless, the primary application scenario for the REECOL compost remains the large-scale rehabilitation of lignite dumping grounds and agricultural land, where improvements in soil fertility and long-term biological regeneration constitute the principal reclamation objectives.

1.3. Scenarios defined and analysed in this report

The cost analyses presented in this report are based on several representative implementation scenarios rather than a single universal business model. This approach reflects the diversity of post-mining sites, reclamation objectives, ownership structures, and technologies developed within the REECOL project. Depending on the technology and market context, the scenarios are analysed from different perspectives, including mining companies implementing reclamation internally, external technology providers commercialising their solutions, or independent assessments of reclamation costs regardless of the implementing entity. The scenarios should therefore be regarded as illustrative business models intended to demonstrate plausible pathways for industrial deployment rather than prescriptive implementation schemes (*Figure 1*).

Scenario defined by GIG-PIB for steered succession (SCENARIO 1) represents an outsourced reclamation coordination model in which a technology provider commercializes the GIG-PIB rehabilitation method by delivering a comprehensive reclamation service to mining companies. The scenario is defined specifically for steered succession of hard coal waste rock heaps to achieve rapid and affordable greening of degraded surfaces to stabilize the soil and prevent the encroachment of invasive species. The service provider in this scenario is responsible for site assessment, rehabilitation planning, procurement of materials, process coordination, monitoring, and licensing of the protected technology, while all field operations are performed by external subcontractors using standard agricultural equipment. This asset-light business model minimizes capital investment, enables high scalability, and reflects a realistic pathway for the market deployment of the developed technology. **Majority of costs related to analyses in this scenario were based on real market quotes and real costs made while performing the field tests of the method in REECOL WP4 and WP5.**

The scenarios defined by POLTEGOR focus on the application of the REECOL compost technology for the biological rehabilitation of post-mining land, particularly lignite mining areas intended for future agricultural use. Unlike the GIG-PIB scenario, the analysis differentiates implementation pathways according to the identity of the investor and the operational scale of the composting system. Two business models are therefore considered. One in which the compost production facility is developed by the feather waste owner, who commercializes the product for mining companies and other customers (SCENARIO 2), and another in which the mining company invests in compost production primarily to support its own reclamation activities while retaining the possibility of marketing surplus compost (SCENARIO 3). **Given the current technology readiness level, the scenarios are based on indicative CAPEX and OPEX assumptions intended to support preliminary feasibility assessment rather than detailed investment appraisal. The majority of investment and operating costs presented in these scenarios are therefore indicative placeholders derived from engineering judgement, market benchmarks, and preliminary supplier information**, while the technological assumptions are based on the REECOL WP4 and WP5 field validation and semi-technical compost production trials.

The scenarios defined by KOMAG focus on the deployment of an integrated non-contact soil rehabilitation technology for the rehabilitation of hard coal waste rock heaps using UAV-based monitoring, environmental

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sensing, and site-specific application of reclamation materials. Unlike the GIG-PIB and POLTEGOR scenarios, the analysis does not compare alternative investor or business models but instead evaluates two complementary operational stages of the reclamation process: initial treatment of the entire site (SCENARIO 4) and monitoring-based supplementary intervention applied only where environmental conditions indicate additional reclamation is required (SCENARIO 5). Although the primary objective of the KOMAG technology is the development and assessment of an automated precision application system, compost was also incorporated into both scenarios as one of the reclamation materials to verify the compatibility of the developed spraying technology with compost application under field conditions. **Cost assumptions were derived from prototype development, field demonstrations, engineering calculations, and representative market prices, and should therefore be regarded as indicative estimates supporting preliminary techno-economic assessment rather than commercial quotations.** It should be noted that field tests of KOMAG's technology conducted under REECOL WP4 and WP5 resulted in site-specific application rates of both seed mixtures and compost that differ from those adopted by GIG-PIB and POLTEGOR in their respective implementation scenarios. Consequently, the cost analysis for the KOMAG scenarios is based on these adjusted application rates.

1.4. Rationale for cost & benefit analyses at early stage of development

Performing a Cost & Benefit Analysis (CBA) at an early stage of technology development specifically while solutions are at Technology Readiness Level 6 (TRL 6) - is essential for transforming research results into practical, industrial-scale applications. Although it is recognized that every post-mining area is unique and investment costs will vary significantly based on site-specific geological, climatic, and logistical conditions, this early assessment serves several critical functions:

Identification of the key cost drivers - the analysis allows developers to identify the primary factors that will influence the final price of reclamation, such as biomass procurement, specialized microbial inoculants, or automated equipment maintenance. This enables structured decision-support for further technical optimization before full-scale commercialization.

Demonstrating implementation potential to stakeholders - preliminary CBA creates a substantive basis for cooperation with industrial stakeholders and mining companies interested in scaling up these solutions. By presenting indicative CAPEX and OPEX figures, the project provides practical placeholders that allow potential investors to perform initial budgeting and pre-feasibility assessments.

Evaluating non-financial ecosystem benefits - the value of post-mining reclamation cannot be captured by direct financial returns alone. Early-stage analysis allows for general assessment of ecosystem services, such as soil organic carbon sequestration, biodiversity improvement, and the reduction of pollutant transfer, all of which align with the strategic goals of the European Green Deal.

Since post-mining sites are not standardized, this report utilizes a scenario-based approach. By comparing different implementation pathways (e.g., internal use by a mining company versus outsourcing to a specialized service provider), the analysis demonstrates the conditions under which these innovative technologies become operationally and economically attractive. While specific costs will differ for every case, the early-stage CBA bridges the gap between theoretical research and practical implementation, ensuring that the developed technologies are not only ecologically effective but also industrially feasible.

Finally, these analyses serve as a starting point for the preparation of joint deployment projects, including those supported by European programs such as the RFCS Big Tickets scheme, by proving the preliminary economic and environmental viability of the proposed solutions.

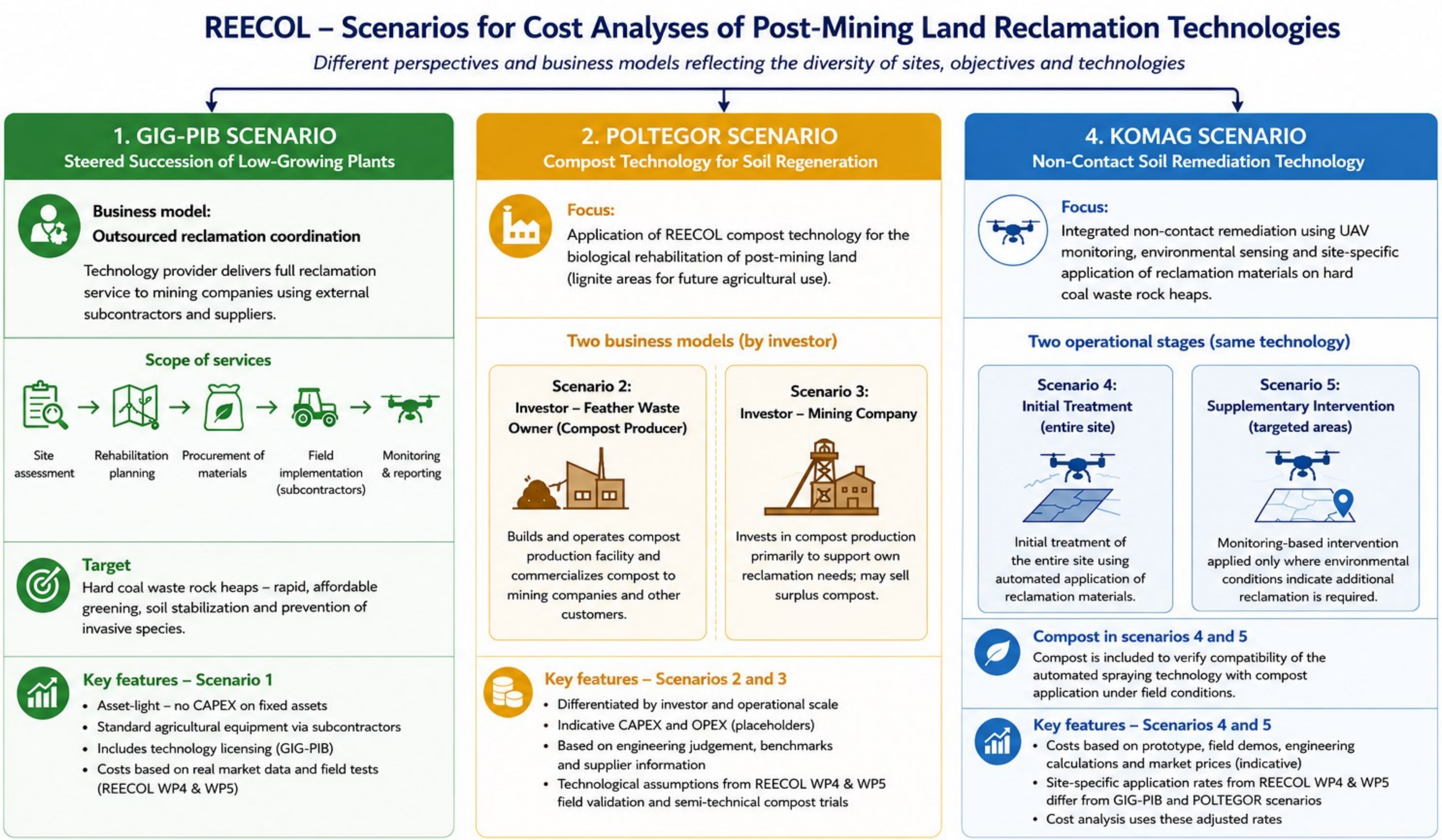

Figure 1. Summary of post-mining reclamation scenarios in this Report (AI supported).

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1.5. General discussion on the benefits and costs

The following scenarios developed in the following chapter all consist in revegetating hard coal waste heaps or lignite dumping grounds with different post mining land use such as agriculture, biodiversity reserve or leisure.

Following this, it is possible to list and discuss the common cost and benefits of the rehabilitation. Some of them are directly monetisable others are considered as qualitative.

1.5.1. Benefits

The projects present internal benefits such as:

- Increased property value on site: expected increase in property/land value/productivity after rehabilitation and redevelopment, income generation opportunities, and possibly even increase in the tax base for increased revenues to municipalities. This is country and site specific and as to be included in the mining company strategy (in particular if they want to sell or must relinquish the rehabilitated areas). An average increase of 3-36% following rehabilitation could be expected (5-15% within 5 km of the rehabilitated site) (Hanniger et al. 2017).
- Provisioning ecosystem services: they can be a valuable income generating opportunity for landowners, especially for agricultural land uses that can provide supplemental income during and after rehabilitation, this is the main benefits of SCENARIOS 2 and 3.
- Increased tax revenues and levies: they are a significant benefit resulting from rehabilitation and redevelopment that can justify investment. For example, restoration or enhancement of the tax base of governments (e.g., property and income taxes) because of brownfield redevelopment can be estimated using market pricing as the expected increase in property value multiplied by the respective property tax and/or the tax revenues from operation, hosting companies and future tax payments. This is country specific.
- Environmental conservation credits: these were highlighted as potential revenue generation through selling wetlands mitigation credits (or carbon credits) based on market pricing under a banking instrument for a rehabilitation and redevelopment project where the high value wetland ecosystem was preserved.
- Renewable energy generation with solar photovoltaic (PV) systems, this was not considered in REECOL scenarios.

The projects present external environmental benefits (that can be assessed and economically valued in terms of final ecosystem services that deliver benefits for human well-being which provide economic value), such as:

- Climate change mitigation through carbon sequestration and storage. It is one of the most considered benefits, especially with the application of nature-based solutions or other brownfield greening proposals. Several costs are available in the literature:
  - The average carbon price in the voluntary carbon market 10 USD/MgCO_2e according to the World Bank (Gasparinnetti et al., 2024),
  - The EU emissions trading system value of 25 EUR/MgCO_2e captured (Krzemień et al., 2022b, 2022a),
  - 39 EUR/MgCO_2e derived from a comprehensive literature review of the social cost of carbon,
  - 233 EUR/Mg CO_2e as the average value of a projected value range for the year 2030 (De Valck et al., 2019),
  - If Biochar : 2,4t CO_2eq per Mg of biochar (Azzi et al., 2019; Papageorgiou et al., 2021).
- Removal and filtration of air pollutants: the removal of air pollution is a potential benefit of brownfield rehabilitation and redevelopment that is particularly relevant in an urban context and conversion to a green space with vegetation or using nature-based solutions. This is not considered in our scenarios unless the sites are located very close to populated areas.
- Hydrological cycle and water flow regulation: The control of erosion is one of the main benefits, it avoids the spread of potential contaminants and particles (suspended matter, dust, etc.). Regulating the flow of water in terms of stormwater runoff, flood control, etc. is also a valuable benefit in both urban areas and agricultural areas to increase water retention for crops.
- Pollination: it is one of the main benefits of SCENARIO 1.

- Biodiversity and habitat quality: it is one of the main benefits of SCENARIO 1.
- Regulation of soil quality and health: the improvement of the soil and development of vegetation in the different scenario are conditioned by the soil quality after rehabilitation.
- Greenfield development savings: A benefit of rehabilitation is to promote redevelopment and reuse of already developed land which prevents the exploitation of greenfield land and loss of ecosystems.

As an example, in a study by De Valck et al. (2019) five urban ecosystem services provided by green infrastructure at brownfield sites are described:

- local climate regulation (0,207 EUR/m^2 vegetation/year),
- air filtration and ventilation (72 EUR/kg PM10 filtered/year),
- recreation (4,5 EUR/visitor/year),
- carbon sequestration (233 EUR/Mg CO_2/year),
- avoided runoff (0,52 EUR/m^3/year).

One can also consider the following social benefits:

- Human health improvements: Removing or reducing the risk for negative health impacts due to contamination is one of the most important benefits of rehabilitation but they were not considered in this project.
- Cultural ecosystem services: Cultural ecosystem services include the non-material benefits people obtain from contact with ecosystems that can influence their well-being (TEEB, 2010). The areas rehabilitated according to scenario 1 can be converted in parc, areas where it is possible to take a walk.

Other external benefits can be an increased property value in surroundings, employment opportunities and agglomeration benefits (such as additional investment as the rehabilitated area can create opportunities).

1.5.2. Costs

The internal project costs are the main source of costs. They typically include the direct types of costs for the rehabilitation and redevelopment project.

Direct rehabilitation and redevelopment costs include:

- design of rehabilitation action,
- project management,
- capital costs:
  - CAPEX (on-site) - the initial site investigation and pollution survey, design of rehabilitation action, site preparatory works and establishment of rehabilitation strategy, and the capital costs of the rehabilitation action,
  - CAPEX (off-site) - costs involved in movement of materials to an off-site landfill such as excavation, disposal, soil handling and tipping fees,
- rehabilitation action,
- monitoring,
- OPEX - administration and management costs, monitoring expenses, decommissioning activities for rehabilitation options, fuel costs (diesel and gasoline consumption), travel expenses, environmental guidance and third-party costs, labour costs, machinery costs,
- project risks (risk of ineffective rehabilitation, reputational risk), to be considered at a feasibility step.

There are also external environmental costs to consider such as:

- Aggregated environmental impacts of the rehabilitation action (to be considered at a feasibility step),
- Air emissions and air pollution from rehabilitation action (to be considered at a feasibility step),
- Air emissions and air pollution from transportation (to be considered at a feasibility step),
- Air emissions from future land use (to be considered at a feasibility step).

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External social costs may be incurred due to the rehabilitation action and transportation associated with the project that could result in economic costs to both the workers carrying out the project and the broader public:

- Worker health and safety costs from rehabilitation action (to be considered at a feasibility step),
- Public safety and public nuisance from rehabilitation action (to be considered at a feasibility step),
- Public safety and public nuisance from transportation (to be considered at a feasibility step).

Other external costs can be:

- The land use latency: Land may not be available for productive use during rehabilitation, which could entail a cost for landowners. This could be seen as a postponed benefit or opportunity cost for landowners especially when considering rehabilitation strategies with different time horizons, e.g., conventional rehabilitation vs. long-term gentle rehabilitation. One of the benefits of SCENARIOS 2 and 3 with high biological activity compost is indeed to accelerate the conversion of the site of an agricultural land use.

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2. Directed succession methods for revegetation on post-mining terrains with a high redevelopment potential

The steered succession of low-growing plants method, is an innovative, cost-effective reclamation technology designed specifically for hard coal waste rock heaps with high potential for future economic redevelopment. The primary objective is to achieve rapid and affordable greening of degraded surfaces to stabilize the soil and prevent two major risks: the encroachment of invasive species and the spontaneous development of dense woody vegetation, both of which can significantly decrease the land's economic value and complicate its future reuse. Unlike standard reclamation that relies on expensive topsoil importation, this technology focuses on accelerating and directing natural succession processes towards a stable, low-growing herbaceous community. The technology can be summarized by two components:

- a low-cost soil additive - typically based on sewage sludge and coal mining or combustion by-products (such as fly ash) that is applied directly to the waste rock. This improver addresses the critical limiting factors of mine heaps, specifically the shortage of available phosphorus and nitrogen, while simultaneously improving the substrate's water-holding capacity;
- a specialized seed mixture of native species for targeted revegetation is sown to establish a community adapted to difficult conditions. The selection (typically 20 herbs and 5 grasses) focuses on plants that occur spontaneously on heaps, have low nutrient requirements, and are drought-resistant. These flowering plants also enhance biodiversity by providing habitats for pollinating insects.

In shortcut, this method transforms a random, wind-carried succession process into a structured biological stabilization. By establishing a native herbaceous cover within two growing seasons, the technology creates an aesthetically pleasing landscape that provides essential ecosystem services (e.g., erosion control, pollination) while maintaining the site's readiness for subsequent industrial or commercial redevelopment. The solution is industrially ready, as field implementation can be performed using standard agricultural equipment.

2.1. Proposed SCENARIO 1 definition

The implementation of the steered succession of low-growing plants method is structured around **an outsourced reclamation coordination model** where a central provider manages the entire process for mining companies by utilizing external subcontractors and suppliers. This business scenario is fundamentally an asset-light strategy, meaning it requires no initial capital expenditures on fixed assets because the physical implementation relies on standard agricultural equipment provided by subcontractors. The coordinator delivers a comprehensive suite of services that begins with preliminary studies of physicochemical and habitat conditions, followed by the development of a specific rehabilitation plan, the procurement of necessary soil additives and seeds, and finally the execution of field tasks.

This structured process is designed to achieve a stable vegetation cover over two distinct growing seasons, with initial soil preparation and sowing in the first year followed by maintenance and additional fertilization in the second. To ensure accountability and documented proof of success, the effectiveness of the reclamation is rigorously verified through advanced monitoring techniques including satellite data, UAV imagery for NDVI index analysis, and traditional field surveys. Furthermore, the model incorporates a specific license fee for the protected GIG-PIB technology, which is justified by the large-scale savings generated for the client relative to standard industry solutions.

2.1.1. Product-market fit

Rehabilitation method developed as part of REECOL Task 4.1 (steered succession of low-growing plants) addresses a real, pressing problem related to the effective reclamation and effective use of land transformed by mining. Developed solution can be implemented to convert post-mining areas into diverse habitats with high aesthetic value and recreational potential, as well as for the temporary greening of areas with high potential for economic reuse. Revegetating such areas with low-growing vegetation aims to reduce the risk of invasive species establishing themselves and to slow down the succession of woody vegetation.

This well-established plant community, characterized by a predominance of herbaceous plants with colourful and fragrant flowers, provides an attractive habitat for pollinating insects. This helps increase biodiversity within anthropogenically altered areas and makes it possible to use such green spaces for honey production.

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2.1.2. Target audience

The target group consists of mining companies, in particular hard coal mines located (but not limited to) in the Upper Silesian Coal Basin, which are responsible for the reclamation of land transformed as a result of mining operations. For example, a REECOL Partner PGG (Polish Mining Group) cover 603 square km, and are located in 42 communes of Silesia region and 3 communes of Małopolska region. A long-term strategy assumes closing all the mines belonging to the PGG until 2049. The process will lead to an appearance on the real estate market terrains with high redevelopment potential. Currently, 15 active mining plants cover areas about 700 ha. Some post-mining areas have less economic value and can be used for purposes related to increasing biodiversity and supporting ecosystem services (pollination, regulation of surface temperature, water retention, erosion). Preliminary spatial analyses indicate that within a 50-km road distance from the wastewater treatment plant in Jastrzębie (the supplier of the soil improver), there are currently 50 non-vegetated post-mining waste dump sites with a total area of 1 800 ha.

2.1.3. Business model

Outsourced Rehabilitation Coordination - a business model based on the coordination of outsourced environmental services. The most important advantages of the adopted business model are:

- no requirements regarding capital expenditures (fixed assets - CAPEX);
- high scalability through subcontracting.

2.1.4. Financial assumptions

The most important factor in assessing the commercialization potential of the developed service is the cost of performing rehabilitation using the developed method.

The scope of cost items includes not only the purchase of materials and the performance of reclamation work, but also preliminary studies and monitoring of the effectiveness of the performed operations required to rehabilitate the site and the costs associated with carrying out the project. The cost estimates also consider the costs of operating the business under the Outsourced Rehabilitation Coordination model and the costs of license fees.

Preliminary Studies

An essential step for the effective application of the developed technology for the reclamation of post mining area is the assessment of the initial habitat conditions. The scope of this analysis includes both an inventory of spontaneous vegetation within the reclaimed site (ex-situ studies) and the collection of soil samples for the determination of basic physicochemical parameters, as well as for pot experiments (ex-situ studies). This scope of research allows for the identification of the baseline level of fertility and the detection of any potential phytotoxicity in the substrate. It should be noted that post-mining waste may contain elevated concentrations of trace elements, including heavy metals, as well as petroleum-derived contaminants, which can negatively affect plant growth. The test results enable the development of a rehabilitation plan. This document specifies guidelines regarding the application rate of soil improver (based on the initial fertility of the substrate) and the selection of the target species composition of the reclamation mix (e.g., depending on the level of soil acidification). In the case of post-mining waste whose properties prevent the growth of pioneer vegetation, it is necessary to carry out additional measures to create favourable habitat conditions (neutralization of excessive soil acidity). Due to most waste dumps within the Upper Silesian Coal Basin do not exhibit strong phytotoxic properties, the additional costs of neutralizing or stabilizing heavy metals were not included in the analysis. However, these costs may arise when applying the method to the reclamation of spoil heaps resulting from open-pit lignite mining or of sites contaminated by heavy industry.

Materials

Material costs include the purchase of seeds of selected pioneer plant species (native herbaceous plants and grasses) and the cost of purchasing a soil improver. Specialized seed companies provide seed mixtures in quantities necessary for large-scale reclamation projects. To establish diverse low-growing vegetation on Północ mining waste heap in Jankowice (Poland) 5 grams of seeds mixture per square meter was used (*see* ***Deliverable 4.1***). For the purposes of this cost analysis, the offer to supply 50 kg/ha of the seed mixture used in the rehabilitation of the Północ spoil tip was taken as the basis. For the purposes of this cost analysis, a quote for the supply of 50 kg of the seed mixture used in the rehabilitation of this post-mining site was used.

The soil improver is a product based on processed sewage sludge and can be produced at waste treatment facilities - ideally located near municipal wastewater treatment plants. In each specific case, the quantity of soil conditioner required is determined based on preliminary tests. To estimate the costs, the quantity used for the rehabilitation of the North spoil heap in Jankowice (Poland) was taken as a basis (*see* ***Deliverable 4.1***). As part of the fieldwork, soil improvers produced at the wastewater treatment plant in Jastrzębie Zdrój were used.

Reclamation services

Based on observations of the test plots within the Północ landfill in Jankowice, it should be assumed that, to achieve the expected vegetation cover, reclamation action must be carried out over two growing seasons. During the first growing season, soil amendments are applied and pioneer plant seeds are sown. During the second growing season, only soil improvers are applied.

Field tests have shown that large-scale implementation of this method (rehabilitation of multiple pastures) is possible using basic agricultural equipment (tractor, fertilizer spreader, seed drill, harrow). Rehabilitation work can therefore be carried out by companies that provide services to farmers. If there is no company providing agricultural services in the immediate vicinity of the reclaimed land, the cost of transporting agricultural equipment must be considered.

To assess the effectiveness of reclamation efforts, it is essential to monitor the reclaimed area. This monitoring is conducted based on spectral analyses. Periodic on-site inspections are also necessary to directly inventory the species composition of the developing vegetation (*Figure 2*). The scope of work in question can be carried out by specialized companies and research institutes.

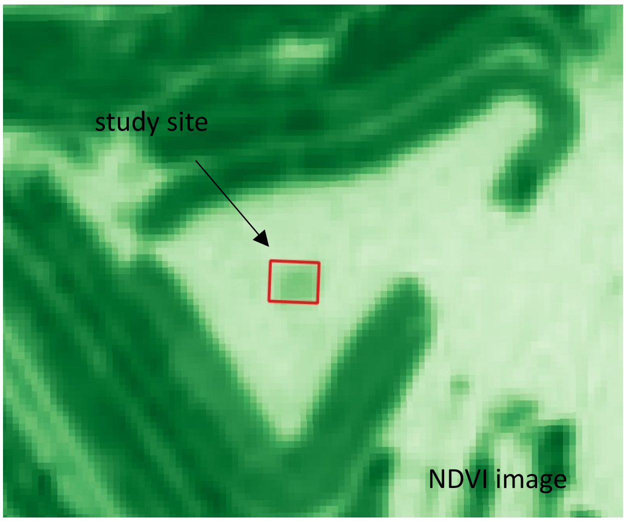

Figure 2. Monitoring the effectiveness of rehabilitation using satellite data, UVA imagery and field surveys.

The company's own costs

Product-related costs include the selection of suppliers of materials and external services, oversight of the coordination of the reclamation process, as well as costs related to marketing, customer service and financial margin.

License fee

This solution is protected by law. This solution is the property of the Central Mining Institute - National research institute (GIG-PIB) in Katowice. The calculation of the license fee considered the fact that the solution was filed for intellectual property protection (patent) and was tested under real-world conditions (industrial implementation using agricultural equipment at the Północ landfill in Jankowice).

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Since rehabilitation is a strictly technological process (e.g., bioremediation, phytoremediation), the amount of the fees is most often based on the actual savings or profits that this method generates compared to traditional solutions (*see next section*). A preliminary estimate of the cost of purchasing a license per hectare has been set at 350 EUR.

Operating Margin

Given that the standard restoration method involves significantly higher costs *(see chapter 2.2)* and has limited potential to provide ecosystem services, it was assumed that the profit margin for a company offering this innovative service could be as high as **10%.**

2.1.5. Proposed scenario – cost summary

Based on the assumptions made, the cost of reclamation for 1 ha of post-mining land is approximately by providing a comprehensive service to the client (a mining company) through an external outsourcing firm, the cost will amount to **12 660 EUR.** Cost analysis was conducted based on market quotes and the construction price bulletin (*source: www.sekocenbud.pl*).

The table below provides a detailed overview of the costs covering the full scope of services in the proposed business model. These prices are based on price quotes and field experience (*Table 1*).

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Table 1. Cost items for developed method of post-mining land rehabilitation.

Cost item		Material requirements [kg/m²]	Cost of material [EUR/kg]	Cost (EUR/m²)	Cost (EUR/ha)
1	**Preliminary Studies**				**1 752**
a	Analysis of the physicochemical parameters of the mining waste				584
b	Assessment of habitat conditions				701
c	Development of a rehabilitation plan (soil amendment dosage and species composition of the reclamation mix)				467
2	**Materials**				**3 802**
a	Reclamation mix (seeds)	0,005	70,63	0,353	3 532
b	Soil improver (processed sewage sludge)	0,5	0,054	0,034	270
3	**Land Reclamation Services**				**3 501**
3.1	**The first growing season**				**1 984**
a	Transportation of soil improver (up to 50 km)		0,0368	0,023	234
b	Transportation of agricultural equipment (up to 50 km)			0,035	349
c	Application of a soil improver			0,047	467
d	Sowing Seeds and Harrowing			0,035	350
e	Monitoring				584
3.2	**Second growing season**				**1 634**
a	Transportation of soil improver (up to 50 km)				234
b	Transportation of agricultural equipment				349
c	Application of a soil conditioner				467
d	Monitoring				584
4	**License fee per hectare**			0,035	350
5	**Labor**				1 869
a	Marketing, customer service, work coordination				1 869
6	**Operating Margin**				1 250
7	**Total cost of the service per hectare (EUR/ha)**				**12 660**

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2.2. Advantages over standard reclamation scenarios

The cost of standard reclamation, which involves creating a layer of at least 5 cm of fertile material on the surface of the spoil pile (most often consisting of native soils) and seeding it with grass, can be around 29 490 EUR per hectare. Cost analysis was conducted based on market quotes and the construction price bulletin (*Table 2*).

Table 2. Costs item of the standard reclamation method.

Cost item	Material requirements [kg/m^2]	Cost of material [EUR/kg]	Cost (EUR/m^2)	Cost (EUR/ha)
Material				
Grass seeds	0,3	4,4	4,6	10772,1
Native soil	50	0,012	0,6	5814,0
Works				
Native soil transport				2325,6
Spreading of native soil (at least 5 cm thick - layer)			1,0	10113,5
Sowing seeds				465,1
Total cost of the service per hectare				**~29 490 EUR/ha**

Steered succession of low-growing plants advantages over standard reclamation by:

- greater biodiversity with higher aesthetic value (e.g. by the presence of plant species with showy flowers) (*Figure 3*),
- there is potential to provide forage for bees (honey production) (*Figure 4*),
- greater water retention and erosion control (deeper root system).

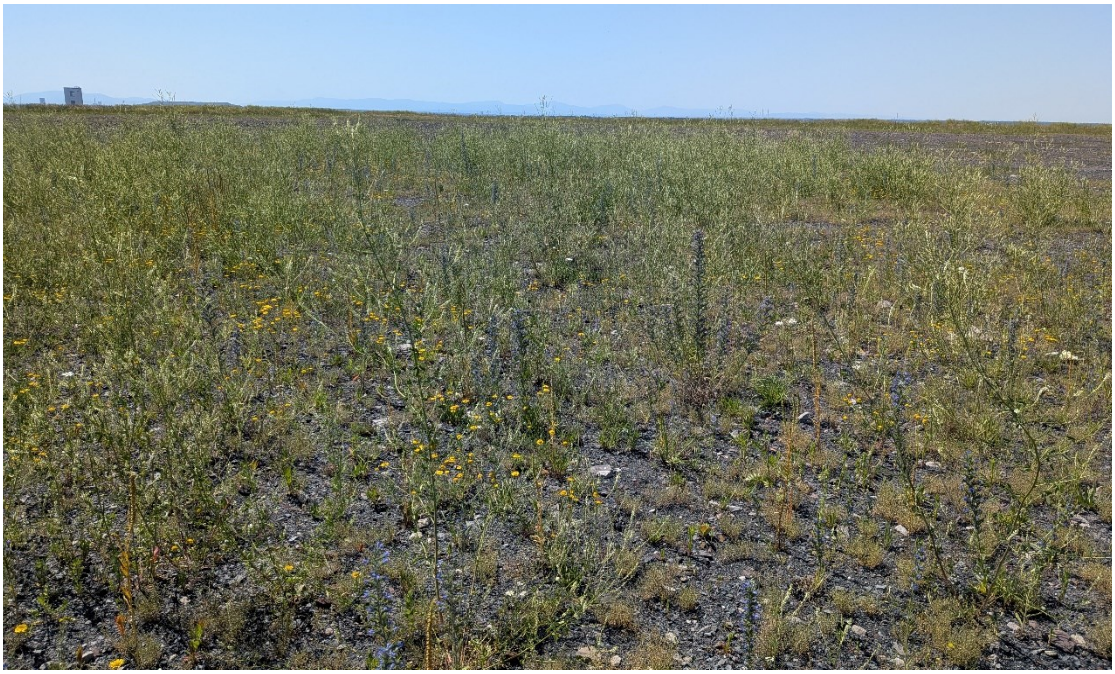

Figure 3. GIG-PIB and PGG - diverse herbaceous vegetation with natural and recreational value.

Figure 4. GIG-PIB and PGG - species with showy flowers that serve as habitats for pollinators.

2.3. Other scenarios

Reclamation costs can also be reduced by having the mining company coordinate the reclamation process directly. In this case, the mining company does not bear the costs of customer service or the margin.

When reclaiming land over larger areas, one should expect the costs of the reclamation work to be lower. This is because the costs of transporting agricultural equipment are incurred only once. In the case of larger areas (over 1 ha) with a homogeneous waste composition, it is also possible to reduce the need for preliminary analyses of soil fertility and phytotoxicity.

Costs may increase if the soil improver and agricultural equipment need to be transported over a longer distance.

2.4. Summary

Experiments conducted at the spoil heap Janina which is owned by PPG and pot experiments using soil provided by the other Project Partners (VUHU, PCC, INNERIS) show that the method used allows for cost-effective revegetation of post-mining areas, both the waste dumps resulting from underground hard coal mining and from open-pit mining. The method creates species-diverse communities that provide habitats for other organisms, particularly pollinators. Covering the area with vegetation limits the spread of invasive species and slows the succession of woody vegetation. For this reason, the method can also be used to ensure the long-term preservation of areas with high potential for economic reuse.

Despite its lower costs compared to standard restoration methods, this method offers greater potential for providing ecosystem services. The service also includes comprehensive monitoring of the results of rehabilitation efforts, which gives the mining company confidence that its reclamation goals will be achieved.

This implementation model, based on an outsourcing company, offers scalability, high margins, and eliminates the need for capital expenditures.

Cost analysis was conducted based on market quotes and the construction price bulletin (www.sekocenbud.pl). The actual costs of providing services using agricultural equipment on an area of 1 ha at Janina heap in Libiąż were used.

3. Technology for soil regeneration by composts of high biological activity

Please note that the CAPEX and OPEX figures in this analysis are indicative only, and would need to be confirmed by quotes from manufacturers and service providers. These assumptions are intended as practical placeholders for initial budgeting and decision-making.

3.1. Purpose and scope of the assessment

This assessment provides a preliminary cost-benefit evaluation of the REECOL technology for soil regeneration using composts of high biological activity in the reclamation of post-mining land. Its purpose is not to deliver a final investment appraisal, but to establish an analytical basis for evaluating the feasibility, implementation potential, and broader value of the solution under realistic industrial conditions.

The assessment is intended to support early-stage decision-making by identifying the main cost drivers, expected benefit streams, and implementation conditions associated with the production and application of the compost. In addition to direct economic aspects, the analysis also considers the wider functional and environmental effects of the solution, since the value of land reclamation technologies cannot be assessed solely through immediate financial returns.

Accordingly, the scope of the assessment includes not only capital expenditure and operating expenditure, but also the potential benefits associated with waste valorisation, reduced dependence on external soil-improving inputs, improved soil quality, enhanced revegetation performance, and the restoration of selected ecosystem functions. These effects are particularly relevant in post-mining areas, where the success of reclamation depends not only on short-term vegetation establishment, but also on the gradual rebuilding of biologically active and structurally stable soil.

The analysis also aims to provide an initial basis for future cooperation with companies interested in scaling up, testing, or implementing the technology in industrial practice, including through joint demonstration or deployment projects. In this sense, the present assessment should be understood as a preparatory step toward future commercial and operational validation rather than as a definitive business case.

Because the technology has so far been validated at laboratory, semi-technical, and field-demonstration scale, the cost assumptions presented in this section should be treated as indicative estimates only. The CAPEX and OPEX values used in the analysis are practical placeholders intended to support preliminary budgeting and option appraisal. Actual costs will depend on the final technical configuration, plant capacity, site-specific conditions, logistics, regulatory requirements, and quotations obtained from equipment suppliers and service providers.

The present assessment is therefore scenario-based and assumption-driven. It is designed to compare plausible implementation pathways and to indicate the conditions under which the REECOL solution may become economically, operationally, and environmentally attractive. It should be read as a structured decision-support exercise for further feasibility work, not as a substitute for detailed engineering design, market verification, or supplier-based cost estimation.

3.2. Assessment dimensions and benefit categories

Given the nature of the REECOL solution and the specific requirements of post-mining land reclamation, the present assessment adopts a broader perspective than a purely financial appraisal. The value of the technology cannot be captured solely through direct revenues or operating costs, because its expected effects also include functional improvements in degraded soil and wider environmental benefits associated with waste valorisation and ecosystem recovery.

For this reason, the assessment is structured around four complementary dimensions: economic, operational, environmental, and strategic. Together, these dimensions provide a more realistic basis for evaluating the implementation potential of the technology under future industrial conditions.

<u>Economic dimension</u>

The economic dimension covers the direct financial implications of implementing the technology. This includes capital expenditure related to the establishment of the compost production system, operational expenditure associated with feedstock handling, processing, transport, labour, utilities, maintenance, and compliance, as well as potential revenues from compost sales where a marketable product pathway is assumed. It also includes avoided or reduced costs, such as lower expenditure on waste disposal and, where applicable, reduced dependence on externally purchased soil-improving agents or mineral inputs.

Operational dimension

The operational dimension refers to the practical performance of the solution in a reclamation context. This includes the ability to secure a reliable supply of feedstocks, organise the composting process at an appropriate industrial scale, and apply the final product effectively on degraded land. It also includes expected effects on reclamation performance, such as improved vegetation establishment, reduced need for repeated interventions, and the potential for more stable and durable rehabilitation outcomes over time.

Environmental dimension

The environmental dimension reflects the fact that the proposed technology is intended not only to support revegetation, but also to contribute to the recovery of selected soil and ecosystem functions. Relevant environmental benefits include the increase in soil organic matter, stimulation of biological activity, improvement of soil structure, enhanced water retention, and support for long-term soil formation processes on post-mining land. Additional benefits may arise from the valorisation of waste streams, reduced pressure on disposal routes, partial substitution of conventional external inputs, and the potential retention of carbon in soil organic matter. At the present stage of technology maturity, these effects should be treated primarily as qualitatively or semi-quantitatively assessed benefits unless supported by robust field-scale data.

Strategic dimension

The strategic dimension captures the broader implementation value of the technology for industrial stakeholders and regional transition processes. This includes the creation of circular-economy pathways based on waste reuse, the development of new cooperation models between waste-generating industries and land reclamation operators, and the possible establishment of new business activities linked to ecological rehabilitation. In the case of mining regions undergoing transformation, the technology may also contribute to the practical repositioning of post-mining land management toward more sustainable and multifunctional end uses.

Not all of these benefit categories can be monetised with the same level of confidence at the present stage. Therefore, the analysis combines indicative economic estimation with qualitative assessment of wider functional and environmental effects. This approach is considered the most appropriate for a technology that has already demonstrated promising results under relevant conditions, but has not yet been deployed at full industrial scale.

3.3. Technology description

The technology developed within the REECOL project is based on the production and application of a compost of high biological activity intended for the reclamation of post-mining land. The solution combines a defined composting recipe with a dedicated microbiological inoculum and an application method designed to improve the physicochemical and biological properties of degraded soils. Its overall objective is to support site revegetation by rebuilding soil functionality rather than by supplying only short-term nutrient input.

The compost formulation is based on three principal waste and byproduct streams selected to provide both nutrient balance and organic matter input. The reference composition consists of:

- 60% wheat straw,
- 20% waste chicken feathers,
- 20% low-calorific lignite.

This combination was designed to achieve an initial carbon-to-nitrogen ratio in the range considered suitable for effective composting, while at the same time enabling the valorisation of difficult or underused residual materials originating from agriculture, the food industry, and mining activity.

A key element of the solution is the use of a dedicated three-strain microbial inoculum developed to enhance the biodegradation of the individual feedstock components. The inoculum includes bacterial strains with complementary enzymatic properties:

- proteolytic strain supporting keratin degradation in feathers,
- cellulolytic strain enabling more efficient decomposition of straw,
- a strain capable of supporting the biosolubilization of lignite into more plant-available humic substances.

In combination, these microorganisms are intended to intensify the composting process and improve the agronomic functionality of the final product.

The innovative character of the solution has also been reflected in intellectual property protection activities. The technology has been covered by two national patent applications filed in Poland by “Poltegor-Institute” Opencast Mining Institute in March 2026:

- P.455182, entitled Compost mixture and method for its production,
- P.455181, entitled Compost inoculum, method for producing the compost inoculum, and method for biodegradation of compost.

These applications strengthen the innovation profile of the solution and indicate its potential for further development and commercialization.

Figure 5. POLTEGOR – Products of static (left) and dynamic (right) composting.

Experimental work carried out within the project demonstrated that the most effective processing route at the semi-technical stage was dynamic composting in rotary bioreactors. Compared with static approaches, this process configuration provided a higher degree of control over the biodegradation conditions and enabled a shorter production cycle. The main operating parameters identified in the project included forced aeration, regular mixing, and moisture control at approximately 60%, with the overall composting cycle reduced to approximately 4-5 weeks under controlled conditions.

The final compost is intended to be used as a soil-improving material in degraded post-mining areas. Under the assumptions adopted for this assessment, the recommended application rate is 1,5 kg/m2, corresponding to approximately 15 Mg/ha, incorporated into the soil at a depth of approximately 15-20 cm around 3-4 months before sowing. This application strategy is intended to support the gradual restoration of biologically active soil, improve moisture retention, stimulate microbial processes, and create more favourable conditions for vegetation establishment.

At the same time, provided that the relevant regulatory and quality requirements are met, the compost may also represent a potential marketable product for agricultural use, particularly in applications where soil organic matter enhancement, biological soil activity, and long-term improvement of soil structure are important.

The technology was developed and validated within the REECOL project at laboratory and semi-technical scale, followed by field application and performance assessment under relevant conditions. On this basis, the solution may be regarded as having achieved TRL 6. Field verification carried out within the project indicated

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positive effects on selected soil parameters and biological activity, supporting its relevance as a reclamation-oriented technology rather than merely a compost production method.

Figure 6. POLTEGOR - field test: control without compost (left) and with compost application (right).

Figure 7. PV – compost field tests. Experimental plot in Velenje, Slovenia.

From the perspective of the present assessment, the technology should be understood as an integrated reclamation solution consisting of three interrelated components: feedstock preparation, controlled compost production, and field application of the resulting product. Its innovative character lies not only in the compost recipe itself, but also in the targeted use of waste-derived components and specialised microbial support to generate a functional soil amendment tailored to the needs of post-mining land rehabilitation.

3.4. Reference scales and logic of implementation scenarios

For the purposes of the present assessment, the economic and environmental performance of the REECOL technology is considered through defined reference scales and implementation scenarios. This approach is intended to provide a structured basis for comparing plausible industrial pathways for compost production and use, while recognising that the final configuration of a future deployment would depend on site-specific conditions, feedstock availability, logistics, regulatory requirements, and the strategic objectives of the implementing entity.

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The reference scaling adopted in this assessment is based on the recommended compost application rate of 1,5 kg/m2, corresponding to 15 Mg/ha. On this basis, two indicative operational scales may be distinguished:

- The first corresponds to the reclamation of 10 ha of land per year, requiring approximately 150 Mg of compost annually, and may be treated as a realistic reference scale for a staged single-year implementation or a defined part of a larger reclamation project. This scale may also be sufficient where the compost is produced primarily for the mining company's own land rehabilitation needs.
- The second represents a larger-scale implementation corresponding to producing approximately 1 500 Mg of compost annually. This larger production volume may be justified not only by more extensive reclamation demand, but also by the possibility of placing part of the output on the agricultural market or other external outlets, subject to compliance with the relevant regulatory and product-quality requirements.

Therefore, while the smaller scale may be more appropriate for initial deployment and internal use, the larger scale provides a more suitable basis for assessing the full industrial and commercial potential of the solution.

For the main part of the present analysis, the 1 500 Mg/year case is adopted as the principal reference scenario. This reflects a scale at which the technology may begin to operate as a realistic industrial system rather than a pilot extension. At the same time, the smaller 150 Mg/year case remains useful as a benchmark for phased implementation, staged investment, or site-specific adaptation where initial operational capacity is expected to be lower.

The scenario logic applied in this assessment is based not only on production scale, but also on the identity of the entity responsible for implementing and operating the composting system. This distinction is important because it determines the sourcing logic, the structure of costs and benefits, the distribution of risks, and the strategic rationale for investing in the technology. In this respect, two implementation scenarios are considered.

3.4.1. SCENARIO 2 - feather waste owner as investor

In the SCENARIO 2, the investor and operator of the composting system is the owner of the feather waste stream, for example a poultry-sector enterprise or processing plant generating significant volumes of feather by-products (*Figure 8*). In this model, the central economic rationale is based on the transformation of a problematic waste stream into a value-added product with potential use in land reclamation and, subject to regulatory compliance, also in the wider soil amendment market. Within this implementation pathway, the mining company is treated primarily as a strategic customer purchasing the compost from the producer for use in its reclamation activities. This role is economically important because it creates a relatively stable and potentially high-volume outlet for the product, thereby reducing market uncertainty during the initial scale-up phase.

At the same time, the cooperation model may go beyond a conventional buyer-supplier relationship, since the mining company may also contribute one of the key feedstock components in the form of low-calorific waste lignite. In such a configuration, the scenario takes the form of an industrial symbiosis model, in which the feather waste owner acts as the principal investor and producer, while the mining company functions both as a strategic off-taker and as a partial feedstock partner. This dual role strengthens the scenario by combining a more secure demand base for the compost with partial integration of the input supply chain, thereby reinforcing both the circular-economy rationale and the practical implementation logic of the model.

The SCENARIO 2 assumes that the feather waste owner seeks to reduce the burden and cost associated with waste management while simultaneously developing a valorisation pathway capable of generating commercial value. Composting with the dedicated inoculum and the additional feedstocks required by the REECOL recipe creates the possibility of converting a difficult-to-manage organic waste stream into a potentially marketable soil-improving product. In this case, the mining company or another land operator becomes the primary downstream user, securing demand for a substantial share of the compost produced, while additional volumes may potentially be directed to external markets where regulatory and quality conditions allow.

From a business perspective, the SCENARIO 2 is particularly relevant where the waste owner faces non-negligible disposal costs, has access to sufficient organizational capacity to operate or subcontract compost production, and can secure a stable outlet for the final product. The scenario is also strongly aligned with circular-economy objectives, since it links waste recovery with environmental rehabilitation and creates a framework for cross-sector cooperation between the agri-food sector and land reclamation operators.

At the same time, this implementation pathway is associated with several important challenges. First, the investor must secure the supply and transport of the remaining feedstock components, especially straw and, where not provided by the mining partner, lignite, which may generate substantial logistical costs depending on distance and local availability. Second, the scenario may require significant upfront investment in processing infrastructure and equipment. Third, the business case depends on the ability to meet regulatory requirements related to waste status, product quality, and market placement. Finally, the practical success of this model depends on the stability of long-term cooperation between the producer and the reclamation-side partner. As a result, the attractiveness of this scenario is likely to be highest where feather disposal costs are material, logistics are manageable, and a reliable demand base for the compost can be established.

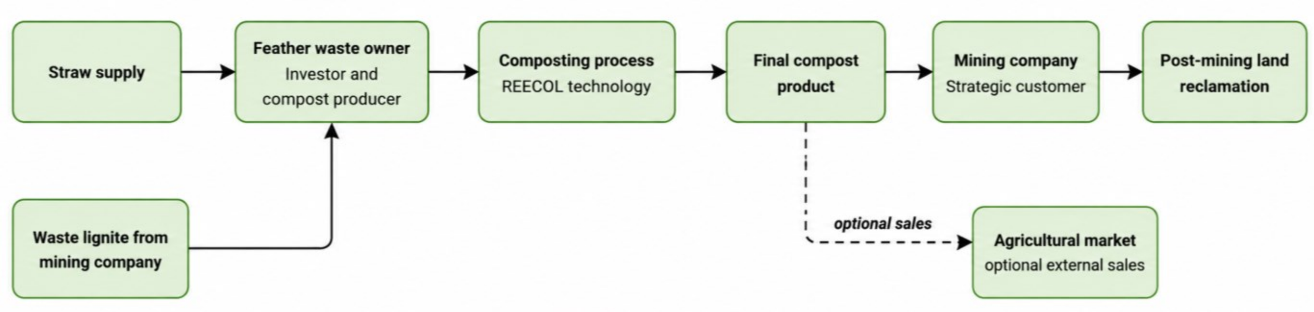

Figure 8. SCENARIO 2 value chain.

3.4.2. SCENARIO 3 - mining company as producer

In the SCENARIO 3, the composting system is implemented and operated by a mining company or another entity responsible for the reclamation of post-mining land (*Figure 9*). In this model, the primary logic is not waste disposal avoidance on the side of the feather owner, but the internal production of a functional soil-improving material for direct use in land rehabilitation. The mining company thus becomes an active producer rather than only a user of reclamation inputs.

The rationale for this scenario is particularly strong where the mining operator has long-term responsibility for degraded land, ongoing reclamation obligations, and access to one of the key feedstock components in the form of low-calorific lignite or other site-available mineral-organic material. By integrating compost production into its reclamation strategy, the mining company may reduce dependence on externally purchased soil-improvement materials, create a more site-adapted rehabilitation input, and potentially improve the long-term effectiveness of revegetation measures.

The SCENARIO 3 also has a strategic dimension extending beyond direct cost comparison. It allows the mining company to reposition part of its operational model toward circular-economy activity by combining internal land rehabilitation needs with the productive use of available residual materials. Where annual reclamation demand does not absorb total production capacity, the scenario may also allow for the sale of surplus compost, provided that the relevant product quality and regulatory conditions are met. In such a case, compost production could evolve from a purely internal support function into an auxiliary business line linked to environmental restoration and land management.

The main constraints of the SCENARIO 3 arise from the need to secure reliable external supplies of feather waste and straw, which remain indispensable components of the reference composting recipe. The mining operator would therefore become dependent on stable cooperation with external partners from the agricultural and food-processing sectors. Additional challenges include the need to develop or contract adequate technical competence in composting operations, manage feedstock logistics and biosecurity requirements, and ensure compliance with relevant regulatory procedures. Consequently, this scenario is likely to be most attractive where the mining company has substantial and recurrent reclamation demand, access to suitable land and infrastructure, and the organizational capacity to integrate compost production into its broader environmental management strategy.

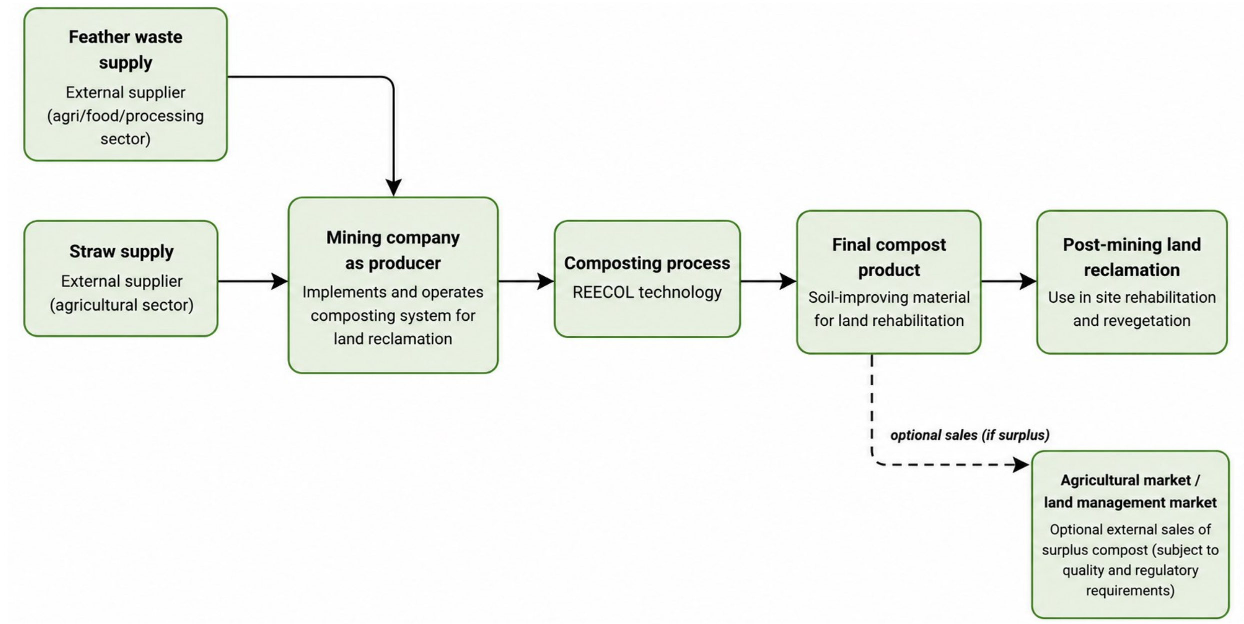

Figure 9. SCENARIO 3 value chain.

3.4.3. Comparative scenario logic

SCENARIOS 2 and 3 represent different but equally plausible industrial pathways for the future deployment of the REECOL technology (*Figure 10*). In SCENARIO 2, the driving force is the valorisation of feather waste and the creation of a marketable product by the waste owner. In SCENARIO 3, the driving force is the internal demand for reclamation material and the strategic integration of compost production into post-mining land management. Accordingly, the two models differ in their cost structure, risk exposure, logistics, and benefit distribution, even where the underlying composting technology remains broadly similar.

For this reason, both scenarios are retained in the present assessment as analytically relevant boundary cases. Together, they make it possible to test how the overall attractiveness of the REECOL solution changes depending on who bears the investment cost, who captures the main benefits, and how the waste streams and product flows are organised. This scenario-based approach is considered particularly appropriate at the current stage of technology maturity, where full-scale deployment data are not yet available and future implementation may take different institutional and business forms.

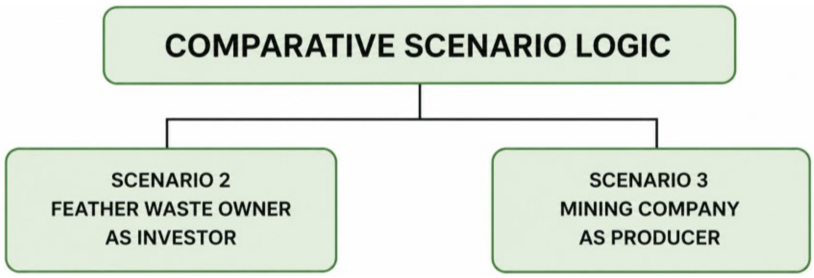

Figure 10. The defined investor/ producer in SCENARIOS 2 and 3.

3.5. SCENARIO 2 analysis - feather waste owner as investor

In the SCENARIO 2, the feather waste owner acts as the principal investor and operator of the compost production system. The business rationale is based on converting an internally generated feather waste stream into a marketable compost product intended primarily for land reclamation and, where feasible, also for external sale as a soil-improving material.

For the purposes of the present assessment, annual production is defined as 1 500 Mg of final saleable compost. This output level is treated as the commercial reference unit for the scenario and reflects an

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industrially relevant production scale. The reference compost composition is assumed to consist of 60% straw, 20% waste feathers, and 20% low-calorific lignite.

The assumed sales structure is mixed. Of the total annual output, 150 Mg is allocated to a strategic mining-sector customer, corresponding to the compost demand associated with the reclamation of 10 ha/year at the adopted application rate of 15 Mg/ha. The remaining 1 350 Mg is assumed to be sold to other customers, including potential agricultural users, subject to regulatory approval, product quality compliance, and market demand.

SCENARIO 2 further assumes that the feather waste stream is available on-site and therefore carries no direct purchase cost and no separate transport cost. By contrast, straw is assumed to be externally sourced, while lignite is assumed to be available without purchase cost but to require transport from a mining area located within an indicative distance of up to 100 km. Product transport to the strategic mining customer is included in the model, whereas transport to other customers is excluded on the assumption that those customers collect the product themselves.

The cost assumptions used in the scenario are based on a combination of project-specific engineering judgement, indicative supplier logic, and market benchmarking. In particular, the assumed range for straw cost is consistent with the broad variability reported for straw prices in Poland in 2025, where prices differed substantially depending on bale type, region, and delivery conditions (www.agronomist.pl). The use of ranges for electricity is also justified by continued volatility in European and Polish power markets in 2025 (www.iea.org; www.euenergy.live).

3.5.1. OPEX indicative assumptions - perspective of investor

The annual operating cost structure includes feedstock procurement and logistics, utilities, labour, maintenance, quality control, insurance, administrative overheads, and commercialization costs. The purpose of these estimates is not to establish a final operating budget, but to provide an indicative basis for comparing cost sensitivity across alternative commercial conditions (*Table 3*).

Table 3. SCENARIO 2 - indicative OPEX assumptions.

Cost item	Assumption	Notes
Straw purchase	50 - 90 EUR/Mg	Placeholder range reflecting variable Polish market conditions for straw
Straw transport	10 - 20 EUR/Mg	Assumes supplier proximity within approx. 50 km
Waste feathers purchase	0 EUR/Mg	Assumed internal feedstock in Scenario I
Waste feathers transport	0 EUR/Mg	Assumes co-location or direct integration with waste-generating facility
Low-calorific lignite purchase	0 EUR/Mg	Assumed residual material supplied without purchase cost
Lignite transport	10 - 30 EUR/Mg	Assumes mining-area proximity within approx. 100 km
Transport to strategic mining customer	10 - 30 EUR/Mg	Included only for the 150 Mg supplied to the strategic client
Transport to other customers	Excluded	Assumes customer collection
Annual electricity cost	12 000 - 14 000 EUR	Includes process electricity and loader operation where electrically powered
Annual water cost	2 000 - 3 000 EUR	Placeholder utility assumption
Annual labour cost	80 000 EUR	Assumes 2 employees under Polish cost conditions
Annual maintenance and repair	12 500 - 31 250 EUR	Assumed at approx. 2-5% of CAPEX

Annual quality control and laboratory analyses	5 000 EUR	Includes routine quality assurance and product compliance checks
Annual insurance	2 000 EUR	Placeholder overhead assumption
Annual administrative costs	2 000 EUR	Placeholder overhead assumption
Annual marketing and sales costs	10 000 EUR	Reflects customer acquisition and market placement for non-contracted product volumes

OPEX values are indicative (uncertainity is ±30%).

The annual electricity estimate should be interpreted as an all-in business operating assumption, not as a direct proxy for day-ahead wholesale power prices. This distinction is important because wholesale electricity values do not reflect the full delivered cost paid by industrial users. At the same time, continued volatility in European electricity markets supports the use of a range rather than a single-point estimate.

Based on the assumptions adopted, total annual OPEX is estimated at approximately 184 000 EUR in the optimistic case, 221 875 EUR in the base case, and 259 750 EUR in the pessimistic case. This corresponds to an indicative operating cost of approximately 123 EUR/Mg, 148 EUR/Mg, and 173 EUR/Mg, respectively (*Table 4*).

Table 4. SCENARIO 2 - total OPEX (optimistic, base, pessimistic).

Variant	Total OPEX (EUR/year)	OPEX (EUR/Mg)
Optimistic	184 000	123
Base	221 875	148
Pessimistic	259 750	173

The largest cost components in the scenario are labour, straw procurement, logistics, and electricity. The model is therefore particularly sensitive to biomass prices, transport distance, and energy cost volatility. The assumption of zero acquisition cost for feathers and lignite significantly improves the apparent attractiveness of the scenario, but this advantage depends on the continued availability of those residual streams under the assumed cooperation model.

3.5.2. CAPEX indicative assumptions - perspective of investor

For SCENARIO 2 the indicative capital expenditure required for implementation at the assumed scale includes the composting system itself, site infrastructure, auxiliary installations, mobile handling equipment, and the regulatory and certification costs necessary to place the product into practical use (*Table 5).*

Table 5. SCENARIO 2 - indicative CAPEX assumptions

CAPEX item	Estimated value (EUR)
Industrial-scale system for dynamic composting	300 000
Warehouse / processing area	150 000
Other installations and automation	40 000
Industrial shredder	30 000
Small loader	60 000
Procedures, permitting and certification	15 000
Weighbridge	30 000
Total CAPEX	**625 000**

CAPEX values are indicative (uncertainity is ±30%).

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The estimated total investment cost is 625 000 EUR. This value should be treated as a preliminary planning estimate only. Actual CAPEX will depend on the final process configuration, supplier quotations, the degree of automation, site preparation needs, utility connections, regulatory obligations, and whether certain assets are purchased, leased, or shared with existing site infrastructure.

3.5.3. SCENARIO 2 - commercial sensitivity and payback

For the base case, the following assumptions are adopted:

- Total CAPEX: 625 000 EUR
- Total annual OPEX: 221 875 EUR
- Annual production: 1 500 Mg
- Base operating cost: 148 EUR/Mg.

On this basis, a simple payback sensitivity analysis was performed for a range of assumed compost selling prices. This calculation is intended as an initial commercial screening tool only. It does not include discounting, financing costs, taxation, depreciation effects, downtime risk, or variation in annual sales volumes (*Table 6*).

Table 6. SCENARIO 2 - selling price sensitivity.

Selling price (EUR/Mg)	Annual revenue (EUR)	Annual OPEX (base, EUR)	Annual operating margin before depreciation and financing (EUR)	Payback period (years)
175	262 500	**221 875**	40 625	15,4
200	**300 000**		**78 125**	**8,0**
225	337 500		115 625	5,4
250	375 000		153 125	4,1
275	412 500		190 625	3,3
300	450 000		228 125	2,7

Under the base-case assumption of annual production of 1 500 Mg and an average selling price of 200 EUR/Mg, the indicative operating margin before capital recovery is approximately 26%. At this price level, the scenario yields an annual operating margin (before depreciation and financing) of approximately 78 125 EUR, corresponding to a simple payback period of about 6,8 years.

These results indicate that the scenario may become commercially relevant at moderate-to-strong selling prices, provided that a stable sales structure can be secured and the assumed cost conditions are maintained. Conversely, at selling prices closer to 150 EUR/Mg, the investment case becomes weak from a commercial perspective. This confirms that the viability of the scenario is particularly sensitive to product market positioning, offtake stability, and logistics efficiency.

3.5.4. Strategic mining customer as the only customer (stress-variant)

A highly conservative variant of SCENARIO 2 may be considered in which the mining company remains the only customer of the investor and purchases compost exclusively for its own reclamation needs, corresponding to 150 Mg/year for the rehabilitation of 10 ha/year at the adopted application rate of 15 Mg/ha. Under this assumption, and at a reference selling price of 200 EUR/Mg, the investor's annual revenue would amount to only 30 000 EUR.

At this level of sales, the business model is not economically viable for a production system designed for 1 500 Mg/year. The annual revenue would remain far below the assumed annual operating expenditure, and the investment case would therefore be commercially unsustainable even before considering capital recovery. This stress-test result indicates that SCENARIO 2 depends fundamentally on either higher contracted demand, successful access to additional external customers, or a substantially smaller production configuration aligned with the limited offtake volume (*Table 7*).

From an analytical point of view, this variant is useful because it shows that the strategic mining customer alone cannot justify the larger industrial-scale investment if its annual demand remains limited to the needs of a 10 ha reclamation programme. In such a case, the mining company may still serve as an important anchor customer, but not as the sole basis for the commercial viability of the investor-side production model.

Table 7. Stress-variant compared with base commercial case for SCENARIO 2.

Variant	Annual sales volume (Mg)	Selling price (EUR/Mg)	Annual revenue (EUR)	Economic interpretation
Base commercial case	1 500	200	300 000	Potentially viable, depending on OPEX and CAPEX assumptions
Stress case - mining company only	150	200	30 000	Not viable for a 1 500 Mg/year plant

The economic viability of SCENARIO 2 is therefore driven not only by production cost, but also by the producer's ability to commercialise compost beyond the initial strategic reclamation customer.

The stress-test variant therefore shows that, where the mining company is the sole customer and annual demand remains limited to approximately 150 Mg, commercial viability cannot be assumed under the reference large-scale production model. In such circumstances, viability would require either a substantially higher unit selling price or a smaller-scale investment configuration aligned with the actual level of contracted demand.

This highly conservative variant further suggests that, if the mining company remains the only customer and its annual demand is limited to approximately 150 Mg, the project would require a different commercial configuration. In such a case, either the compost selling price would need to be significantly higher to compensate for the limited sales volume, or the investment would need to be implemented in a smaller-scale system more closely matched to the secured level of demand. Accordingly, a 1 500 Mg/year production facility would be difficult to justify if based solely on a single reclamation customer with relatively low annual offtake.

3.5.5. Perspective of the mining company as strategic client

From the perspective of the mining company acting as the strategic customer, the model assumes annual procurement of 150 Mg of compost, corresponding to the reclamation of 10 ha/year at the adopted application rate of 15 Mg/ha. Basic assumptions:

- Reclaimed area: 10 ha/year
- Compost demand: 150 Mg/year
- Compost purchase price: 200 EUR/Mg

On this basis, annual expenditure on compost amounts to:

$$150 \times 200 = 30\ 000 \text{ EUR/year}$$

This corresponds to a compost purchase cost of:

$$30\ 000/10 = 3\ 000 \text{ EUR/ha}$$

excluding the mining company's own costs related to handling, transport within the site, spreading, soil incorporation, and site supervision.

3.5.6. Cost of reclamation attributable to REECOL compost

From the mining company's point of view, the relevance of SCENARIO 2 is not limited to direct procurement cost. The use of compost may also improve reclamation performance by supporting soil organic matter build-up, biological activity, water retention, and vegetation establishment. In this sense, the product should not be viewed solely as a purchased input, but as a functional reclamation material with potential to generate longer-term environmental and land-management value.

From the perspective of the mining company, the compost should not be regarded as a complete reclamation solution in itself. Rather, it should be considered as part of an integrated biological reclamation strategy that may also involve legumes, other revegetation-supporting plant species, and additional soil-improving amendments selected according to site-specific requirements. Its main function is to enhance the biological and structural quality of degraded soil, thereby improving the effectiveness of complementary reclamation measures.

Under this interpretation, one of the main benefits for the mining company is the potential reduction in the time needed for biological reclamation, particularly during the initial phase of soil rehabilitation. Through its contribution to soil organic matter accumulation, microbial activation, moisture retention, and structural improvement, the compost may support faster establishment of a functional soil layer and more stable vegetation development. For the mining company, this time-saving effect may represent a significant practical advantage, even where the compost is used in combination with other reclamation measures rather than as a standalone input.

Where the mining company also contributes low-calorific waste lignite to the supply chain, its role extends beyond that of a conventional customer. In such a configuration, the company participates in a broader industrial symbiosis model that links residual material valorisation with environmental rehabilitation. This may strengthen both the operational logic and the strategic attractiveness of the scenario.

In order to include other cost attributable to compost application, in addition to compost purchase, compost spreading and incorporation costs should be included as well as site supervision and quality control (*Table 8*).

Table 8. Cost of reclamation attributable to REECOL compost in SCENARIO 2.

Item	Value
Compost application rate	15 Mg/ha
Compost purchase cost	200 EUR/Mg
Compost cost per hectare	3 000 EUR
Compost spreading	80 - 140 EUR/ha
Compost incorporation	100 - 180 EUR/ha
Site supervision/ quality control	30 - 70 EUR/ha
Total reclamation cost attributable to compost	**3210 - 3390 EUR/ha**

3.5.7. Environmental and strategic implications

The value of SCENARIO 2 is not limited to direct revenues and operating margins. It also includes a set of environmental and strategic effects that are relevant for the broader appraisal of the technology.

From an environmental perspective, the scenario supports the valorisation of problematic or underused residual streams, most notably feather waste and low-calorific lignite. Instead of remaining a disposal burden or low-value by-product, these materials are incorporated into a productive pathway linked to soil improvement and land reclamation. The resulting compost may contribute to the rebuilding of organic matter, stimulation of soil biological activity, improvement of soil structure, and enhancement of water retention capacity in degraded post-mining areas.

From a strategic perspective, the scenario creates a framework for cross-sector cooperation between waste-generating agri-food companies and mining-sector reclamation operators. This industrial symbiosis logic strengthens the circular-economy profile of the solution and may create the basis for future commercial partnerships, demonstration projects, or larger-scale implementation schemes. The possibility of selling part of the output beyond the strategic reclamation customer also increases the strategic flexibility of the model, particularly if agricultural-market access can be achieved under the relevant regulatory and product-quality conditions.

Although these benefits are not monetised in the present assessment, they may reduce future reclamation costs, shorten reclamation timelines, and improve compliance with environmental obligations.

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3.6. SCENARIO 3 analysis - mining company as an investor / producer

In the SCENARIO 3, the mining company acts as the principal investor and operator of the compost production system. In this model, the primary rationale is the internal production of a functional soil-improving material intended to support the biological reclamation of post-mining land. The mining company therefore becomes both the producer and the primary user of the compost, while retaining the possibility of directing part of the output to external customers where this is economically and regulatorily feasible.

For the purposes of the present assessment, annual production may again be defined at 1 500 Mg of final saleable compost, in order to maintain comparability with the SCENARIO 2 and to reflect a scale relevant for industrial operation. The reference compost composition is assumed to consist of 60% straw, 20% waste feathers, and 20% low-calorific lignite.

Within SCENARIO 3, the mining company is assumed to use part of the compost internally for land reclamation purposes. At the adopted application rate of 15 Mg/ha, the rehabilitation of 10 ha/year requires approximately 150 Mg of compost annually. This means that even a relatively limited annual reclamation programme may justify a baseline level of internal demand. At the same time, larger production volumes may still be economically relevant if the mining company intends to place surplus compost on external markets, including the agricultural sector, provided that the relevant regulatory and product-quality requirements are fulfilled (*Figure 11*).

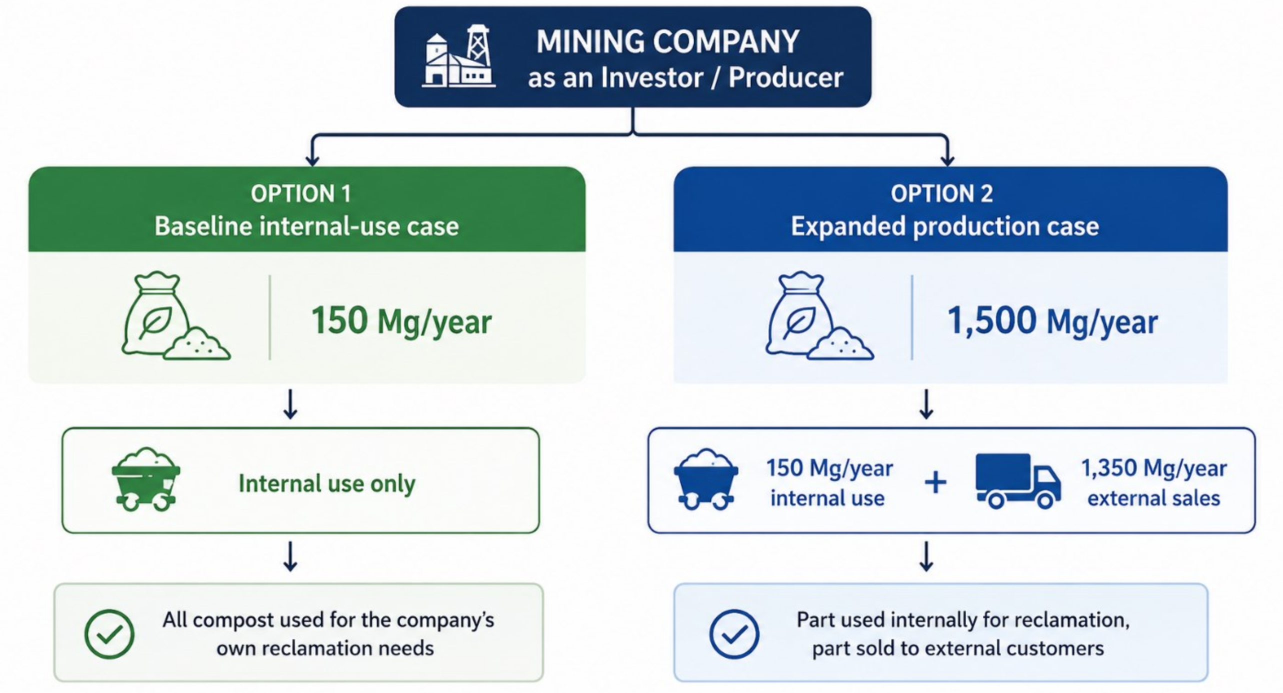

Figure 11. SCENARIO 3 - baseline internal-use production vs. expanded production case.

A key distinguishing feature of this scenario is that one of the principal feedstock components, namely low-calorific lignite, is assumed to be available directly within the mining company's own resource base. This strengthens the implementation logic of the model by partially integrating feedstock supply and reducing dependence on external sourcing for one of the major recipe components. By contrast, waste feathers and straw remain externally sourced materials, and the viability of the scenario therefore depends on the stability, accessibility, and logistical cost of supply from external partners.

From an implementation perspective, SCENARIO 3 assumes that compost production is integrated into the broader environmental management strategy of the mining company. The investment rationale is based on a combination of direct and indirect benefits, including reduced dependence on externally purchased reclamation inputs, improved control over the quality and availability of a key soil amendment, possible time savings in biological reclamation, and the option to create additional value through sales of compost not required for internal reclamation use (*Table 9*).

Table 9. SCENARIO 3 - baseline internal-use production vs. expanded production case - assumptions.

Parameter	Baseline internal-use case	Expanded production case	Notes
Annual compost production	150 Mg/year	1 500 Mg/year	Smaller case reflects internal reclamation demand; larger case assumes surplus production + external sales
Reclaimed area covered internally	10 ha/year	10 ha/year minimum	At 15 Mg/ha, 10 ha/year requires 150 Mg
Application rate	15 Mg/ha	15 Mg/ha	Equivalent to 1.5 kg/m2
Compost composition	60% straw / 20% feathers / 20% lignite	60% straw / 20% feathers / 20% lignite	Reference REECOL recipe
Low-calorific lignite purchase cost	0 EUR/Mg	0 EUR/Mg	Assumed internal residual stream
Lignite transport cost	0 - 10 EUR/Mg	0 - 10 EUR/Mg	Low or negligible if available on-site or near-site
Waste feathers purchase cost	0 EUR/Mg or low-cost waste stream	0 EUR/Mg or low-cost waste stream	Depends on contract model with feather supplier
Waste feathers transport cost	15 - 35 EUR/Mg	15 - 35 EUR/Mg	Included in Scenario II because feathers are externally sourced
Straw purchase cost	50 - 90 EUR/Mg	50 - 90 EUR/Mg	Placeholder range reflecting regional variability
Straw transport cost	10 - 20 EUR/Mg	10 - 20 EUR/Mg	Assumes supply within approx. 50 km
Sales structure	Internal use only	150 Mg internal use + 1 350 Mg external sales	External sales assumed only in expanded case
Marketing and sales cost	Excluded or minimal	Included	Relevant only if surplus is sold
Main business rationale	Internal reclamation support	Internal use + sale of surplus	Distinguishes the two variants

3.6.1. SCENARIO 3 - indicative OPEX assumptions

The annual operating cost structure in SCENARIO 3 includes feedstock procurement and logistics, utilities, labour, maintenance, quality control, and administrative overheads. In contrast to SCENARIO 2, the present scenario assumes that low-calorific lignite is available within the mining company's own resource base, which reduces dependence on external sourcing for that component. At the same time, straw and waste feathers remain externally sourced, meaning that transport and supply reliability remain significant cost drivers.

A second important distinction concerns the commercial logic of the scenario. In the baseline internal-use case, compost production is treated primarily as an internal support function for land reclamation, and therefore no dedicated marketing or sales cost is assumed. In the expanded production case, where surplus compost is placed on external markets, additional commercialization costs are included to reflect customer acquisition, market placement, and associated handling (*Table 10*).

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Unlike SCENARIO 2, the objective of the baseline case is not revenue generation but cost avoidance through internal production of reclamation material. Consequently, the economic assessment should be interpreted primarily in terms of avoided procurement costs rather than direct commercial profitability.

Table 10. SCENARIO 3 - indicative OPEX assumptions.

Cost item	Baseline internal-use case (150 Mg/year)	Expanded production case (1 500 Mg/year)	Notes
Straw purchase	50 - 90 EUR/Mg	50 - 90 EUR/Mg	Same benchmark range as Scenario I
Straw transport	10 - 20 EUR/Mg	10 - 20 EUR/Mg	Assumes supply within approx. 50 km
Waste feathers purchase	0 EUR/Mg or low-cost	0 EUR/Mg or low-cost	Depends on cooperation model
Waste feathers transport	15 - 35 EUR/Mg	15 - 35 EUR/Mg	Included because feathers are externally sourced
Low-calorific lignite purchase	0 EUR/Mg	0 EUR/Mg	Assumed internal residual stream
Lignite transport	0 - 10 EUR/Mg	0 - 10 EUR/Mg	May be negligible if internal site logistics only
Electricity	1 200 - 1 400 EUR/year	12 000 - 14 000 EUR/year	Baseline case scaled proportionally to 10% of expanded case
Water	200 - 300 EUR/year	2 000 - 3 000 EUR/year	Baseline case scaled proportionally to 10% of expanded case
Labour	8 000 EUR/year	80 000 EUR/year	Assumes partial staff allocation in the smaller-scale case
Maintenance and repair	2 - 5% of CAPEX	2 - 5% of CAPEX	Smaller systems often remain relatively cost-intensive per unit of output
Quality control and lab analyses	3 000 - 5 000 EUR/year	5 000 EUR/year	Basic quality assurance remains necessary in both cases
Insurance	1 000 - 2 000 EUR/year	2 000 EUR/year	Placeholder assumption
Administrative overhead	1 000 - 2 000 EUR/year	2 000 EUR/year	Placeholder assumption
Marketing and sales	0 EUR/year	10 000 EUR/year	Included mainly in the expanded production case
Internal costs of spreading/incorporation	Excluded here	Excluded here	Better treated under reclamation-side operating costs

OPEX values are indicative (uncertainty is ±30%).

In SCENARIO 3, the OPEX structure is expected to differ from SCENARIO 2 mainly because the mining company benefits from direct access to low-calorific lignite, but must bear the cost of securing and transporting feather waste from external sources. As a result, the economic attractiveness of the scenario depends less on internal waste valorisation at the feedstock source and more on the balance between internal reclamation demand, external feedstock logistics, and the possibility of reducing dependence on externally purchased reclamation materials. In the expanded production case, the scenario also becomes partly market-dependent, since the sale of surplus compost may be necessary to justify operation at a scale significantly exceeding the mining company's own internal annual demand.

Because SCENARIO 3 includes two distinct operating logics, namely a baseline internal-use case and an expanded production case, total annual OPEX is presented separately for each variant. This distinction is necessary because the smaller internal-use case is associated with lower total annual expenditure but significantly higher unit cost, reflecting the limited production volume and weaker scale effects. By contrast, the expanded production case benefits from stronger scale effects and provides a more suitable basis for combining internal reclamation use with potential external sales (*Tables 11-12*).

Table 11. SCENARIO 3 - total OPEX for the baseline internal-use case.

Variant	Total OPEX (EUR/year)	OPEX (EUR/Mg)
Optimistic	24 850	166
Base	33 150	221
Pessimistic	41 450	276

Table 12. SCENARIO 3 - total OPEX for the expanded production case.

Variant	Total OPEX (EUR/year)	OPEX (EUR/Mg)
Optimistic	184 000	123
Base	221 875	148
Pessimistic	259 750	173

For the baseline internal-use case, annual electricity and water costs were estimated proportionally to the production volume, using the 1 500 Mg/year case as the reference and scaling utility costs to 10% of that level for a 150 Mg/year operation. The comparison demonstrates a clear economy-of-scale effect. Although the expanded production case requires substantially higher annual operating expenditure, the unit production cost decreases from 166 - 276 EUR/Mg in the baseline case to 123 - 173 EUR/Mg, improving the overall cost competitiveness of compost production.

3.6.2. SCENARIO 3 - indicative CAPEX assumptions

From the capital-investment perspective, SCENARIO 3 may require a broadly similar technical configuration to that assumed in SCENARIO 2, since the core composting process remains comparable. Accordingly, the same general CAPEX structure is retained as the reference full-investment case. However, in the case of the mining company, the composting installation may potentially be integrated into the existing operational base to a greater extent than in a standalone investor model. In particular, selected assets and infrastructure, including handling equipment, storage areas, utilities, weighing facilities, or internal transport arrangements, may already be available on site.

For this reason, two CAPEX variants are distinguished in SCENARIO 3. The first is a reference full-investment case of 625 000 EUR, reflecting a dedicated project configuration. The second is an integrated-site case, in which the effective investment requirement may be lower due to the adaptation of existing mining-site infrastructure and, where applicable, a smaller-scale or simplified technical configuration. Under this variant, indicative total CAPEX is estimated for 230 000 EUR (*Table 13*).

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Table 13. SCENARIO 3 - indicative CAPEX assumptions.

CAPEX item	Baseline internal-use case (EUR)	Expanded production case (EUR)	Notes
Industrial-scale dynamic composting system	150 000	300 000	Core process equipment still required; lower values may apply in smaller-scale or simplified configurations
Warehouse / processing area	30 000	150 000	May be reduced if existing infrastructure is adapted
Other installations and automation	20 000	40 000	Depends on existing utilities and control systems
Industrial shredder	15 000	30 000	Still assumed to be required, but smaller
Small loader	0	60 000	May already exist on the mining site in the integrated-case configuration
Procedures, permitting and certification	15 000	15 000	Still required
Weighbridge	0	30 000	May be shared with existing site facilities
Indicative total CAPEX	**230 000**	**625 000**	**Integrated-site logic may materially reduce entry cost**

CAPEX values are indicative (uncertainity is ±30%).

The reference full-investment case assumes that the mining company develops the composting installation as a dedicated project with its own handling and support infrastructure. By contrast, the integrated-site case assumes that selected existing mining-site assets or facilities, such as storage areas, utilities, a loader, or weighing infrastructure, can be used for the composting operation. In addition, the lower end of the integrated-site range may also reflect a smaller-scale or simplified technical configuration. For this reason, the effective CAPEX requirement in SCENARIO 3 may be substantially lower than in a standalone implementation model.

3.6.3. SCENARIO 3 - commercial sensitivity and payback

In SCENARIO 3, the commercial interpretation of the investment depends on whether the composting system is used primarily as an internal reclamation support function or as a combined internal-use and market-oriented production model. For this reason, the economic assessment cannot rely exclusively on product sales logic. A distinction should therefore be made between the baseline internal-use case, in which the mining company produces compost mainly for its own reclamation needs, and the expanded production case, in which internal use is supplemented by external sales of surplus output.

In the baseline internal-use case, the annual demand associated with reclamation of 10 ha/year corresponds to approximately 150 Mg of compost, assuming an application rate of 15 Mg/ha. At this scale, the composting system is justified primarily through its operational and reclamation value, rather than through direct market revenue. Accordingly, a conventional simple payback analysis based solely on sales income would not fully reflect the economic rationale of the investment. In this configuration, the key question is not only the market value of compost, but also the extent to which internal production reduces dependence on purchased reclamation inputs, improves control over material quality and availability, and contributes to faster or more robust biological reclamation.

By contrast, in the expanded production case of 1 500 Mg/year, the mining company uses only part of the output internally and seeks to place the remaining volume on external markets. Under this configuration, the investment can also be assessed using a commercial sensitivity approach similar to that applied in SCENARIO 2, while still recognising that internal use provides an additional non-market value component.

For comparability, the following base assumptions may be adopted for the expanded production case:

- Total CAPEX: 625 000 EUR in the reference full-investment case
- Indicative integrated-site CAPEX: 230 000 EUR, depending on the extent of infrastructure reuse and the final technical scale
- Annual production: 1 500 Mg
- Internal use: 150 Mg/year
- External sales: 1 350 Mg/year
- Reference selling price: 200 EUR/Mg for externally marketed compost.

Under these assumptions, commercial sensitivity depends primarily on the achievable selling price of surplus compost, the extent to which annual OPEX can be controlled, and the degree to which existing mining-site infrastructure reduces entry cost. If the external market is able to absorb the surplus volume at a commercially acceptable price, the scenario may combine internal reclamation benefits with an additional revenue stream. However, if external market access is weak or uncertain, the economic case becomes less dependent on direct financial return and more dependent on avoided procurement costs and reclamation-side performance gains.

A simple payback approach may therefore be used only for the expanded production case and should be treated as a preliminary commercial indicator rather than as a full financial appraisal. As in SCENARIO 2, such an indicator does not include discounting, financing costs, depreciation, taxes, downtime risk, or uncertainty in annual sales volumes.

Table 14. SCENARIO 3 - internal-use equivalent value (150 Mg/year).

Reference external compost price (EUR/Mg)	Fixed average internal demand (Mg/year)	Equivalent avoided purchase cost (EUR/year)
175		26 250
200		**30 000**
225		33 750
250	**150**	37 500
275		41 250
300		45 000

Table 15. SCENARIO 3 - equivalent annual economic value (expanded 1 500 Mg/year).

External compost price	Avoided purchase (150 Mg)	Sales revenue (1 350 Mg)	Total annual value (EUR)
175	26 250	236 250	262 500
200	**30 000**	**270 000**	**300 000**
225	33 750	303 750	337 500
250	37 500	337 500	375 000
275	41 250	371 250	412 500
300	45 000	405 000	450 000

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The results presented in *Tables 14-15* demonstrate the different economic logic of the two implementation variants. In the baseline internal-use case, the primary benefit arises from avoiding the purchase of externally supplied compost, with the equivalent annual value ranging from 26 250 EUR to 45 000 EUR depending on the assumed market price.

In the expanded production case, the mining company benefits from both avoided procurement costs associated with internal compost use and additional revenue generated through the sale of surplus production. At the reference selling price of 200 EUR/Mg, the combined annual economic value amounts to approximately 300 000 EUR, comprising 30 000 EUR of avoided procurement costs and 270 000 EUR of potential sales revenue.

These values should be interpreted as indicative measures of the annual economic value generated by the composting system rather than as estimates of annual profit, since operating expenditure, financing, taxation, depreciation, and other financial factors are not included.

3.6.4. Perspective of the mining company summarized

In SCENARIO 3, the mining company implements and operates the composting system primarily to support its own reclamation needs, while retaining the option to sell surplus output externally (e.g., to agricultural users), subject to regulatory and product-quality requirements. Assumptions:

- Reclaimed area (internal): 10 ha/year
- Application rate: 15 Mg/ha
- Internal compost demand: 150 Mg/year
- Internal operating cost (baseline internal-use case): 33 150 EUR/year
- CAPEX for internal-use system (integrated/smaller configuration): 230 000 EUR.

Internal production (SCENARIO 3, internal-use):

- Annual OPEX = 33 150 EUR/year
- OPEX per Mg = 33 150 / 150 = 221 EUR/Mg
- OPEX per hectare = 33 150 / 10 = 3 315 EUR/ha (excluding spreading/incorporation)
- Annualised CAPEX for 10 years of operations = 230 000 / 10 = 23 000 EUR/year
- Full internal “cost to serve” (OPEX + annualised CAPEX) = 33 150 + 23 000 = 56 150 EUR/year
- Implied internal per Mg cost = 56 150 / 150 = 374 EUR/Mg
- Implied per hectare = 5 615 EUR/ha.

3.6.5. Cost of reclamation attributable to REECOL compost

From the mining company’s point of view, the relevance of SCENARIO 3 is not limited to direct production cost. Internal compost production and use may improve reclamation performance by supporting soil organic matter build-up, biological activity, water retention, and vegetation establishment. In this sense, the compost should not be viewed merely as an internally produced input, but as a functional reclamation material with the potential to generate longer-term environmental and land-management value.

The compost should not be regarded as a complete reclamation solution in itself. Rather, it should be considered as part of an integrated biological reclamation strategy that may also involve legumes, other revegetation-supporting plant species, and additional soil-improving amendments selected according to site-specific requirements. Its main function is to enhance the biological and structural quality of degraded soil, thereby improving the effectiveness of complementary reclamation measures.

Under this interpretation, one of the principal benefits for the mining company is the potential reduction in the time needed for biological reclamation, particularly during the initial phase of soil rehabilitation. By contributing to soil organic matter accumulation, microbial activation, moisture retention, and structural improvement, the compost may support faster establishment of a functional soil layer and more stable vegetation development. For the mining company, this time-saving effect may represent a significant practical advantage, even where the compost is used in combination with other reclamation measures rather than as a standalone input.

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Where the mining company also utilises low-calorific waste lignite as one of the compost components, its role extends beyond conventional input management. In such a configuration, internal production becomes part of a broader industrial symbiosis model that links residual material valorisation with environmental rehabilitation. This strengthens both the operational logic and the strategic attractiveness of Scenario II by integrating waste management with land restoration.

To capture the full cost of internal application, the analysis should include, in addition to production (OPEX) and capital costs (CAPEX), the on-site costs of compost spreading and incorporation, as well as site supervision and quality control related to field application (*Table 16*).

Table 16. Cost of reclamation attributable to REECOL compost in SCENARIO 3.

Item	Value
Compost application rate	15 Mg/ha
Implied internal per Mg cost	374 EUR/Mg
Compost cost per hectare	5 615 EUR
Compost spreading	80 - 140 EUR/ha
Compost incorporation	100 - 180 EUR/ha
Site supervision/ quality control	30 - 70 EUR/ha
Total reclamation cost attributable to compost	**5 825 - 6005 EUR/ha**

3.6.6. Comparative interpretation with SCENARIO 2 and rationale for the expanded production

Unit economics (reference external price 200 EUR/Mg).
Spreading/incorporation and supervision are the same for both scenarios.

In SCENARIO 2 (purchase for reclamation) cost per hectare is **3 000 EUR/ha** for 10 ha.

In SCENARIO 3 (internal production) cost per hectare is **5 615 EUR/ha** for 10 ha.

At the 10 ha/year anchor and an external benchmark of ~200 EUR/Mg, SCENARIO 3 is more expensive on a per-hectare basis once CAPEX is included. Internal production at this small scale is therefore not justified by near-term unit cost minimization alone. SCENARIO 3 can still be rational at 10 ha/year, when:

- supply security, product quality control, and delivery scheduling are critical to reclamation progress,
- time-saving effect in biological reclamation (earlier soil functionality and vegetation stability) has strategic value for land management,
- external prices are volatile/seasonally high,
- grants or site-integration lower effective CAPEX.

Otherwise it is recommended for mining company reclaiming 10 ha of land annually to include expanded production case and improve cashflows with sales revenue of compost surplus produced.

3.6.7. Environmental and strategic implications

The value of SCENARIO 3 extends beyond direct operating costs and any potential revenues from surplus sales. It encompasses environmental and strategic effects that are important for a comprehensive appraisal of the technology from the mining company's standpoint.

From an environmental perspective, internal production and use of compost supports the valorisation of underused residual materials, in particular low-calorific lignite available on site and externally sourced feather waste. Rather than remaining a disposal liability or low-value by-product, these materials are channelled into a productive pathway linked directly to soil improvement on post-mining land. The resulting compost can contribute to rebuilding soil organic matter, stimulating soil biological activity, improving soil structure, and enhancing water-retention capacity - effects that are particularly relevant in degraded post-mining substrates.

From a strategic perspective, SCENARIO 3 enables the mining company to internalise a key part of the reclamation value chain, improving control over amendment quality, availability, and scheduling. It also embeds the operation within an industrial-symbiosis framework: on-site lignite is utilised productively, while cooperation with external partners (e.g., feather and straw suppliers) strengthens the circular-economy profile of reclamation activities. Where production exceeds internal needs, the possibility of placing surplus compost on external markets - subject to regulatory and product-quality compliance - adds strategic flexibility and can support partnerships, demonstration projects, or future scale-up.

Although these benefits are not monetised in the present assessment, they may translate into operational advantages over time, including reduced dependence on externally purchased inputs, shorter timelines to achieve stable biological reclamation, and enhanced alignment with environmental obligations and regional transition objectives.

3.7. Market analysis and business environment

The market environment for bioeconomy, circular nutrient recovery, and regenerative agriculture is becoming more favourable for the commercialization of advanced compost and bio-based soil improvers. Across Europe, policy and market pressures are encouraging the replacement of part of mineral fertilizer use with products derived from biological waste streams and recycled materials. The global organic fertilizer market is projected to reach $13,6 billion by 2029, with a robust Compound Annual Growth Rate (CAGR) of 11,5% (https://www.marketsandmarkets.com/).

The primary target segments for the REECOL compost include organic and conventional farms, agri-food enterprises, municipalities managing organic waste, and companies specializing in the reclamation of degraded post-mining areas. While the current market is abundant with standard organic fertilizers, there is a distinct niche for products with proven high biological activity capable of deep soil regeneration. In the Polish context, significant market potential exists in regions with high concentrations of poultry farms (suppliers of the feather waste fraction) and proximity to lignite mines, such as Konin or Turów. Companies like Green Crops (https://green-crops.pl/), which integrate advanced soil monitoring with organic fertilization, exemplify the growing demand for innovative soil conditioners. This demand is further bolstered by European policy frameworks, including the European Green Deal, the "Farm to Fork" strategy, and the EU Soil Mission, all of which provide financial and regulatory support for initiatives improving soil health.

3.8. Commercialization pathways and competitive advantages

Commercialization of the REECOL compost can be executed through several scenarios, including technology licensing, own pilot production, public-private partnerships (PPP), or hybrid models. Licensing the know-how is a particularly attractive strategy for scaling the solution to international markets (e.g., Asia-Pacific, North America) without requiring high capital expenditure (CAPEX) from the technology owner. The foundation for these models is strong intellectual property protection; the technology is currently the subject of two patent applications in Poland (P.455182 and P.455181) covering both the unique mixture composition and the specific microbial inoculum. A key competitive advantage of the product is its economic efficiency during periods of high mineral fertilizer prices. Analysis suggests that conventional NPK fertilizers can be significantly more expensive than the operating costs (OPEX) of the REECOL production system, provided there is access to low-cost raw materials like feathers and straw. Furthermore, unlike synthetic fertilizers, the compost offers long-term ecosystem benefits: it increases organic matter content, improves water retention, and restores soil structure, which is critical for the successful reclamation of lignite-based substrates.

3.9. Legal conditions and product certification

Placing the compost on the market requires compliance with rigorous national and EU legal frameworks. The central act at the European level is Regulation (EU) 2019/1009 concerning fertilizing products, alongside the Waste Framework Directive (2008/98/EC). From a commercialization standpoint, chicken feathers must first be formally classified as organic waste that, through appropriate processing, loses its waste status and becomes a valuable soil improver. The certification process must involve detailed laboratory analyses to confirm the product's safety, specifically the absence of heavy metal contamination and pathogens. Tests conducted during the project confirmed that the REECOL compost meets the safety standards for Hg, Cr, Ni, Pb, Cd, Cu, and Zn (*see* ***Deliverable D4.3***). Additionally, in accordance with the Polish Act on Fertilizers and

Fertilization, the product must obtain specific permits from the Ministry of Agriculture before being traded. Ensuring repeatable quality and biological stability across production batches will be a decisive factor for the long-term market success of the technology.

Sources for cost assumptions for technology for soil regeneration by composts of high biological activity:

Indicative operating costs were estimated using publicly available market information (IEA, Eurostat, Statistics Poland - GUS), agricultural market benchmarks (straw prices), supplier information, engineering assumptions, and operational experience gained during REECOL pilot implementation. Actual operating costs will depend on plant capacity, local labour costs, energy prices, logistics, and contractual conditions.

Indicative CAPEX values were derived from publicly available information on industrial composting equipment offered by major European suppliers (e.g., Eggersmann, Komptech, BACKHUS, Lindner), complemented by engineering judgement and experience from pilot-scale implementation within the REECOL project. Final investment costs should be verified through supplier quotations during the engineering design stage.

OTHER REFERENCES:

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4. Technology for non-contact rehabilitation and control of soil parameters with use of bio-waste.

Within Task 4.5, KOMAG performed a preliminary cost analysis of the non-contact soil rehabilitation technology developed under Task 4.2 (*see* ***Deliverable 4.2***), considering the planning, implementation and monitoring stages of the reclamation process.

The analysis distinguishes between capital expenditure (CAPEX) and operating expenditure (OPEX). Costs were calculated on a per-hectare basis and related to the duration of reclamation activities. The assessment is based on data obtained during field trials, technical design parameters of the developed system, engineering assumptions, and representative unit prices of materials and utilities. Capital expenditures associated with the prototype equipment and supporting infrastructure were annualized using a straight-line depreciation approach, allowing them to be expressed as unit reclamation costs. The results obtained should be regarded as indicative estimates intended to support the comparison of the analyzed reclamation scenarios. Two scenarios differing in the scope of activities were considered in the analysis:

- SCENARIO 4 represents the implementation of the complete reclamation treatment over the analyzed area;
- SCENARIO 5 represents supplementary reclamation covering up to 10% of the site area and implemented only where additional intervention is indicated by environmental monitoring results.

In both scenarios were evaluated using the same calculation methodology. An exchange rate of EUR 1 = PLN 4,26 was adopted throughout the analysis.

4.1. Technology of a non-contact soil rehabilitation

The technology developed under Task 4.2 of the REECOL project is an integrated non-contact soil rehabilitation system intended to support the reclamation of post-mining land through the precise, automated and site-specific application of reclamation materials (*see* ***Deliverable 4.2***) The solution combines environmental monitoring, remote sensing, spatial analysis and automated field operations into a single decision-supported technological system, enabling reclamation measures to be adapted to the actual condition of the site and applied only where they are required.

Figure 12. Contactless soil rehabilitation technology during reclamation treatments.

The technology is based on three complementary subsystems operating within a common workflow. The first subsystem comprises an unmanned aerial vehicle (UAV) equipped with RGB and multispectral cameras, enabling the acquisition of high-resolution imagery and the generation of vegetation indices, including the Normalized Difference Vegetation Index (NDVI). The second subsystem is a mobile environmental monitoring station providing continuous measurements of soil temperature, soil moisture, pH, atmospheric parameters and particulate matter concentration. Together, these data provide the basis for assessing the condition of the reclamation site and identifying areas requiring intervention. The third subsystem is an automated spraying system designed to perform the controlled application of reclamation materials according to predefined operational scenarios.

The operational concept is based on the preparation of a digital treatment plan using information collected from the UAV and the environmental monitoring station. The reclamation area is divided into operational zones referenced by GPS coordinates, and appropriate treatment scenarios are assigned to each zone according to the current environmental conditions. The automated spraying system subsequently carries out the required reclamation operations with a high level of positional accuracy and repeatability.

As tested in site-specific conditions during REECOL, a key feature of the developed technology is the sequential application of reclamation materials. Unlike conventional approaches based on the simultaneous application of multiple components, the developed system performs separate spraying operations, each designed to fulfil a specific function within the reclamation process. In the first stage, a water-based seed-mulch mixture is applied to establish vegetation cover, reduce the risk of erosion and create favorable conditions for seed germination. In a subsequent and independent operation, a compost-water suspension is applied to improve soil quality, increase organic matter content and stimulate long-term biological regeneration of the degraded substrate. Where required, additional treatments, such as irrigation or the application of water-compost mixtures, may also be carried out as separate operations. The separation of these treatment stages enables each reclamation material to be applied under conditions optimized for its intended function, improving both vegetation establishment and the long-term restoration of soil properties.

Following the completion of reclamation treatments, the site remains under continuous environmental monitoring. Updated UAV surveys and measurements from the monitoring station make it possible to evaluate reclamation effectiveness and identify areas requiring supplementary intervention. This adaptive approach allows reclamation activities to be adjusted to changing environmental conditions and supports efficient use of materials and operational resources throughout the reclamation process.

Figure 13. ITG KOMAG drone operator during a flight over the KWK ROW Ruch Jankowice waste heap.

The technology was developed to increase the effectiveness and sustainability of post-mining land reclamation through precise, demand-driven application of reclamation materials while reducing unnecessary consumption of water, seeds and soil amendments. The integration of monitoring, spatial analysis and automated field operations supports more efficient resource utilization, improves the uniformity of material distribution and facilitates evidence-based management of reclamation activities.

The technology was designed, constructed and validated within the REECOL project through laboratory investigations and field demonstrations. The performed validation confirmed the operational feasibility of the integrated system and demonstrated the effectiveness of sequential, site-specific reclamation treatments under real environmental conditions. From the perspective of the present assessment, the technology should therefore be regarded as an integrated reclamation solution combining environmental monitoring, decision-support tools and automated sequential application of reclamation materials, offering significant potential for future industrial deployment.

Please note that, in the case of site-specific conditions, the field tests of KOMAG technology conducted within REECOL WP4 and WP5 resulted in the determination of site-specific application rates for both seed mixtures and compost, which differ from those adopted by GIG-PIB and POLTEGOR in their respective implementation scenarios for different sites and assumptions. It should also be emphasized that, during the implementation of the device tests at the Jankowice heap, standard reclamation seed mixtures were used due to their lower cost. However, in line with the project assumptions, the final technology will propose the use of seed mixtures selected by GIG-PIB, whose effectiveness has been confirmed in field trials and which demonstrate improved resistance to water and temperature stress. In the cost analyses for SCENARIOS 4-5, the seed mixture application rates were adjusted to the values adopted by GIG-PIB in order to reflect a more target-oriented technological approach. On the other hand, the compost application rate was adjusted to site-specific conditions, highlighting the increased amount of compost required for hard coal heaps.

4.2. Assumptions for SCENARIOS 4 and 5

4.2.1. Reclamation system

In the analysed scenarios, it was assumed that the reclamation material spraying system developed in the Project would be used. A summary of the costs of the components used in the system applied during the research work is presented in *Table 17*. **It should be noted that this solution is of a prototype nature, and the values given correspond to the purchase or acquisition costs of the components in the current demonstration version**.

The total cost of the prototype components amounts to 9 390 EUR. Assuming straight-line depreciation over a period of 5 years, this corresponds to an annual cost of 1 878 EUR/year. Due to the seasonal nature of reclamation works, an effective infrastructure utilization period of 6 months was assumed, corresponding to a cost of 313 EUR/month of the season. The system cost was included as a common element for the SCENARIOS 4 and 5 and was used for the further determination of the CAPEX share in the unit reclamation costs.

Table 17. Cost breakdown of the reclamation material spraying system components (SCENARIOS 4-5).

Component	Quantity	Cost [EUR]	Total [EUR]
steel construction	1	938,97	938,97
AFG1038B pump unit	1	3 170,94	3 170,94
PP-52 water spray nozzle	1	18,31	18,31
hydrant nozzle	1	23,56	23,56
electric actuator	1	657,28	657,28
motor G-1-63M2-6-0,12-90/11-230/400V-S3-70%-RAL9022-3 – KACPEREK	1	70,94	70,94
gear MR-32/24,5-90/11-WJ/1-B3 KACPEREK	1	119,54	119,54
IBC tank 1000L FI 150 Lid	3	134,98	404,93
BC mixers with IBC 150 lid	2	742,32	1 484,65
breather plug SFV.1 10mb-C9 54691-C9 Elesa+Ganter	3	6,27	18,81
1" PVC lock nut	3	0,14	0,42
heavy-duty reinforced PVC suction hose, ØC65, 10 m	1	13,59	13,59
HT1000-2 liquid level sensor	3	48,28	144,85
IBC adapter connector, female thread S60x6 / male thread 2"	3	1,66	4,97
air preparation unit 1/2" FRL	1	49,30	49,30
PU 12/8 mm 50mb	1	56,97	56,97
pressure transmitter Typ A10 6bar	1	87,79	87,79
pressure transmitter Typ A10 10bar	1	87,79	87,79
electrovalve 2N50-M NC DN50 2" 24VDC	3	121,95	365,85
electrovalve 2N50-M NO DN50 2" 24VDC	1	142,94	142,94
brass electrovalve 2V08 1/4" NC 24VDC	2	13,17	26,34
electrovalve 2N32-M NC DN32 1 1/4" 24VDC	2	52,29	104,58
other electrical equipment (inverters, push-buttons, rail)	1	575,12	575,12
generator set EXTRALINK 5,5kW	1	821,60	821,60
Total CAPEX - prototype cost			**~9 390 EUR**
Total annual system cost assuming 5-year depreciation			**~1 878 EUR**

4.2.2. Environmental monitoring and UAV

In addition to the spraying system, the analysis also included the monitoring infrastructure used at the stages of site reconnaissance, assessment of environmental conditions, and verification of reclamation results.

The common elements of this infrastructure include the UAV system together with its accessories and data-processing facilities. The UAV infrastructure considered in the analysis comprises:

- a drone with accessories, with a total value of ~11 737 EUR;
- a software valued at 3 521 EUR;
- an online image hosting platform costing 234,74 EUR/year;
- a computer hardware for data processing, valued at ~6 737 EUR.

Assuming a depreciation period of 3 years for the UAV system and software, and 5 years for the computer hardware, the total annual cost resulting from depreciation and maintenance of the supporting facilities amounts to 6 668,20 EUR/year (*Table 18*).

Assuming repeated use of the equipment at different locations, at a rate of 4 survey flights per month, i.e. 48 flights per year, the cost of a single flight was estimated at 138,92 EUR.

In addition, for the purposes of SCENARIO 5, a mobile AIRS measurement station was included. The station is housed in a mobile cabinet with a power supply system and GPRS transmission, and is equipped with sensors for suspended particulate matter, atmospheric parameters, and soil temperature and moisture, together with an installation mast and accessories. The total cost of this item amounts to ~5 746 EUR. For the purposes of the calculation, straight-line depreciation over a period of 5 years was assumed, corresponding to a cost of 1 149 EUR/year. Due to the seasonal nature of reclamation works, an effective infrastructure utilization period of 6 months was assumed, corresponding to a cost of 191,53 EUR/month of the season. A summary of the monitoring infrastructure costs is presented in *Table 18*.

Table 18. Costs of UAV and environmental monitoring infrastructure (SCENARIOS 4-5).

Infrastructure component	Total cost [EUR]	Depreciation period [years]	Annual cost [EUR/year]
UAV system	9 389,67	3	3 129,89
Accessories	2 347,42	3	782,47
Software	3 521,13	3	1 173,71
Computer hardware for data processing	6 737,10	5	1 347,40
Online image hosting platform	234,74	1	234,74
Total annual cost			**6 668,20**
AIRS measurement station	5 745,77	5	1 149,15
Total annual cost including AIRS			**7 815, 35**

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4.3. SCENARIO 4 analysis

4.3.1. Scope of the SCENARIO 4

SCENARIO 4 covers the baseline reclamation treatment for the entire analysed spoil tip area. First, UAV-based site monitoring is carried out to determine the initial NDVI map and assess the surface condition. This is followed by the implementation stage, which includes the spraying of reclamation material. The spraying process is carried out in two cycles: application of a mixture of cellulose mulch, working liquid and seeds, followed by application of a compost-water mixture.

4.3.2. UAV monitoring costs

In SCENARIO 4, the cost of site monitoring using UAV was included. This cost covers the use of the UAV infrastructure and data-processing facilities, accounted for a depreciation basis. Labour costs associated with the survey flight, data analysis and work organization are presented separately in the further part of the scenario.

4.3.3. Basis of the adopted assumptions

The assumptions regarding the composition of the reclamation mixtures were adopted on the basis of the results of field trials carried out under the Project, as well as reference data (*see* ***Deliverables 4.1 - 4.3***).

For the mulch-seed mixture, a cellulose mulch application rate of 1 100 kg/ha and a grass seed application rate of 50 kg/ha were assumed. Based on the proportion used during the trials, it was calculated that approximately 30,1 kg of mulch corresponded to 1 000 L of working liquid. In the subsequent calculations, the volume of working liquid for this mixture was assumed to be 36 600 L/ha. In addition, according to the adopted composition of the mixture, approximately 1,2 kg of seeds corresponds to 1 000 L of water. In the case of the compost mixture, the application of a 5 mm thick layer was assumed, corresponding to a mixture volume of 50 000 L/ha. For this mixture, a compost-to-water volumetric ratio of 3:1 was applied, corresponding to the consumption of 37 500 L/ha of compost and 12 500 L/ha of water.

A summary of the demand for materials and utilities is presented in *Table 19*, while their cost is shown in *Table 20*. The adopted parameters formed the basis for the subsequent calculations of material demand, water consumption, spraying time, and unit reclamation costs per 1 ha. In the calculation of material costs, it was assumed that water constituted the carrier liquid for the mulch-seed mixture; therefore, the cost of liquid utilities was estimated jointly based on the unit price of water.

Table 19. SCENARIO 4 - Material and utility requirements per 1 ha.

Consumable material	Value adopted for calculations	Unit
Cellulose mulch	1 100	kg/ha
Seeds from GIG-PIB	50	kg/ha
Water for preparation of the mulch-seed mixture	36 600	L/ha
Compost from POLTEGOR	18 750	kg/ha
	(37 500)	(L/ha)
Water for the compost mixture	12 500	L/ha
Total water	49 100	L/ha

Please note that, unlike SCENARIOS 2 and 3, the compost application rate in the KOMAG scenarios was defined according to the requirements of the spraying technology. As the developed system applies a compost-water suspension from storage tanks, the compost quantity is expressed in liters rather than in kilo- or megagrams (Mg), as used in SCENARIOS 2 and 3. According to ***Deliverable 4.3*** of REECOL, compost mixture has ~50% moisture content and ~500 kg/m³ average bulk density.

4.3.4. Assumed unit costs of consumable materials

The cost analysis presented in this section is based on the unit cost of the compost developed and presented by POLTEGOR (see base variant in SCENARIO 2) and the unit cost of the grass seed mixture developed and presented by GIG-PIB (see SCENARIO 1). The unit price of cellulose mulch was adopted based on representative market prices. The water cost was estimated using the average 2025 water and wastewater tariff for the Silesian Voivodeship (15,42 PLN/m³), which was considered representative of the Upper Silesian mining region. This corresponds to 0,0036 EUR/L and was used as the reference unit cost in the calculations. These values were used as the reference assumptions for the calculations presented below.

Table 20. SCENARIO 4 - cost of consumable materials.

Consumable material	Source of assumption	Unit price [EUR/kg, EUR/L]	Cost [EUR/ha]
Cellulose mulch	Market price	1,10 EUR/kg	1 205,87
Seeds	GIG-PIB (SCENARIO 1)	70,54 EUR/kg	3 532
Compost	POLTEGOR (SCENARIO 2)	0,20 EUR/kg	3 750
Water	Average 2025 water price (Upper Silesian Poland)	0,0036 EUR/L	176,76
Total cost [EUR/ha]			**8 664,63**

4.3.5. System capacity and treatment implementation time

The analysis took into account the nozzle used in the spraying system, with a capacity of 100 L/min. On this basis, the spraying time for the individual mixtures and the total treatment implementation time per 1 ha of area were determined.

For the mulch-seed mixture, the spraying time was 6,1 h/ha, while for the compost mixture it was 8,33 h/ha. Thus, the total time required to carry out the basic reclamation treatment amounts to 14,43 h/ha and refers to the effective spraying time. This corresponds to an area capacity of approximately 0,069 ha/h, i.e. approximately 693 m²/h.

Assuming that the effective spraying time within one working day is 7 hours, carrying out the treatment over an area of 1 ha corresponds to approximately 2,06 working days, i.e. 2 days and 26 minutes of effective spraying time. Since the calculations are presented on a per-hectare basis, this value should be regarded as a reference unit. In practical applications, reclamation works are typically carried out over substantially larger areas, where the spraying operation continues over consecutive working days without interruption. The values presented refer to the effective spraying time only and do not include technological breaks, tank filling time, material handling, or other auxiliary activities. The results are presented in *Table 21*.

Table 21. System capacity and time required for the reclamation treatment.

Mixture	Sprayed mixture volume [L/ha]	Assumed nozzle capacity [L/min]	Spraying time [s/m²]	Spraying time [h/ha]
Mulch-seed mixture	36 600	100	2,5	6,10
Compost-water mixture	50 000	100	3,0	8,33
Total spraying time 1 ha				**14,43**

4.3.6. Costs of operating the spraying system

To relate the capital cost of the system to the unit cost of reclamation, a simplified depreciation-based allocation model was adopted. An effective system utilization period of 6 months per year was assumed. Based on the effective spraying time of 14,43 h/ha and 7 hours of effective spraying per working day, the system productivity was estimated at approximately 10,7 ha per month, corresponding to approximately 64 ha of treated area per year.

The operating cost of the system was estimated based on the unit power rating, the effective spraying time and the adopted electricity price. For a system with a power rating of 1,5 kW and a total operating time of 14,43 h/ha, the energy consumption amounts to 21,65 kWh/ha. At the adopted net electricity price of 0,20 EUR/kWh, this corresponds to an electricity cost of 4,33 EUR/ha. The electricity price was assumed to be 0,20 EUR/kWh, corresponding to the average electricity price for industrial consumers in Poland in 2025 (Eurostat data) (*Table 22*).

Table 22. Operating cost of the spraying system.

System power [kW]	Operating time [h/ha]	Electricity consumption [kWh/ha]	Electricity price [EUR/kWh]	Electricity cost per 1 ha [EUR]
1,5	14,43	21,65	0,20	4,33

4.3.7. Labour cost

For the purposes of the calculation, a two-person crew was assumed for all field operations associated with the reclamation process, while the UAV data processing and analytical work were assumed to be carried out by a single operator. In SCENARIO 4, one UAV survey campaign is assumed, which, together with the processing of the acquired data, requires a total of 11,5 labour hours. This value includes:

- 4 hours of fieldwork related to carrying out the UAV mission and acquiring data,
- 4 hours of image processing,
- 2 hours of material analysis,
- 1,5 hours allocated to mission preparation and organizational activities.

For the implementation stage, 14,43 hours of effective spraying per 1 ha were assumed. In addition, approximately 2 hours of auxiliary activities and system start-up were included, giving a total of 16,43 hours of fieldwork. As these field activities were assumed to be carried out by a two-person crew, they correspond to 32,86 person-hours per hectare. Therefore, the total work associated with SCENARIO 4, i.e. UAV monitoring and field reclamation activities, amounts to approximately 44,36 person-hours per hectare. An hourly labour rate of 7,37 EUR/h (31,40 PLN/h) was adopted; therefore, the labour cost for SCENARIO 4 amounts to 326,93 EUR per hectare.

4.3.8. OPEX of SCENARIO 4

The summary of operating costs for SCENARIO 4 includes the main costs directly associated with the implementation of the full reclamation campaign, i.e. UAV monitoring, consumable materials, electricity, and labour. The total OPEX for SCENARIO 4 amounts to ~9 100 EUR/ha. Due to the comparative nature of the analysis, logistical and organizational costs, such as transport, daily allowances, and other costs dependent on local implementation conditions, were not included (*Table 23*).

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Table 23. Operating cost breakdown (OPEX) for SCENARIO 4.

Component	Cost [EUR/ha]
UAV monitoring infrastructure	104,19
UAV survey and data processing labour	84,76
Cellulose mulch	1 205,87
Seeds	3 532,00
Compost	3 750,00
Water	176,76
Electricity	4,33
Reclamation spraying labour	242,17
Total OPEX of SCENARIO 4	**9 100,08**

4.3.9. CAPEX of SCENARIO 4

In the analysis, it was assumed that the costs of the UAV infrastructure, although arising from depreciation, were allocated directly to individual survey flights and included in operating costs (OPEX) as monitoring costs. In contrast, the cost of the spraying system was accounted for as a CAPEX component per unit area, due to its direct relationship with the implementation of the reclamation treatment (*Table 24*).

Table 24. Capital cost breakdown (CAPEX) for SCENARIO 4.

Component	Cost [EUR/ha]
Depreciation of the spraying system	29,25
Depreciation of the UAV monitoring infrastructure	included in OPEX costs
Total CAPEX of SCENARIO 4	**29,25**

4.3.10. Total unit cost of SCENARIO 4

The total unit cost of SCENARIO 4 amounts to ~9 129 EUR/ha. The dominant share of this value is represented by operating costs, while the contribution of capital costs allocated through depreciation of the spraying system is relatively small. SCENARIO 4 was adopted as the baseline variant for further comparisons (*Table 25*).

Table 25. Total unit cost of SCENARIO 4.

Component	Cost [EUR/ha]
Total OPEX of SCENARIO 4	**9 100,08**
Total CAPEX of SCENARIO 4	29,25
Total cost of SCENARIO 4	**9 129,33**

4.4. SCENARIO 5 analysis

SCENARIO 5 covers supplementary intervention measures initiated based on site monitoring results. In this variant, it is not assumed that the supplementary treatment must be preceded by the prior full reclamation of the entire area. The decision to carry out the spraying treatment is based on an assessment of site condition performed using UAV monitoring and ground-based monitoring.

First, a UAV survey flight is conducted to identify areas requiring intervention, including surfaces with insufficient vegetation cover or deteriorated vegetation parameters. In addition, ground-based monitoring using a measurement station was included, allowing the assessment of environmental and soil conditions.

Based on the combined analysis of data obtained from aerial and ground-based monitoring, it was assumed that supplementary treatment was required. For the purposes of the analysis, it was assumed that the scope of supplementary measures covers up to 10% of the total area, which, when expressed per reference unit, corresponds to 0.1 ha for each 1 ha of analysed land.

It was assumed that, if the treatment is initiated, the material and technological parameters remain the same as for the baseline treatment. This means that the same application rates of reclamation materials, mixture compositions, nozzle capacity, and analogous method of calculating spraying time, energy consumption, and labour hours were applied in the calculations. Costs directly related to the execution of spraying were calculated proportionally to the area covered by the supplementary treatment, whereas monitoring costs were treated as an essential element in identifying areas requiring intervention.

4.4.1. Material and utility demand for SCENARIO 5

In SCENARIO 5, it was assumed that the supplementary measures cover a maximum of 10% of the analysed area. Therefore, the demand for materials, utility consumption, and spraying time were calculated proportionally for 0,1 ha in relation to the values adopted for the baseline scenario. The required quantities are presented in *Table 26*. It was assumed that the mixture compositions, material application rates, and technological parameters remain the same as in SCENARIO 4, with only the area covered by the treatment being changed.

Table 26. Consumable material demand for 0,1 ha of land.

Consumable material	Value adopted for calculations	Unit
Cellulose mulch	110	kg
Seeds	5	kg
Water for preparation of the mulch-seed mixture	3 660	L
Compost	1 875	kg
	3 750	L
Water for the compost mixture	1 250	L
Total water consumption	4 910	L

The above values were adopted as the basis for further calculations of material costs, energy consumption, and spraying time for the supplementary treatment covering 0,1 ha.

4.4.2. Spraying time and energy consumption in SCENARIO 5

In SCENARIO 5, it was assumed that supplementary treatment covers 10% of the analysed area, i.e. 0,1 ha. With the same technological parameters as those adopted for the baseline scenario, the total spraying time for 0,1 ha amounts to 1,44 h, corresponding to 10% of the time determined for 1 ha in SCENARIO 4. For a spraying system with a power rating of 1,5 kW, this corresponds to an electricity consumption of 2,16 kWh. At a net electricity price of EUR 0,20/kWh, the cost of electricity consumption for the supplementary treatment was estimated at EUR 0,43.

4.4.3. Labour cost in SCENARIO 5

For SCENARIO 5, the labour cost was not calculated solely in proportion to the treated area, as supplementary reclamation requires both a reassessment of site conditions and the implementation of additional reclamation measures. Consequently, the labour input includes the complete UAV survey campaign together with data processing and interpretation, as well as field operations associated with supplementary reclamation. For the purposes of the calculation, the following assumptions were adopted:

- UAV survey and data processing: 11,5 person-hours;
- effective spraying time for 0,1 ha: 1,44 h;
- auxiliary field activities, including system preparation and work organization: 1,0 h.

The total field operation time therefore amounts to 2,44 h. As these activities are performed by a two-person crew, they correspond to 4,88 person-hours. Consequently, the total labour input for SCENARIO 5 amounts to 16.38 labour hours. Assuming an hourly labour rate of EUR 7,37/h (PLN 31,40/h), the labour cost for SCENARIO 5 was estimated at EUR 120,72 per hectare of the analysed area.

4.4.4. Monitoring infrastructure in SCENARIO 5

For SCENARIO 5, a single UAV survey campaign was assumed as the basis for identifying areas requiring supplementary reclamation. The survey provides the information necessary to identify areas with insufficient vegetation cover or deteriorated environmental conditions requiring additional intervention.

SCENARIO 5 also includes the AIRS mobile measurement station, which provides environmental and soil monitoring data supporting the decision-making process for supplementary reclamation. Although the baseline analysis assumes a single UAV survey campaign, the methodology also allows additional verification surveys to be carried out after the supplementary treatment, if required, to assess its effectiveness.

The annual cost of operating the AIRS monitoring station amounts to 1 149,15 EUR. Considering the seasonal nature of reclamation works, an effective infrastructure utilization period of six months per year was assumed, corresponding to a monthly cost of EUR 191,53 during the reclamation season.

For the purposes of SCENARIO 5, the AIRS monitoring station was treated as a fixed monitoring infrastructure cost supporting environmental assessment and decision-making. Consequently, this cost was not allocated proportionally to the treated area but was considered a fixed cost associated with maintaining monitoring capability throughout the supplementary reclamation process.

4.4.5. OPEX of SCENARIO 5

The unit prices of reclamation materials, water and electricity adopted for SCENARIO 5 are identical to those described in SCENARIO 4 (assumed unit costs of consumable material) (*see* ***section 4.3.4***). The same reference prices and calculation assumptions were applied to ensure consistency and comparability between the analysed scenarios.

For SCENARIO 5, the operating costs associated with supplementary reclamation were determined using the same calculation methodology as adopted for SCENARIO 4. Material consumption, water demand, electricity consumption and spraying labour were calculated proportionally for a treated area of 0,1 ha, while the costs of UAV monitoring infrastructure and the associated UAV survey and data processing labour were assumed in full, as the identification of areas requiring supplementary reclamation necessitates a complete monitoring campaign regardless of the extent of the subsequent treatment.

The operating cost (OPEX) for SCENARIO 5 therefore represents the combined cost of one monitoring campaign and the implementation of supplementary reclamation over an area corresponding to 0,1 ha. The cost breakdown is presented in *Table 27*.

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Table 27. Operating cost breakdown (OPEX) for SCENARIO 5.

Component	Cost for 1 ha of monitoring and 0,1 ha of surface treatment [EUR]
UAV monitoring infrastructure	104,19
UAV survey and data processing labour	84,76
Cellulose mulch	121,00
Seeds	353,20
Compost	375,00
Water	17,68
Electricity	0,43
Reclamation spraying labour	35,97
Total OPEX of SCENARIO 5	**1 092,23**

The total operating cost (OPEX) for SCENARIO 5 amounts to 1 092,23 EUR and represents the combined cost of one UAV monitoring campaign together with supplementary reclamation treatment covering 0,1 ha. The adopted methodology ensures direct comparability with SCENARIO 4 by applying identical unit prices and calculation assumptions, while accounting for the reduced treatment area.

4.4.6. CAPEX of SCENARIO 5

All costs presented for SCENARIO 5 are expressed per 1 ha of analysed area. The scenario assumes that one complete UAV monitoring campaign is carried out over the entire analysed hectare, while supplementary reclamation treatment is implemented only on 0,1 ha, corresponding to the assumed maximum area requiring additional intervention.

Table 28. Capital cost breakdown (CAPEX) for SCENARIO 5.

Component	Cost [EUR/ha]
Depreciation of the spraying system per 0.1 ha	2,93
Cost of using the AIRS measurement station during 1 month of the season	191.53
Depreciation of the UAV monitoring infrastructure	included in OPEX
Total CAPEX of SCENARIO 5	**239,17**

For SCENARIO 5, the depreciation of the spraying system was allocated using the same methodology as adopted for SCENARIO 4. Although supplementary reclamation is assumed to cover only 0,1 ha, the analysis is expressed per 1 ha of monitored area, and therefore the depreciation of the spraying system remains a unit CAPEX component.

In addition, the AIRS mobile measurement station was included as a fixed monitoring infrastructure cost supporting environmental monitoring and decision-making regarding the implementation of supplementary reclamation. As described in the previous sections, the depreciation of the UAV monitoring infrastructure was allocated directly to monitoring activities and is therefore included in the operating costs (OPEX).

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4.4.7. Total cost of SCENARIO 5

The total unit cost of SCENARIO 5 amounts to EUR 1 331,40 per analysed hectare. This value represents the cost of monitoring 1 ha of reclaimed land together with the implementation of supplementary reclamation measures over 0,1 ha, corresponding to the assumed maximum area requiring additional treatment.

Table 29. Total unit cost of SCENARIO 5.

Component	Cost [EUR/ha]
Total OPEX of SCENARIO 5	**1 092,23**
Total CAPEX of SCENARIO 5	**239,17**
Total cost of SCENARIO 5	**1 331,40**

Compared with Scenario 1, the monitoring-based approach substantially reduces the costs associated with reclamation materials, electricity consumption and field operations by limiting the treatment only to locations where monitoring indicates that intervention is necessary. At the same time, the fixed costs of environmental monitoring infrastructure remain an important component of the overall cost structure, reflecting the decision-support role of monitoring within the developed reclamation technology.

4.5. Economic interpretation and commercial implementation considerations

The cost analysis presented in this deliverable provides a technical and economic basis for assessing the commercial implementation potential of the non-contact soil rehabilitation technology developed within the REECOL project. The calculated values represent the estimated costs of performing reclamation activities under the adopted technical assumptions and should not be interpreted as market service prices.

The analyses carried out for SCENARIO 4 and SCENARIO 5 demonstrate two complementary stages of the reclamation process rather than two competing service models. SCENARIO 4 represents the initial reclamation of the entire degraded area, while SCENARIO 5 represents supplementary reclamation applied only to locations identified through environmental monitoring as requiring additional intervention. Consequently, practical implementation may involve only SCENARIO 4 or a combination of SCENARIO 4 followed by one or more supplementary reclamation campaigns (SCENARIO 4), depending on monitoring results.

4.5.1. Indicative commercial pricing assumptions

The costs calculated in the previous sections represent the direct implementation costs of the proposed technology. In practical commercial applications, additional indirect costs should also be considered, including:

- transport of equipment and personnel,
- administrative and organizational costs,
- insurance,
- routine servicing and maintenance,
- replacement of consumable components,
- unplanned maintenance and minor repairs,
- business overheads and commercial profit.

As these costs strongly depend on the scale of operation, organizational structure and local market conditions, they were not included directly in the cost analysis. Instead, three indicative pricing models are proposed to illustrate the potential commercial implementation of the technology (*Table 30*).

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Table 30. Pricing models explained.

Pricing model	Applied multiplier	Interpretation
Cost recovery	100%	Direct implementation cost only
Standard commercial implementation	120%	Direct costs with an allowance for indirect operating costs
Commercial implementation	140%	Direct costs including indirect costs and commercial margin

The proposed multipliers are intended solely for illustrative purposes and should not be interpreted as recommended market prices. Their purpose is to demonstrate the influence of indirect operating costs and commercial margins on the final service price.

4.5.2. Indicative service prices

Based on the calculated implementation costs, indicative service prices may be estimated using the pricing models presented above (*Table 31*).

Table 31. Indicative service prices.

Service	Direct implementation cost [EUR/ha]	120% pricing model [EUR/ha]
Initial reclamation (SCENARIO 4)	9 129,33	10 955,20
Supplementary reclamation (SCENARIO 5)	1 331,40	1 597,68

4.5.3. Long-term equipment utilization and depreciation assumptions

The economic analysis presented in this deliverable is based on a depreciation approach, whereby the acquisition costs of the individual components of the developed technology are allocated over their expected operational lifetime. Depending on the type of equipment, straight-line depreciation periods of three or five years were adopted in accordance with the assumptions presented in the previous sections.

Considering the seasonal character of post-mining land reclamation, an effective operating period of six months per year was assumed for all major equipment. Based on the expected operational performance of the developed technology, the annual treatment capacity was estimated at approximately 64 ha, corresponding to approximately 320 ha treated during the adopted five-year operational period of the spraying system.

The adopted depreciation methodology distributes the capital costs of the spraying system, UAV monitoring equipment, AIRS mobile measurement station, and the remaining technical infrastructure progressively over successive reclamation project. Consequently, the calculated unit CAPEX values presented in this deliverable represent the capital cost contribution allocated to each analysed hectare rather than the full acquisition cost of the equipment.

Following completion of the adopted depreciation periods, the acquisition costs of the individual system components are considered fully depreciated. Consequently, future reclamation projects would no longer include these capital cost components, while the remaining costs would primarily consist of operating expenses together with routine maintenance, replacement of consumable parts and, where necessary, refurbishment or modernization of the equipment.

The adopted methodology reflects the intended long-term utilization of the developed technology and provides a realistic basis for assessing its economic performance under repeated operational deployment.

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4.5.4. Economic benefits of the developed technology

The economic analysis demonstrates that the principal benefit of the developed technology is not the reduction of the initial reclamation cost, but the optimization of subsequent reclamation activities through monitoring-based decision making.

The baseline approach (SCENARIO 4) assumes full reclamation of the analysed area, whereas SCENARIO 5 limits supplementary reclamation exclusively to locations identified through UAV and environmental monitoring as requiring additional intervention. Under the assumptions adopted in this analysis, supplementary reclamation covers a maximum of 10% of the analysed area, resulting in a total implementation cost of 1 331,40 EUR per 0,1 ha of land, compared with 9 129,33 EUR per hectare for full reclamation.

This demonstrates the economic benefit of the monitoring-based approach. Following the initial reclamation campaign, any supplementary intervention can be limited to the areas identified by environmental monitoring instead of requiring reclamation of the entire area again. As a result, the consumption of reclamation materials, field operation time and labour input are significantly reduced while ensuring that reclamation measures are applied only where they are actually needed.

An additional economic advantage results from the repeated utilization of the developed spraying system. Since the acquisition cost of the equipment is distributed over its assumed operational lifetime through depreciation, the technology becomes increasingly cost-effective with successive reclamation projects. Following completion of the depreciation period, the capital cost component associated with the spraying system is no longer incurred, leaving primarily operational costs together with any future maintenance or equipment modernization costs.

The presented results confirm that integrating environmental monitoring with targeted supplementary reclamation improves the overall economic efficiency of post-mining land reclamation while supporting more sustainable use of technical resources and reclamation materials. The field trials conducted by ITG KOMAG confirmed the practical applicability and effectiveness of the developed non-contact reclamation technology (*Figure 14*).

Figure 14. Successful vegetation established during field trials of the developed non-contact reclamation technology conducted by ITG KOMAG at the Jankowice spoil heap.

4.6. Summary of SCENARIOS 4-5

The scenario analysis made it possible to determine the unit costs of reclamation using the developed spraying system and to identify the main cost components in the individual treatment implementation variants.

SCENARIO 4, covering the full reclamation treatment for the analysed area, constitutes the baseline variant and the reference point for further comparisons.

SCENARIO 5 represents a variant of supplementary measures initiated based on UAV monitoring as well as environmental and soil monitoring results, assuming that the treatment covers up to 10% of the area. Although SCENARIO 5 involves a smaller spraying scope, its cost structure is more heavily burdened by fixed costs related to monitoring and the availability of technical infrastructure. For this reason, this variant should not be interpreted as a simple linearly scaled-down equivalent of SCENARIO 4. At the same time, SCENARIO 5 enables reclamation measures to be carried out in a more precise, targeted and justified manner, limiting their scope exclusively to areas requiring intervention.

SCENARIO 5 may therefore be regarded as a more effective solution from the point of view of the practical organization of reclamation works. It is based on monitoring and allows decisions to be made in a more informed manner, adapted to actual site conditions. This approach reduces the need to carry out unnecessary treatment over the entire spoil tip area and allows the available material and technical resources to be used more efficiently. It is also worth emphasising that the developed spraying system is better suited to supplementary and intervention-based measures than to covering the entire spoil tip area as quickly as possible within a single campaign. Its technical characteristics and operating mode are more favourable to the implementation of repeated, localised treatments than to intensive large-scale reclamation. The presented analysis relates to the prototype version of the spraying system developed and used under the project. It cannot be ruled out that the cost of a full implementation version may be higher; however, this would require a separate and more detailed analysis. The economic viability of the proposed solution will depend to a large extent on the intensity of system use. In the case of continuous use across multiple locations and reclamation campaigns, the share of capital costs in the unit cost decreases, thereby improving the overall economic performance of the solution.

Sources for cost assumptions for the technology for non-contact rehabilitation and control of soil parameters with use of bio-waste:

The unit cost of the grass seed mixture and compost was adopted from the assumptions developed by GIG-PIB and POLTEGOR-Institute, respectively. The cellulose mulch price was based on market prices from ProAgro (www.proagro.info.pl). The water cost was estimated using the average 2025 water and wastewater tariff for the Silesian Voivodeship, based on a compilation of publicly available local water and wastewater tariffs published by Mojawoda.com (www.mojawoda.pl). The electricity price was adopted from the 2025 energy price data published by Forum Energii (www.forum-energi.eu). The capital costs of the developed technology, including the spraying system and monitoring system components, were determined on the basis of the actual costs incurred during the construction and integration of the prototype system.

5. Reclamation costs references in Europe

5.1. Introduction

Data from France, Québec, Australia, Canada and the USA were harvested.
All the cost are converted to EURO 2025.

The objective of this chapter is to compile reclamation costs from different sources to compare with the cost obtained in REECOL CBA scenarios. The following reclamation activities were investigated:

- Hydroseeding and hydromulching,
- Fertile soil supply, transport and implementation,
- Compost supply and implementation.

The main sources of information were the following:

- France: most of the costs were collected from BRGM's Post Mining Division (in charge of the post mining management for the French State).
- Quebec: all the costs were collected from Gestim[1] Database (Gestion des Titres Miniers – Ressources Naturelles et Forêts) managed by Quebec government and which host all the mining reclamation plans.
- Australia: North South Wales mine rehabilitation cost estimate tool (2025 version)[2]
- USA: California Caltrans (Contract Cost Data) which host road maintenance cost data including compost, hydroseeding, hydromulching.

5.2. Compost costs

Compost costs (including implementation) are strongly dependent on their quality and show a large variability.

Data collected in France varies between 27 EUR/m^3 (for 216 m^3) to 170 EUR/m^3 (for 2700 m^3).

Data collected in USA (100 costs collected in 2024):

- 139 EU/m^3 (0-100 m^3), so 278 EUR/Mg
- 62 EUR/m^3 (100-500 m^3), so 124 EUR/Mg
- 50 EUR/m^3 (> 500 m^3), so 100 EUR/Mg

This confirms that POLTEGOR compost cost in SCENARIO 2 (200 EUR/Mg) stands in the higher range of international costs. And POLTEGOR compost cost in SCENARIO 3 (expanded production case), if sell at 150 EUR/Mg is in the medium-high range.

5.3. Hydromulching – hydroseeding costs

The harvested costs for hydroseeding are exposed in the following table (*Table 32*).

[1] https://gestim.mines.gouv.qc.ca/MRN_GestimP_Presentation/ODM02105_eula.aspx

[2] https://www.resources.nsw.gov.au/resources-regulator/mine-rehabilitation/determining-a-rehabilitation-security-deposit

Table 32. Costs for hydroseeding.

Hydroseeding		
Unit cost (EUR 2024/m²)	Q (m²)	Country/ Region
0,7	36 000	France
1	4 000	France
0,5	26 500	France
0,4	9 300	France
0,4	16 200	France
1,6	5 800	France
0,8	20 000	France
1,22	12 200	Quebec
1,98	19 800	Quebec
0,32	3 200	Quebec
1,47	56 000	Quebec
1,07	17 600	Quebec
1,87	1 500	Quebec
1,29	270 000	Quebec
0,69	563 556	Quebec
0,69	290 000	Quebec
1,4	-	Australia
0,8	500000	Finland

From this, it is possible to extract the following costs for hydroseeding:

- 1,1 EUR/m² for areas bellow 2 ha,
- 0,8 EUR/m² for areas above 2 ha.

In complement, the Australian NSW Rehabilitation Cost Estimation Tool of 2025 (for mining sites) developed by the government gives detailed costs on hydroseeding according to the application (*Table 33*):

Hydroseeding

- Using pasture seed, with:
  - A mulch applied at 200kg/ha,
  - A binder applied at 12kg/ha,
  - Pasture seed at $17.65 per kg and 42.5kg per ha,
  - Fertiliser and water incorporated into mix,
  - 3 577 EUR/ha (including furniture and application).
- Using native seed, with:
  - A mulch applied at 200kg/ha,
  - A binder applied at 12kg/ha,
  - Pasture seed at $920 per kg and 17.65kg per ha,
  - Fertiliser and water incorporated into mix,
  - 10 011 EUR/ha (including furniture and application).

Hydromulching

- For flats and medium slopes and pasture seed:
  - A mulch applied at 5 000kg/ha (binder included),

- Pasture seed at \$17.65 per kg and 42.5kg per ha,
- Fertiliser and water incorporated into mix,
- 13 575 EUR/ha (including furniture and application).

- For flats and medium slopes and native seed:
  - A mulch applied at 5 000kg/ha, (binder included),
  - Pasture seed at \$920 per kg and 17.65kg per ha,
  - Fertiliser and water incorporated into mix,
  - 20 008 EUR/ha (including furniture and application).
- For steep slopes with a fibre reinforced matrix, pasture seed:
  - A mulch applied at 6 500kg/ha, (binder included),
  - Pasture seed at \$17.65 per kg and 42.5kg per ha,
  - Fertiliser and water incorporated into mix,
  - 21 793 EUR/ha (including furniture and application).
- For steep slopes with a fibre reinforced matrix, native seed:
  - A mulch applied at 6 500kg/ha, (binder included),
  - Pasture seed at \$920 per kg and 17.65kg per ha,
  - Fertiliser and water incorporated into mix,
  - 28 227 EUR/ha.
- For biotic growth medium, pasture seed:
  - A mulch applied at 10 000kg/ha, (binder included),
  - Pasture seed at \$17.65 per kg and 42.5kg per ha,
  - Fertiliser and water incorporated into mix,
  - 29 118 EUR/ha (including furniture and application).
- For biotic growth medium, native seed:
  - A mulch applied at 10 000kg/ha, (binder included),
  - Pasture seed at \$920 per kg and 17.65kg per ha,
  - Fertiliser and water incorporated into mix,
  - 36 042 EUR/ha (including furniture and application).

Table 33. Costs of hydroseeding and hydromulching.

	Seed cost EUR/ha	Fertilizer cost EUR/ha	Water cost EUR/ha	Application cost EUR/ha	Total Cost EUR/ha	Total Cost EUR/m²
Hydroseeding - pasture seed	458	223	366	2 531	3 577	0,36
Hydroseeding - native seed	7 015	99	366	2 531	10 011	1,00
Hydromulching - for flats and medium slopes and pasture seed	458	223	366	12 528	13 575	1,36
Hydromulching - for flats and medium slopes and native seed	7 015	99	366	12 528	20 008	2,00
Hydromulching - for steep slopes with a fibre reinforced matrix, pasture seed	458	223	366	20 747	21 793	2,18

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Hydromulching - for steep slopes with a fibre reinforced matrix, native seed	7 015	99	366	20 747	28 227	2,82
Hydromulching - for biotic growth medium, pasture seed	458	223	366	28 072	29 118	2,91
Hydromulching - for biotic growth medium, native seed	7 015	99	732	28 072	36 042	3,60

It is possible to compare these costs with SCENARIO 4, considering the following differences:

- Water cost in Australia is 0.6 EUR/m3 (3,6 EUR/m^3 in SCENARIO 4), it corresponds to a decrease of 147 EUR.
- Median Labour cost is 1425 AUD/week so 22 EUR/hr (considering 38 hours per week), it corresponds to a labour cost increase of 646 EUR/ha in SCENARIO 4.

It is not possible to adjust energy cost with precision, but we can assume a total adjusted cost of 10 000 EUR/ha which is reasonable compared to Australia (NSW) costs (between 3 500 and 36 000), considering moreover that:

- SCENARIO 4 consider 50 kg/ha of seed compared to 12.5 to 42.5 in Australia,
- SCENARIO 4 consider a solid mass of 19 900 kg/ha (seed + mulch + compost) compared to 242,5 to 10 000 kg/ha in Australia,
- SCENARIO 4 includes monitoring.

Another element to consider are the transport costs in Australia which are significantly higher compared to Europe given the distances.

5.4. Soil implementation

The rehabilitation may need the implementation of a layer of fertile soil before revegetation. The following table presents the costs harvested from different countries. The costs vary with distance, unfortunately this information is not always available (*Table 34*).

Table 34. Costs of fertile soil layer implementation.

Soil			
Unit cost (EUR/2024)	**Quantity (m^3)**	**Distance (km)**	**Country/ region**
26	2 700	-	France
44	2 700	-	France
3,4	1 500	0	France
16	2 100	-	France
24	2 100	-	France
6,8	6 490	3	France
5,3	6 000	0	France
20	2 320	-	France
28	2 320	-	France
25,4	60	-	France
31	8 000	-	France
6,93	4 200	4	Quebec

5,41	557	-	Quebec
17,5	2 562	-	Quebec
6,5	-	0	Quebec
7	5 280	0	Quebec
5	43 000	0	Quebec
4,85	158 000	0	Quebec

The cost of spreading (no transport) is between 3, 4 and 7 EUR/m³. From Australia-NSW mine rehabilitation cost estimate tool, there are costs for "Source, cart and spread growth media" with distance:

- <200 m: 2,19 EUR/m³
- 200-500 m: 2,21 EUR/m³
- 500-1000 m: 2,55 EUR/m³
- 1000-1500 m: 2,89 EUR/m³
- 1500-2000 m: 2,92 EUR/m³
- 2000-2500 m: 3,16 EUR/m³
- 2500-3000 m: 3,4 EUR/m³
- 3000-4000 m: 3,64 EUR/m³
- 4000-5000 m: 4,13 EUR/m³
- 5000-6000 m: 4,61 EUR/m³
- >7 km: 4,85 EUR/m³

5.5. Standard reclamation method costs

Using the cost defined in the previous chapters it is possible to estimate standard reclamation method costs according to different scenarios.

If the surface needs the spreading of fertile soil before vegetation implementation:

- Fertile soil spreading over 5 cm (volume 500 m³; density 1,3; 650 tonnes) and 50 kg/ha of seed:
  - Soil sourcing: [12 EUR/Mg]: 78 000 EUR/ha
  - Soil transport [0.18 – 0.25 EUR/Mg x km in EU], distance 15 km:1 755 – 2438 EUR/ha
  - Soil spreading [3,4 – 7 EUR/m³]: 1 700 – 3 500 EUR/ha
  - Seed sourcing [70 EUR/kg]: 3500 EUR/ha
  - Seed sowing: 500 EUR/ha
  - Total: 15 255 to 17 737 EUR/ha.
- Fill spreading over 20 cm and hydromulching or hydroseeding:
  - Soil sourcing: [0 EUR/Mg]: 0 EUR/ha
  - Soil transport [0.18 – 0.25 EUR/Mg x km in EU], distance 5 km : 2 340 – 3 250 EUR/ha
  - Soil spreading [3,4 – 7 EUR/m³]: 6 800 – 14 000 EUR/ha
  - Hydromulching [1,36 – 3,6 EUR/m²]: 13 600 – 36 000 EUR/ha
  - Hydroseeding [1,1 EUR/ha]: 11 000 EUR/ha
  - Total with hydromulching: 22 740 – 53 250 EUR/ha
  - Total with hydroseeding: 20 140 – 28 250 EUR/ha.

If the surface allows for direct spreading of the vegetation:

- Hydromulching [1,36 – 3,6 EUR/m²]: 13 600 – 36 000 EUR/ha.

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6. Summary, conclusions and recommendations

The Report presented a preliminary Cost-Benefit Analysis (CBA) of the three innovative post-mining land reclamation technologies developed within Work Package 4 of the REECOL project. The assessment aimed to evaluate their technical, economic, environmental, and implementation potential under realistic industrial conditions, thereby supporting future large-scale deployment and commercialization.

The technologies assessed include: (i) steered succession of low-growing vegetation for the rapid stabilization of hard coal waste heaps, (ii) an integrated non-contact soil rehabilitation system combining UAV monitoring with precision application of reclamation materials, and (iii) soil regeneration using high-biological-activity compost, produced from organic waste streams within a circular economy framework.

Recognising that post-mining sites differ substantially in terms of geological, environmental, and operational conditions, the Report adopted a scenario-based approach rather than proposing a single universal business model. Five representative implementation scenarios are analysed from the perspectives of technology providers, mining companies, and compost producers. These scenarios illustrated alternative commercialization pathways, investment structures, and operational models, enabling comparison of costs, benefits, and implementation risks under different market conditions.

Because the technologies remain at a pre-commercial stage, the presented CAPEX and OPEX values should be regarded as indicative estimates intended to support preliminary feasibility assessment rather than detailed investment appraisal. The analyses identify the principal cost drivers, evaluate operational requirements, and estimate potential economic performance while also considering wider environmental and strategic benefits, including soil organic carbon sequestration, biodiversity enhancement, improved soil functionality, waste valorisation, and reduced reliance on virgin reclamation materials.

The report demonstrated that the value of innovative reclamation technologies extends beyond direct financial returns. Their successful implementation may contribute to accelerated ecological restoration, improved ecosystem services, circular economy objectives, and the sustainable transformation of former mining regions.

It was possible within these analyses to monetize the costs of proposed scenarios (CAPEX, OPEX). Other costs such as monitoring, CO_2 emissions due to the implementations of the scenarios (transport, implementation, etc.) were not considered at this pre-feasibility step.

The internal benefits were studied under the form of avoided costs while comparing the scenarios with standard reclamation methods. The other benefits such as increased property value, provisioning of ecosystem services, tax revenues, CO2 storage, erosion control, biodiversity, pollination, cultural services, were not monetarize at this step but only discussed qualitatively.

A next step (in another project), based on more advanced feasibility studies, will be to implement this monetarization:

- SCENARIO 1: value of the increase in biodiversity, pollination service, erosion control and contaminant filtration, CO_2 storage increase, cultural services, increase in value of the land.
- SCENARIOS 2 and 3: value as agricultural land, acceleration of the rehabilitation compared to standard rehabilitation (reduction of the land use latency), CO_2 storage increase, increase in the land value.

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