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Article

Closure as a New Beginning: Repurposing Post-Mining Sites into Industrial Eco-Parks Backed by Virtual Power Plants

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Abstract

The accelerated closure of hard coal mines across Europe contrasts with Poland's continued structural reliance on coal extraction and coal-based power generation, increasing the urgency of credible post-mining development models. This article investigates the potential transformation of the end-of-life Bobrek coal mine in Bytom (Poland), drawing on methodological and business-model insights from the European Union (EU) Research Fund for Coal and Steel (RFCS) POTENTIALS and GreenJOBS projects. A combined methodological framework is applied, including structural analysis to identify key transformation variables, morphological analysis to explore alternative redevelopment pathways, and multicriteria assessment to configure coherent scenarios integrating renewable energy systems and circular-economy activities. The results show that an industrial eco-park backed by a virtual power plant (VPP), comprising photovoltaic installations, a mine-water-based geothermal heating system, and small-scale wind turbines, is technically feasible and environmentally sustainable. In parallel, three circular-economy business lines, the recycling of end-of-life photovoltaic panels, waste electrical and electronic equipment (WEEE), and refrigeration units, were assessed as possible economic cores of the envisaged eco-park. Overall, the proposed model enables effective reuse of mining infrastructure, supports low-emission industrial activity, and aligns with EU climate policy objectives. The Bobrek site may serve as a reference for post-mining redevelopment in other coal regions.

Keywords: coal mine; end of life; virtual power plant; industrial eco-park; renewable energy; post-mining redevelopment; POTENTIALS project; GreenJOBS project

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1. Introduction

Coal mine closures increasingly occur within the wider energy transition and are rarely limited to technical completion of extraction. Closure entails long-term environmental management, land-use change, and significant social impacts on communities whose employment and identity have been shaped by mining. When closures take place under time pressure, the central challenge is to convert closure into a managed transition:

legacy risks must be controlled while new, durable economic functions are created in line with climate and sustainability objectives.

Across Europe, post-mining trajectories show that starting conditions matter. In several Western European countries, hard coal extraction has already ceased, enabling decades of restructuring and redevelopment [1–5].

In Central and Eastern Europe—and particularly in Poland—underground hard coal mining remains embedded in regional economies and continues to shape development pathways [6].

The Upper Silesian Coal Basin is characterised by interconnected mines and coal-related industries, and coal-linked employment remains substantial. Consequently, mine closures in Upper Silesia represent not only an energy-sector transition, but a broader socio-economic challenge.

End-of-life mines are not only sources of environmental and safety risk. They also contain assets that can support redevelopment if mobilised strategically. These include surface areas suitable for reconfigured land use, grid and transport connections, water-management infrastructure, and underground workings that may enable new energy functions. The practical question is how to configure viable pathways that combine technical feasibility with credible economic activity and local benefit.

Energy-oriented reuse options have expanded in recent years. Mine-water systems have been assessed and implemented as low-temperature geothermal resources for heating and cooling applications [7–9]. Above ground, photovoltaic installations and wind turbines can be deployed on reclaimed waste facilities and other disturbed land where constraints permit [10]. Other options include the utilisation of coal-mine methane [11] and energy storage concepts such as shaft-based gravitational storage and underground pumped-storage systems [12,13].

Germany illustrates the breadth of post-mining energy concepts developed over a long period of restructuring, including mine-water geothermal energy, methane-based heat and power, biomass on restored land, and underground storage concepts [10].

Non-energy redevelopment has also played a visible role in many regions, including cultural, recreational, and tourism functions such as heritage and geotourism initiatives [14]. However, outside a limited number of flagship projects, many post-mining applications—especially energy-related ones—remain at pilot scale. Persistent barriers include regulatory uncertainty, investment risk, and the difficulty of aligning business cases with closure timetables and local socio-economic priorities.

These observations point to a gap in site-level research and practice: energy assets and industrial redevelopment are often planned in parallel rather than as a coordinated system. In particular, the operational coordination of multiple assets (distributed generation, flexible demand, and low-temperature heat recovery) and the governance mechanism through which they can act as a unified local energy actor are still less explicitly treated in post-mining redevelopment studies.

To address this gap, we operationalise an integrated concept: an industrial eco-park backed by a virtual power plant (VPP). In this configuration, distributed renewable generation and geothermal heat recovery are coupled with circular-economy industrial activities that create local demand and support diversification. The VPP provides the coordinating layer to manage distributed resources and flexible loads, allowing the site to function as an integrated energy–industry hub rather than a set of isolated single-technology projects.

Against this background, the present study develops a redevelopment concept for the end-of-life Bobrek hard coal mine in Bytom (Poland), which ceased production at the end of 2025. Building on insights from the RFCS POTENTIALS and RFCS GreenJOBS projects, we apply an integrated framework combining structural analysis, morphological

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analysis, and multicriteria assessment to identify coherent redevelopment pathways and to clarify not only which options are feasible but also how they can be orchestrated as an integrated system.

The proposed solution couples a VPP (photovoltaic installations, mine-water geothermal heating, and small-scale wind turbines) with three circular-economy business lines centred on recycling end-of-life photovoltaic panels, waste electrical and electronic equipment (WEEE), and refrigeration units.

The novelty of this work lies in (i) combining, within a single post-mining site concept, a VPP-based coordination layer with an eco-industrial park and concrete circular-economy business lines and (ii) applying a transparent, reproducible scenario workflow to move from a broad option space to a coherent, site-specific redevelopment portfolio that explicitly integrates energy supply with industrial demand.

Section 2 presents the study site and methods; Section 3 reports the scenario results and the corresponding technical and business concepts; Section 4 discusses implications and transferability; and Section 5 summarises the conclusions.

2. Materials and Methods

2.1. The Bobrek Mine and the GreenJOBS Project

The analysis is framed within the RFCS-funded GreenJOBS project ("Leveraging the competitive advantages of end-of-life underground coal mines to maximise the creation of green and quality jobs"), which aims to support mining companies and regional stakeholders in designing innovative post-mining business plans through the deployment of emerging renewable energy and circular-economy technologies, thereby promoting sustainable local economic development and maximising the creation of green, quality jobs.

The project's approach is premised on leveraging five competitive advantages of underground coal mines: (1) mine water as a resource for geothermal energy and green hydrogen production; (2) existing grid connections that can be adapted for electricity injection; (3) extensive waste-heap areas suitable for photovoltaic and wind installations; (4) deep underground infrastructure appropriate for unconventional pumped hydro energy storage using dense fluids; and (5) fine coal waste streams that can be recycled into dense fluids, soil substitutes for land restoration, and sources of rare earth elements.

This study focuses on the Bobrek coal mine, property of Węglokoks Kraj SA (Bytom, Poland), which was closed at the end of 2025 due to rockburst hazards and limited remaining hard coal resources. Bobrek mine is located in the central part of the Upper Silesian urban–industrial region, within the densely developed city of Bytom. The immediate surroundings of the mine comprise a complex mosaic of residential, industrial, and post-industrial areas, forming a highly interdependent spatial and functional system shaped by a long history of heavy industry and mining.

The mine lies between the Bobrek and Karb districts, both characterised by compact residential estates and local community facilities, and benefits from direct access to regional road and rail transport corridors. These infrastructural connections facilitate efficient links with neighbouring industrial sites and create favourable conditions for integrating future post-mining activities into the broader urban and economic fabric of the city.

Figure 1 presents a cross-section of the Bobrek mine area illustrating the shafts and the underground workings.

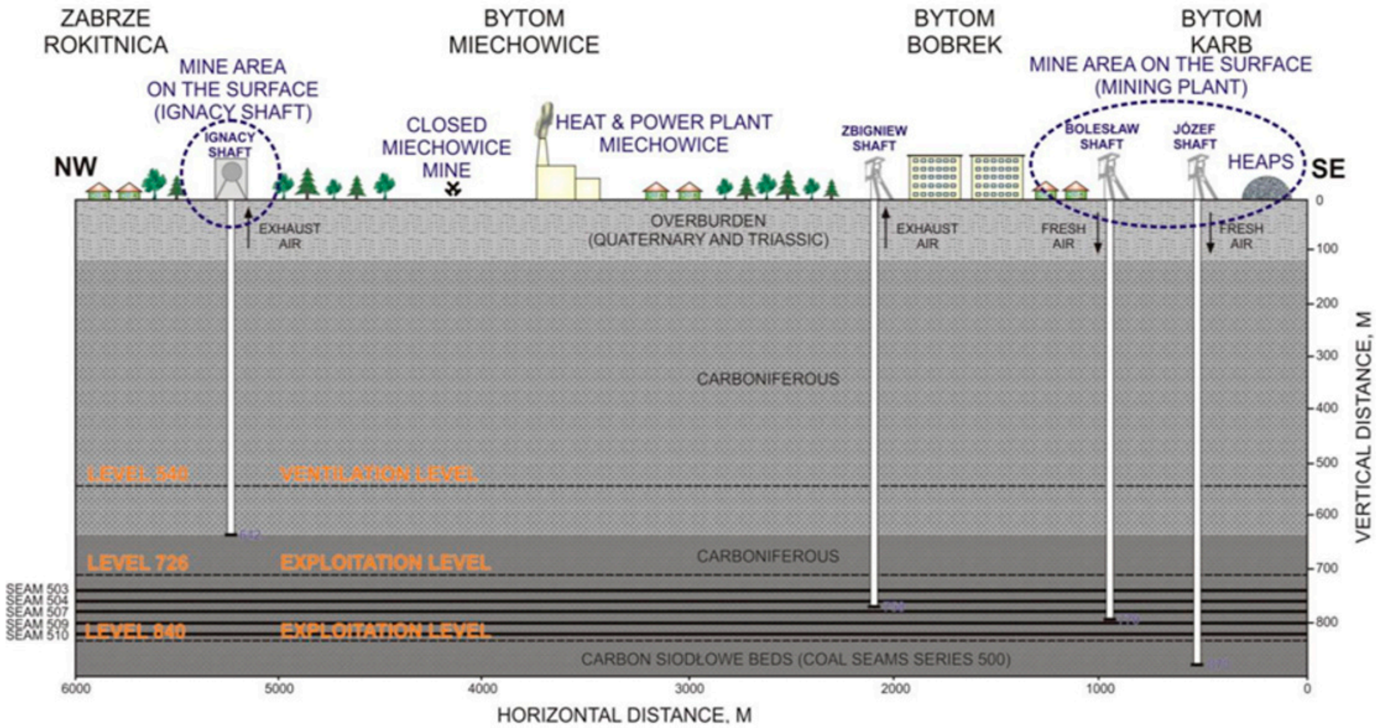

Figure 1. Cross-section of the Bobrek mine area.

The territorial and methodological framing of the analysis is further informed by the RFCS-funded POTENTIALS project, which focuses on the synergistic redevelopment of coupled end-of-life coal mines, coal-fired power plants, and closely related neighbouring industries [15].

POTENTIALS emphasises the identification and assessment of integrated business models that enable sustainable, coordinated reuse of existing assets and resources, supporting economic diversification and job creation in Coal Regions in Transition while addressing the challenges associated with accelerated coal phase-out processes.

2.2. Deciding on Future Developments

The POTENTIALS project is closely aligned with the European Green Deal priorities [16], particularly those concerning the delivery of clean, affordable and secure energy and the advancement of a clean, circular industrial economy. The project contributes to accelerating the energy transition by examining pathways for renewable energy deployment, identifying enabling policy conditions that facilitate large-scale integration of renewables, and supporting spatially balanced development models that can reinforce local self-reliance and long-term sustainability.

The redevelopment of end-of-life coal mining sites builds on both the physical legacy of mining operations (e.g., buildings, utilities and transport access) and distinctive landscape features (including voids, shafts and waste heaps). By redirecting these assets towards post-closure uses, repurposing strategies can help counteract the decline in economic activity and support socio-territorial transition by creating new economic functions and renewed place-based ties for local communities.

To structure the analysis, an integrated methodological framework is implemented. It combines (i) structural analysis to determine the most influential variables shaping post-mining transformation, (ii) morphological analysis to construct and compare plausible redevelopment alternatives, and (iii) multicriteria assessment to synthesise the results into internally consistent scenarios that jointly incorporate renewable energy solutions and circular-economy activities.

2.2.1. Structural Analysis: Technical-Variable Assessment

Before conducting the structural analysis, a broad set of variables deemed pertinent to the Bobrek mine context was compiled and then progressively refined. The screening process focused on eliminating overlap and retaining those variables that most effectively represent the system. The resulting set includes both internal and external determinants, capturing technical conditions (e.g., mine-water parameters or available waste-heap area) as well as evaluation-related aspects (e.g., costs, feasibility, and regional competitiveness) associated with renewable energy deployment, existing assets and resources, and circular-economy opportunities.

Subsequently, an expert elicitation step was carried out to characterise interdependencies within the system. Using their domain knowledge, the participating experts assessed the strength of each variable's effect on the others, thereby establishing a consistent representation of cause-and-effect relations among the selected technical and evaluative variables.

On this basis, a structural analysis of mutual influences was conducted to isolate the variables with the most significant systemic importance. The MICMAC tool, developed by Institut d'Innovation Informatique pour l'Entreprise (3IE), was applied to examine direct, indirect and potential influence pathways [17]. This procedure enabled the organisation of the variables into a structured, grouped dataset and supported the identification of the key technical drivers shaping post-mining transformation.

Expert judgement inputs for the structural analysis were obtained through a two-round Delphi process. The panel comprised 40 experts with 3–40 years of coal/mining-related experience, representing Poland (40%), Spain (15%), Greece (10%), Germany 17.5%, and European organisations (17.5%). Expert competence was characterised using the coefficient of expert competence (0.5–1.0).

To reduce inconsistency and individual bias, values without unanimity in Round 1 were identified and re-assessed in Round 2, where experts revised divergent entries and provided short justifications; the final matrix values were then consolidated during dedicated workshops.

The MICMAC direct influence matrix was completed on a four-level ordinal scale (0–3), where 0 indicates no direct influence, 1 weak influence, 2 strong influence, and 3 very strong influence, with an additional "P" flag used by experts to denote a potential future influence later mapped to the 0–3 scale for the potential matrices. The assessment is directional ($i \rightarrow j$ may differ from $j \rightarrow i$). The final matrix values were consolidated through a two-round Delphi-based process.

2.2.2. Morphological Analysis: Scenario Assessment

Morphological analysis is a structured way to broaden the range of conceivable futures by systematically exploring alternative configurations of a complex system. Because scenario quality depends strongly on the choice and sequencing of key variables, together with the specification of plausible alternatives, this stage is decisive in producing scenarios that are internally consistent, credible and transparent.

In this study, morphological analysis is employed to examine how the elements identified through the structural analysis could be recombined into distinct redevelopment pathways. While commonly applied to scenario construction, the method is also well-suited to exploring technological evolution and defining novel product or service concepts.

The analysis was implemented using the MORPHOL software environment, also developed by Institut d'Innovation Informatique pour l'Entreprise (3IE).

MORPHOL reduces the initial morphological space by applying exclusion constraints and selection criteria, eliminating combinations that are logically, technically,

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spatially, or operationally incompatible. An example of a rejected configuration is an open-pit-dependent option (e.g., floating PV/open-pit hydro-type configurations) combined with an underground, densely urban mine context, such as Bobrek, which is structurally incompatible with the site morphology and land-use constraints. This corresponds to the filtering logic already stated in the manuscript (actions tied to open-pit configurations were excluded for Bobrek).

An example of retained configuration is the VPP + mine-water geothermal + PV (and small wind where feasible) configuration, retained because it leverages Bobrek's transferable assets (mine-water resource and existing infrastructure) and remains internally coherent at the pre-feasibility level.

The output was a "scenario space" comprising the set of feasible system configurations generated from the defined variables and their alternatives. The resulting scenarios were then reviewed, filtered and synthesised into a portfolio of relevant business-model options, excluding combinations that did not offer meaningful synergies among end-of-life coal mine assets, associated energy infrastructure and closely related surrounding industrial activities.

2.2.3. Evaluating Scenario Options by Multicriteria Assessment

Scenario options and their associated micro-scenarios (i.e., complementary components intended to be combined with other scenario elements to form an integrated business model) were appraised through a multicriteria assessment approach [18]. The evaluation was implemented using the MULTIPOL tool (MULTIcriteria and POLicy), developed by Institut d'Innovation Informatique pour l'Entreprise (3IE).

For each policy dimension, scenarios were assigned aggregate scores and organised into classification profiles, enabling systematic comparison of scenario performance against the policy set. In parallel, a set of evaluation criteria consistent with this study's overarching aims and operational objectives was established.

For the MULTIPOL evaluation, workshop-based cross-checks were also applied to ensure that scoring for comparable technologies did not diverge implausibly, and agreed amendments were circulated for verification. All criteria were assigned equal weights (weight = 1). Differentiation among options arose from the expert scoring of actions/micro-actions against criteria (0–20; technical criteria may also take negative scores where relevant) and from the policy–criteria relationship matrix, in which a total of 100 points are distributed across criteria for each policy.

Appendix B provides a simplified example to illustrate the scoring and weighting procedure used in the MULTIPOL assessment.

Finally, Figure 2 presents the linkages MICMAC → MORPHOL → MULTIPOL.

Because these tools are not universally familiar, Table 1 summarises their role and outputs within the MICMAC–MORPHOL–MULTIPOL workflow.

Table 1. Summary of foresight tools used in this study (MICMAC–MORPHOL–MULTIPOL).

Tool	Objective in This Study	Main Output (Used in the Next Step)
Delphi-based structural analysis + MICMAC	Identify and prioritise the key variables driving the post-mining redevelopment system and clarify their influence/dependence structure through expert elicitation.	Set of key driving variables (influential and/or relay variables) and their structural positions; this reduced set is used to define the most discriminating dimensions for scenario construction.
Morphological analysis (MORPHOL)	Systematically generate internally consistent redevelopment configurations by combining plausible states/modalities of the key variables and filtering incompatible combinations.	Consistent scenario configurations (morphological "paths") representing alternative redevelopment options; a reduced shortlist of coherent scenarios is forwarded to evaluation.

Multicriteria policy evaluation (MULTIPOL)	Compare shortlisted scenarios against policy objectives and criteria using expert scoring and weighting to support transparent selection of preferred redevelopment portfolios.	Scenario rankings and policy-level profiles (weighted scores by criteria and aggregated by policy axes), supporting the selection of final scenarios for techno-economic appraisal.

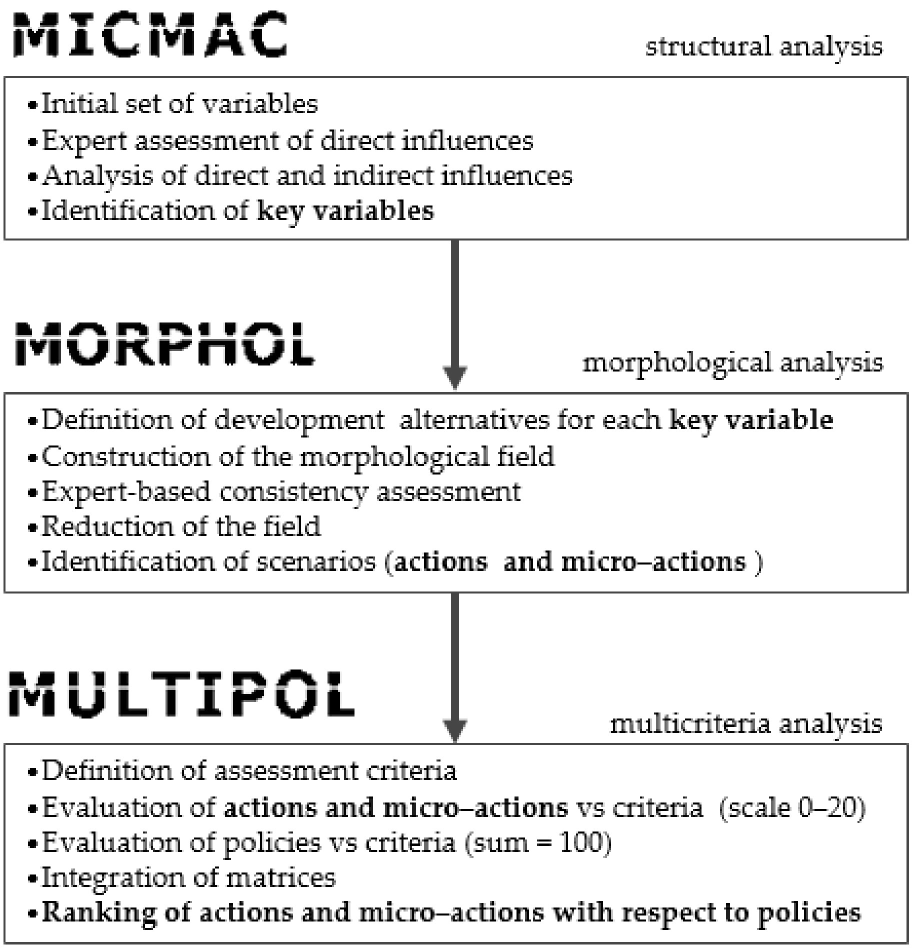

Figure 2. Linkages between structural analysis, morphological analysis, and multicriteria assessment.

With the policy framework and evaluation criteria established, the scenarios were appraised across the selected dimensions. The resulting performance profiles provide a structured basis for assembling site-specific business models, which in practice are most effectively realised as integrated packages combining several mutually reinforcing components [19,20]. For the Bobrek case, the preferred configuration is an eco-industrial park underpinned by a virtual power plant (VPP) concept.

2.3. Economic Diversification Potential

The industrial eco-park planned for the Bobrek mine site will be conceived as an integrated circular-economy zone that utilises the site's spatial, infrastructural, and environmental assets. Its structure will be based on distinct functional areas, each dedicated to renewable energy generation, resource recovery, and low-emission industrial processes [21]. The configuration of these areas will reflect the mine's spatial layout, the availability of reclaimed post-mining land, and the potential for synergies among energy, recycling, and logistics operations.

In operational terms, such an eco-industrial park should be organised around local district networks capable of linking multiple distributed energy sources with diverse

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demand points. This type of networked arrangement supports higher PV uptake by enabling energy users to also function as prosumers, including facilities with surplus electricity from rooftop installations.

To strengthen implementation viability and enhance local economic impact, the eco-industrial park should be accompanied by a targeted enabling framework—such as fiscal relief for incoming industries and facilitated access to preferential financing—designed to stimulate diversification, improve investment attractiveness, and accelerate the transition from a mono-industrial mining legacy towards a more resilient local economy.

Three circular-economy business lines—processing end-of-life photovoltaic panels, waste electrical and electronic equipment (WEEE), and refrigeration units—were examined as potential economic anchors for the envisaged eco-park. Each activity is intended to prioritise short-distance logistics and to improve the efficiency of material, resource and energy flows within the park while supplying secondary materials and components relevant to Europe's industrial transition and broader decarbonisation objectives.

The recycling activities were intentionally assessed at a pre-feasibility level (Table 2). At this stage, producing single-point IRRs/NPVs would be highly sensitive to locally contingent parameters that are not yet contractually defined, notably (i) secured waste-stream volumes and gate-fee structures, (ii) logistics and pre-treatment requirements, and (iii) market access and price realisation for recovered fractions.

The PV end-of-life treatment line is retained primarily as a strategic, environmentally justified option, but it is not currently a robust standalone business line under business-as-usual conditions; reaching break-even would require the restructuring of fixed costs and/or improved revenue conditions, potentially supported through targeted programmes or technological step changes (e.g., automation and reduced energy intensity).

By contrast, WEEE and refrigeration-appliance recycling can act as the economic "anchors" of the eco-park, provided that reliable supply contracts and downstream market channels are secured.

Table 2. Indicative screening-level implementation envelope for the eco-park recycling lines (order-of-magnitude ranges).

Recycling Line	Role in Eco-Park Logic	CAPEX (Indicative)	OPEX (Indicative, Annual)	Direct Employment (Indicative)	Key Condition/Note
PV panels (end of life)	Strategic/environmentally justified; candidate for phased deployment	HIGH	HIGH	MEDIUM	Under business-as-usual conditions, revenues may not offset total costs; break-even depends on cost restructuring and market/regulatory conditions.
WEEE/e-waste	Potential economic anchor	MEDIUM	MEDIUM	MEDIUM	Viability depends on securing stable input streams (contracts/gate fees) and outlets for recovered fractions.
Refrigeration equipment	Potential economic anchor (complementary to WEEE)	MEDIUM	MEDIUM	MEDIUM	As above; performance driven by supply reliability and compliance requirements (e.g., the handling of refrigerants). (Pre-feasibility envelope consistent with the study scope.)

2.4. Technical Concept: Virtual Power Plant

The envisaged virtual power plant (VPP) will comprise a photovoltaic installation, small-scale wind turbines, and a mine-water-based geothermal energy system, trying to achieve both technical feasibility and environmental sustainability.

Operationally, the VPP is conceived as a digitally managed coordination layer (energy management/Supervisory Control and Data Acquisition (SCADA) logic) that integrates distributed generation and site loads by forecasting PV/wind output and demand, scheduling controllable assets (e.g., storage charging/discharging and flexible electricity consumption associated with heat production) and optimising the split between on-site self-consumption and grid export, thereby providing system flexibility and potential balancing value:

- The PV installation will serve as the primary electricity-generating element of the VPP planned for the Bobrek mine site. Its design will be based on the technical characteristics of the reclaimed post-mining land, in particular a former coal stockpile of approximately 8 hectares, which provides promising solar exposure and is structurally suitable for ground-mounted PV systems.
  The energy output of the PV installation is estimated using the Photovoltaic Geographical Information System (PVGIS) [22].
- Despite the generally low-wind regime in the Bobrek mine area, a small-scale wind turbine installation located in the surroundings of the Ignacy shaft is nonetheless considered in the analysis. This location is the only area on site that meets the spatial and technical suitability requirements for such an installation.
  The purpose of including this option is to assess the potential feasibility of a limited wind energy investment under locally constrained conditions, rather than to identify an optimal wind resource location.
- Finally, a mine-water-based geothermal heat source is analysed to assess the potential for utilising the available mine-water resource at approximately 29 °C. The analysis is motivated by both the thermal characteristics of the mine water and the proximity of potential heat consumers, namely, the Bytom–Karb residential area and the Bobrek industrial facilities.
  This configuration allows the feasibility of low-temperature geothermal heat recovery to be evaluated under realistic local demand and infrastructure conditions, to identify whether mine water can be effectively integrated into a district heating and industrial heat supply scheme [23].
  Based on site data for Bobrek, the pumped mine water is near-neutral, with moderate suspended solids and high salinity dominated by chlorides and sulphates. Reported trace metals are low. For mine-water geothermal heat recovery, the main operational concern is not toxicity but salinity-driven scaling/corrosion risk (chlorides/sulphates) and, secondarily, suspended solids. The preferred concept for Bobrek is indirect/closed-loop heat exchange, which limits direct exposure of equipment to saline water and reduces treatment needs to filtration and material selection, rather than full desalination.
  In addition, recognising recent advances in the broader geothermal fluids field—where integrated membrane-based processes have been proposed for selective recovery of dissolved resources (e.g., lithium) from geothermal brines (Zegeye et al., 2025)—we note that such resource-recovery pathways may represent a complementary long-term option, subject to site-specific hydrochemical characterisation and treatment feasibility [24].

2.5. Regulatory and Permitting Considerations

Regulatory and permitting considerations constitute an important practical boundary condition for implementation, but the present work is intentionally positioned at a pre-feasibility level focused on option screening and techno-economic comparison rather than on design-stage consenting.

In Poland, the deliverability of the proposed components (PV energy, mine-water geothermal energy, recycling lines, and any optional wind element) would ultimately depend on the applicable spatial-planning provisions, environmental decision-making procedures (including where relevant assessments of noise, landscape, biodiversity, and community acceptance), grid connection conditions and licensing, and—where mine water is utilised—authorisations linked to water and environmental protection frameworks.

Because these requirements are strongly dependent on final engineering design choices, consultation outcomes, and operator-specific constraints, a comprehensive permitting pathway analysis is best undertaken as a subsequent, dedicated workstream. Moreover, a number of key inputs for such an assessment (e.g., detailed infrastructure condition, closure sequencing, legacy constraints and liabilities) may be commercially or operationally confidential and cannot be fully reported in an academic article.

Regulatory and permitting due diligence is identified here as a necessary next step to move from scenario selection to investment readiness, rather than as an objective of the present manuscript.

2.6. Economic Assessment: Cost–Benefit and Financial Indicators

The economic evaluation is performed using a discounted cash flow (DCF) model over a 20-year operating horizon, reflecting the anticipated technical service life of the technologies involved. It computes the principal financial metrics: net present value (NPV), internal rate of return (IRR), and payback period (PP). The analysis accounts for the following components:

- Capital expenditure (CAPEX): Investment costs include: (i) a total installed cost for the utility-scale PV installation (EUR 5.12 million); (ii) the onshore wind turbine installation (EUR 8.00 million); and (iii) the geothermal energy installation (EUR 7.20 million).
- Operating expenditure (OPEX): Annual operating and maintenance costs were estimated for: (i) the utility-scale PV installation (approximately EUR 0.11 million per year); (ii) the onshore wind turbine installation (approximately EUR 0.35 million per year); and (iii) the geothermal energy installation (approximately EUR 0.261 million per year).
- Revenues and quantified benefits: For the cost–benefit analysis, a representative wholesale electricity price for industrial consumers in Poland is required. This study adopts the Fixing I index of the Polish Power Exchange (TGE), which reflects the volume-weighted average price of the Day-Ahead Market base-load product and is commonly used as a proxy for wholesale electricity prices in energy system analyses.
  Based on 2025 monthly Fixing I prices and traded volumes, an annual average wholesale price of 105.47 EUR/MWh is obtained and applied in the economic calculations. This value represents pure wholesale energy costs, excluding network tariffs, taxes, and other charges, and is suitable for assessing electricity generation and self-consumption at the market level.
- Discounting and performance metrics: For energy-infrastructure modelling in Poland, the Polish Energy Regulatory Office set a fixed nominal pre-tax WACC of 7.48% for electricity system operators for 2023–2028 and indicated an additional reinvestment premium with a minimum level of 1% (i.e., a minimum uplift on top of the base WACC in that regulatory context) [25]. It constitutes a recent Poland-specific reference point, sometimes used as a baseline when motivating discount-rate assumptions for energy network-type investments.
  Discounting is applied using a real after-tax weighted average cost of capital (WACC) for 2025 of 1.88%, calculated using a Polish inflation assumption of 4.10% [26] via the Fisher equation. The real after-tax discount rate of 1.88% is used as the baseline for the energy-infrastructure components (PV and mine-water geothermal energy), because it is derived from a Poland-specific regulated energy-sector benchmark (Polish Energy Regulatory Office's WACC methodology for electricity system operators) and represents a reasonable reference for long-life, lower-risk energy assets.

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However, parts of the broader redevelopment concept—particularly brownfield industrial redevelopment and circular-economy processing lines—can entail additional market, technology and feedstock risks. Where such activities are financed on a purely private basis, a higher risk-adjusted discount rate would be required.
The economic results in this paper should be interpreted primarily as a public-policy/social-planning pre-feasibility appraisal to support option prioritisation in a Just Transition context, while differentiated discounting is explored through sensitivity ranges.

2.7. Sensitivity and Uncertainty Analysis

Following the computation of the principal financial metrics—net present value (NPV), internal rate of return (IRR) and payback period (PP)—a sensitivity and uncertainty assessment is undertaken to test the resilience of the economic results.

Sensitivity analysis is used to identify which inputs have the greatest influence on the calculated indicators, thereby highlighting the key drivers of project viability. Uncertainty analysis complements this by characterising the plausible dispersion of outcomes and the extent to which the investment case may change under alternative market conditions and operational realities.

Considered together, these procedures strengthen the robustness of the economic appraisal by demonstrating how the project behaves across a range of credible conditions, rather than relying solely on a single-point forecast.

3. Results

3.1. Selecting a Scenario

The first step in the structural analysis was to define the technical variables relevant to the Bobrek mine (Table 3). The analyses took into account 38 technical variables characterising individual elements of hard coal mines, grouped into three categories: (i) technical variables adopted for the underground part of the hard coal mine (16); (ii) technical variables adopted for the surface part of the hard coal mine (8); and (iii) technical variables adopted for the synergy of the mine with its surroundings (14).

Of course, not all sources agreed on the importance of the variables, or even on which aspects should be formalised as variables and which should not. A detailed explanation of the variables is provided, enabling a clearer understanding of their relations in the subsequent analysis. The complete list of the 38 technical variables used in the Bobrek case together with short definitions is presented in Appendix A.

Table 3. Excerpt from the unsorted list of variables developed by POTENTIALS project partners: the Central Mining Institute (GIG); Hulleras del Norte, S.A. (HUNOSA); and the University of Oviedo (UNIOVI).

N°	Key Variable	Defined by	Verified by	Short Definition
1	Depth of mine	GIG	UNIOVI	The variable determines the maximum depth of the mine—the depth at which the deepest exploitation level is located or where the deepest workings/goafs are located—that can be adapted to produce green energy.
2	Ground movement	GIG	UNIOVI	The variable determines the possible tectonic movement of rock mass influencing underground workings/reservoirs/shafts and infrastructure on the surface (after the end-of-life of the coal mine with or without the flooding of the mine).

3	Geological singularities of the mine	GIG	UNIOVI	The variable refers to the existence of singular geological structures in the mine: impermeable strata, absence of faults, etc. (with no geological disturbance).
4	Methane surface emissions	HUNOSA	GIG	The variable determines the concentration, flow and an estimation of future emissions of Abandoned Mine Methane.

Next, different experts stated the influence of each variable on the remaining system variables, providing a matrix of these influences based on their knowledge and expertise (Table 4).

Table 4. Part of the influence matrix.

N°	Key Variables	Depth of Mine	Ground Movement	Geological Singularities	Methane Surface Emissions	Methane Resources	Coal Spontaneous Ignition	Processing Plant Capacity
1	Depth of mine	-	3	3	3	**3**	1	0
2	Ground movement	0	-	0	1	0	1	0
3	Geological singularities of the mine	3	3	-	2	2	2	0
4	Methane surface emissions	1	0	0	-	0	0	0
5	Methane resources	0	0	0	3	-	0	0
6	Coal spontaneous ignition	0	0	0	1	0	-	0
7	Coal-processing-plant capacity	1	0	0	0	0	0	-

MICMAC software was applied to examine the network of direct, indirect and potential interactions among the selected variables. This process resulted in a structured classification of variables according to their levels of influence and dependence within the system. On this basis, the key technical variables were allocated to distinct categories (most notably key factors, impact (or determinant) factors, and result factors), which identify those elements requiring particular attention in subsequent scenario development (Figure 3).

Finally, a limited set of key technical variables was retained for the morphological analysis to keep the range of possible configurations, the so-called morphological space, at a manageable level. The selected variables capture the most decisive site-specific conditions, including, among others, the character of the surrounding area, the availability of space for new developments, existing infrastructure assets, land-use constraints, limitations related to waste-heap redevelopment, the flooding status of the mine, and the quality of pumped mine water.

The application of MORPHOL software resulted in the definition of a scenario space encompassing all technically and contextually feasible combinations of the system components. The resulting scenarios were subsequently organised and refined into a set of relevant business-model options, following the exclusion of configurations that, although feasible, would not generate meaningful synergies:

- Virtual power plant (VPP): This option involves the coordinated management of renewable energy generation, including solar photovoltaic and wind installations on waste heaps as well as geothermal resources. The electricity produced can either be exported to the grid or supplied directly to industrial and commercial consumers in the surrounding area [27].

- Green hydrogen facility: This option involves establishing a green hydrogen production unit that generates renewable hydrogen via the electrolysis of mine water using electricity from renewable sources. It represents an alternative pathway for utilising surplus renewable electricity, either instead of grid injection or direct on-site consumption by nearby industries.
- Eco-industrial park: This option envisages the development of an eco-industrial park as an integrated platform combining sustainable energy generation with circular-economy activities. The primary objective is to minimise waste and environmental impacts by encouraging short-distance logistics and optimising on-site material, resource, and energy flows.

  Renewable energy technologies—such as solar, wind, and geothermal systems—would supply electricity and heating and cooling services to participating enterprises [28].
- Cultural heritage and sports/recreational areas powered by green energy: This option assumes the continued production of renewable energy at the former coal mine and associated energy infrastructure, combined with their adaptive reuse for tourism, cultural heritage and recreational functions.

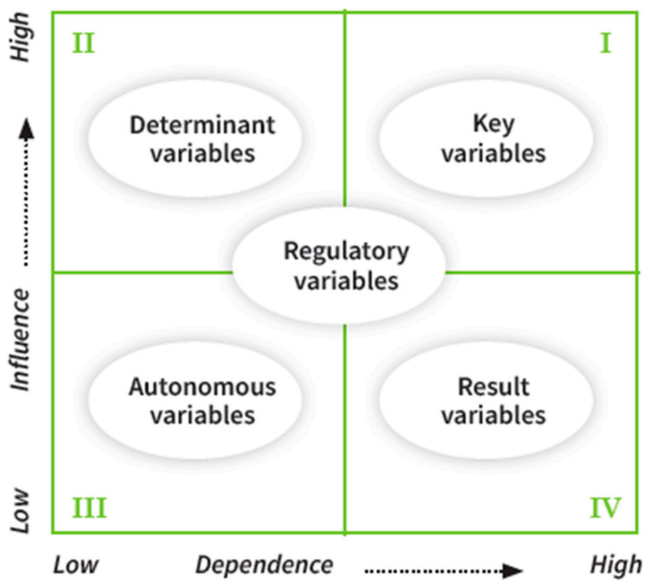

Figure 3. Grouping of technical variables by dependency and influence.

Subsequently, the evaluation was conducted using MULTIPOL (MULTIcriteria and POLicy) software, applying a set of assessment criteria derived directly from the study's objectives and aligned with policy priorities under the European Commission's 2019–2024 agenda, notably the European Green Deal.

The criteria were defined through iterative consultations involving the research team, external experts and relevant stakeholders within a participatory planning framework. This process aimed to identify shared priorities and to integrate them consistently into the subsequent stages of the analysis. The assessment criteria adopted are outlined below:

- Energy security: The ability to ensure a reliable and affordable supply across energy carriers and sources.
- Renewable resources (greening): The extent to which non-renewable resource use is reduced through the deployment of renewable energy sources, in line with technical and economic feasibility.
- Investment cost: The level of capital expenditure (CAPEX) required for implementation, with higher costs indicating more demanding investment conditions.

- Benefits: The expected economic returns and value added generated by the investment.
- Regional development: The contribution to regional competitiveness, economic prosperity and overall social and commercial impacts at the local level.
- Environment: The magnitude of environmental and ecological effects associated with the action.
- Job creation: The anticipated impact on employment generation.

On the other hand, the European Green Deal policies were:

- Climate: No net emissions of greenhouse gases (GHGs) by 2050.
- Growth: Economic growth decoupled from resource use.
- People: No person and no place left behind.

Once the criteria and policy dimensions had been defined, the scenarios were assessed against them. The outputs included policy-specific scenario rankings and a proximity (closeness) map linking scenarios to policy priorities, which helps to identify the most suitable actions while accounting for alignment across policies and the degree of convergence between individual scenarios and policy objectives.

These results also provide a robust foundation for assembling site-specific business models, which are typically configured as coherent combinations of complementary scenarios.

For each policy dimension, scenarios were assigned an average score and summarised through classification profiles that facilitate structured comparison. In addition, potential sensitivity to uncertainty and the presence of less compatible alternatives were examined through a scenario classification map based on the mean values and associated standard deviations obtained for each policy. Results are presented in Table 5.

Table 5. Result of the evaluation of scenarios related to policies.

Key Variables	Climate Policy	Growth Policy	People Policy	Mean	Standard Deviation
Virtual power plant	13.3	9.4	7.4	**10** [1]	2.5
Green hydrogen plant	**16.4** [1]	10.5	10.9	12.6	2.7
Eco-industrial park	12.5	**12.9** [1]	**15.9** [1]	13.8	1.5
Cultural heritage and sports/recreation	10	8	9.2	9.1	0.8

[1] Numbers in bold indicate the highest values achieved within each policy.

To clarify the breadth of alternatives considered, the four scenarios evaluated for Bobrek represent a site-specific down-selection from a wider scenario space developed within the POTENTIALS workflow using MICMAC–MORPHOL–MULTIPOL, which identifies 13 actions and 10 micro-actions spanning renewable generation, storage, circular-economy options, and complementary enabling measures and evaluates them against European Green Deal-aligned policy dimensions (Climate, Growth, and People), including uncertainty screening via mean–standard deviation sensitivity mapping and correspondence-based “closeness” analysis.

Because several actions in the broader portfolio are structurally tied to open-pit configurations (e.g., floating PVs, open-pit pumped hydro storage, agrophotovoltaics or fisheries) and are not applicable to an underground, densely urban mine such as Bobrek, they were excluded at the case-study filtering stage.

The retained Bobrek shortlist is intentionally limited to options that directly leverage the site’s transferable assets (mine-water resource, waste-heap space, existing grid connection and proximity to industrial/residential demand) and that can be meaningfully compared at a pre-feasibility level, resulting in the four scenarios reported in Table 3.

The eco-industrial park emerges as the most favourable option, achieving the highest scores under both the Growth and People policy dimensions and the highest overall mean value. On this basis, it represents the preferred scenario for the Bobrek site. This configuration may be further strengthened by selectively integrating elements from the second-ranked scenario, provided that they enhance overall coherence and performance.

By contrast, although the green hydrogen plant attains the highest score under the Climate policy dimension, it is associated with several significant constraints.

First, green hydrogen production is not yet economically viable without targeted subsidies, which are generally more challenging to secure than broader financial incentives aimed at stimulating territorial diversification and attracting external investment (e.g., tax relief for industrial activities or access to preferential financing from national authorities or the European Investment Bank).

Second, the feasibility of a green hydrogen facility is strongly influenced by water quality; in the Polish context, mine water is often highly contaminated, which would substantially increase the costs associated with water treatment and purification.

The virtual power plant (VPP) constitutes an optimal complement to the eco-industrial park. It achieves the highest score under the Climate policy dimension and the third-highest overall mean value, ranking immediately after the green hydrogen option.

On this basis, the selected development pathway for the Bobrek mine comprises an eco-industrial park integrated with a VPP, combining strong environmental performance with broader socio-economic benefits.

3.2. Eco-Industrial Park

The eco-industrial park is proposed as the core land-use and economic programme for the Bobrek post-mining site, providing a structured setting for low-emission industrial activity based on circular-economy processes and powered by locally available renewable energy.

In practical terms, the concept seeks to convert the former mine from a single-purpose extractive facility into a multi-tenant production area where co-located operators can exchange services and resources (e.g., shared logistics, utilities, and recovered material streams) while reducing transport demand through proximity.

Bobrek is embedded in a strongly urbanised and industrial environment (Figure 4), where historic links between the mine and nearby heavy-industry facilities have shaped both settlement patterns and daily mobility.

For this reason, redevelopment planning must explicitly consider the needs of local communities and the prospective “customers” of new site activities, including nearby companies that could use energy and/or services delivered from the repurposed mine area.

At the same time, the technical feasibility of any redevelopment pathway is conditioned by existing site constraints: the surface infrastructure includes numerous facilities in varying condition, with a substantial share likely requiring demolition, while selected historic buildings remain under conservator protection and impose functional and spatial limitations on future layouts.

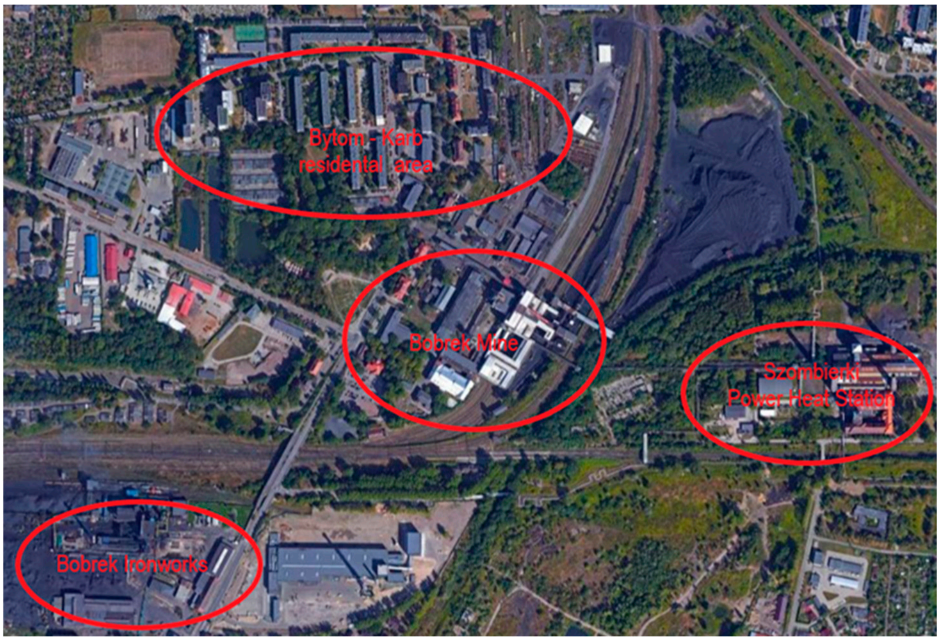

Figure 4. Surrounding industrial facilities.

From a logistics perspective, the site benefits from rail proximity and broader regional accessibility, yet it also faces a critical "last-mile" bottleneck. Rail tracks run through the mine area, and the surrounding rail system provides connections to regional nodes, while the broader Upper Silesian area benefits from proximity to major road corridors.

However, access to the mine itself is currently constrained by reliance on a single local road connection and an overburdened overpass that requires repair. These access issues are not merely operational inconveniences: they directly influence the feasibility of introducing new industrial functions and, consequently, the job-creation capacity of the proposed eco-park.

The eco-industrial park programme presented here reflects an explicit process of option screening and stakeholder discussion, during which certain candidate activities were deprioritised or discarded. In particular, proposals for biomass processing and refuse-derived fuel (RDF) preparation were flagged as socially contentious in an area characterised by residential neighbourhoods, with local stakeholders highlighting a high likelihood of public opposition to activities linked to odours and nuisance.

In contrast, e-waste recycling is viewed as comparatively more acceptable under local conditions while also offering a more straightforward pathway for industrial reuse of existing infrastructure and workforce retraining.

The eco-park is framed around three complementary proposals that can be spatially separated yet operationally integrated (Figure 5): (i) a photovoltaic (PV) end-of-life treatment line, (ii) a central transport and manoeuvring zone, and (iii) e-waste and household refrigeration-appliance recycling.

The first development area (approx. 4.72 ha) is reserved for a modular installation intended to treat ~500–2000 t/year of end-of-life PV panels. This activity aligns with circular-economy priorities and responds to the growing need for PV waste management.

Nevertheless, the analyses conducted for the Bobrek case indicate that PV-panel recycling does not presently constitute a robust standalone business line under "business-as-usual" market conditions.

In particular, the assessed variants exhibit weak financial performance (negative or marginal indicators and long payback times), mainly due to the combination of high capital requirements and substantial operating costs relative to expected revenues.

Figure 5. Spatial layout of the three functional areas of the industrial eco-park: (1) a photovoltaic (PV) end-of-life treatment line of 4.72 ha, (2) a central transport and manoeuvring zone of 2.34 ha, and (3) e-waste and household refrigeration-appliance recycling of 2.91 ha.

For this reason, the PV-recycling line is retained in the eco-park concept as a strategic, environmentally justified option. Still, its implementation would likely require either targeted external support (e.g., dedicated programmes) or a step change in process design (e.g., automation and reduced energy intensity identified as potential game-changers in the reviewed evidence base).

The second area (approx. 2.34 ha) is conceived as the operational backbone of the eco-industrial park, organising internal traffic and material handling for all planned recycling lines.

The proposed functions include heavy-vehicle circulation routes, unloading and buffer areas, container staging, parking, and an entry-control point equipped for weighing and monitoring. Notably, the concept leverages multimodal handling by linking the zone to a railway siding, thereby supporting inbound waste deliveries and outbound shipments of recovered fractions.

In the Bobrek context—where site access is currently constrained—this internal logistics node is not auxiliary but enabling: it concentrates transport impacts, improves operational safety, and strengthens the feasibility of industrial activity in a densely built-up setting.

The third area (approx. 2.91 ha) is intended to host two complementary processing lines: an e-waste line (up to ~5000 t/year) and a refrigeration-equipment line (up to ~2000 t/year). The installations are planned around automated dismantling, separation, and purification steps, with the explicit intention of repurposing existing industrial infrastructure (including the coal-processing facilities) to shorten deployment time and reduce investment risk.

In contrast to PV-panel recycling, the available economic evidence indicates that e-waste and refrigeration processing can constitute the eco-park's primary financial driver. For the assessed variants, reported performance includes high internal rates of return and relatively short payback periods, contingent on a stable supply of input material streams and viable markets for recovered fractions.

However, the option screening also identified two implementation sensitivities that must be managed from the outset: (i) the competitive landscape of e-waste recycling (which can influence margins and contracting opportunities) and (ii) the need to secure sufficient waste streams through contractual arrangements and logistics planning.

Finally, the eco-industrial park is not proposed as an isolated redevelopment element. It is designed to operate in tandem with the site's broader renewable energy strategy (VPP), which can provide low-emission electricity and heat for industrial loads, thereby strengthening environmental performance and improving the site's attractiveness to investors and operators.

In this combined model, economically self-sustaining recycling lines underpin business continuity. In contrast, environmentally necessary but economically weaker activities (such as PV-panel recycling) can be pursued opportunistically when enabling funding and/or technological conditions are met.

3.3. Virtual Power Plant (VPP)

The VPP is conceived as a decentralised energy system that aggregates multiple renewable generation units into a single, digitally monitored and coordinated platform [9].

Its primary role is to supply renewable electricity to industrial consumers in the vicinity of the closing Bobrek mine, thereby strengthening local energy self-sufficiency and supporting the planned eco-industrial park. In principle, a VPP may also integrate energy storage assets (e.g., batteries or other storage technologies) to enhance flexibility and better balance variable generation and demand; however, energy storage is not considered within the Bobrek configuration analysed in this study.

The generation portfolio is expected to be anchored in solar photovoltaics, complemented, where technically and spatially feasible, by small-scale wind turbines and geothermal energy.

Photovoltaic deployment is envisaged on reclaimed post-mining land, particularly waste-heap and stockpile areas, enabling the productive reuse of previously degraded surfaces and limiting conflicts with other land uses.

This approach is consistent with circular-economy principles and Climate policy objectives while also avoiding interference with underground mine workings. Moreover, the proximity of the local electricity distribution network supports practical grid connection and facilitates integrating PV output into the VPP operating scheme.

Within this configuration, the PV system constitutes the principal electricity-generating component of the proposed VPP. Its preliminary layout is based on the physical and technical attributes of the reclaimed surface, notably a former coal stockpile area of approximately 8 ha, which offers favourable solar exposure and suitable ground conditions for ground-mounted PV arrays (Figure 6).

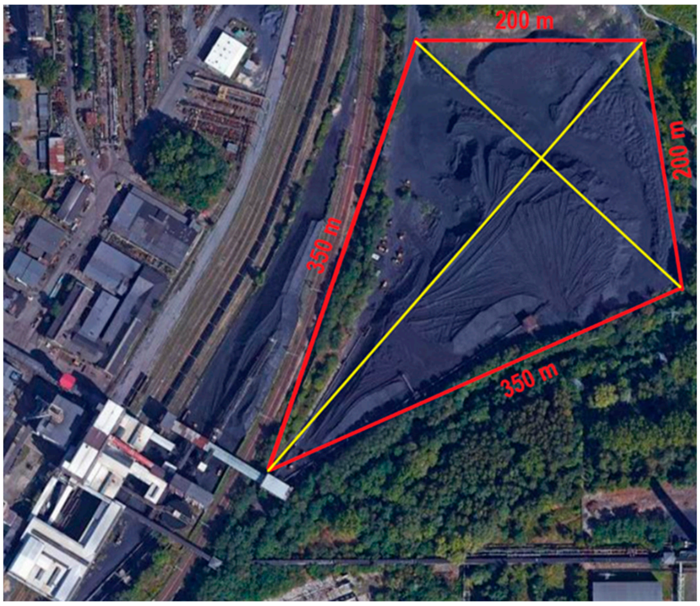

Figure 6. Location of the coal stockpile area designated for the PV installation at the Bobrek mine.

The PVGIS tool was utilised to assess the feasibility of this project. PVGIS is a reliable tool for estimating the performance of photovoltaic systems by simulating energy production, system losses, and environmental effects for a specific location. This report outlines the analysis results and evaluates the site's suitability for a PV energy installation.

The PVGIS model used for this analysis is a grid-connected crystalline silicon PV system with the characteristics shown in Figure 7.

The proposed Bobrek photovoltaic installation has a planned capacity of 8 MWp (approximately 1 MWp per hectare). It is expected to generate 8.55 GWh per year, based on an annual in-plane irradiation of 1332.61 kWh/m^2.

The array is assumed to be oriented due south with a 39° tilt. Under these conditions, total system losses are estimated at 19.65%, and the interannual variability of output is approximately 439.85 MWh.

The key design assumptions adopted for this configuration include the use of 660/665 Wp modules and an installation density of 1225 modules per hectare. For the economic context, the Fraunhofer Institute for Solar Energy Systems reports a global weighted average total installed cost for utility-scale PVs in 2024 of 639 EUR/kWp (≈0.64 EUR/Wp), with a 5th–95th percentile range of 452–1489 EUR/kWp (≈0.45–1.49 EUR/Wp). It assumes a fixed OPEX of 13.3 EUR/kW for PV systems above 1 MWp [29].

For the cost–benefit analysis, the electricity price to be applied should represent wholesale market conditions relevant to industrial consumers in Poland. The reference price is derived from the Fixing I index of the Polish Power Exchange (Towarowa Giełda Energii—TGE), which corresponds to the monthly volume-weighted average cost of the Day-Ahead Market (DAM) base-load product (TGeBase) [30].

This index reflects realised market prices across all 24 h of the day. It is widely used in national and international energy system analyses as a robust proxy for wholesale electricity prices faced by continuously operating industrial installations.

Based on monthly Fixing I prices and corresponding traded volumes for 2025, a volume-weighted annual average wholesale electricity price of 105.47 EUR/MWh is calculated. This value is adopted as the reference electricity selling price in the economic calculations. The price reflects pure wholesale energy costs and excludes transmission and distribution tariffs, system charges, taxes, levies, value-added tax and supplier margins.

As such, it is appropriate for assessing the financial performance of electricity generation and self-consumption options at the market level, in line with the objectives and scope of the cost–benefit analysis.

Table 6 summarises the deployment parameters of the PV installation at Bobrek.

Table 6. PV deployment parameters [1].

Parameter	Value
Installed capacity	8 MWp
Estimated investment (plant life: 20 years)	5.12 MEUR
Annual expenditure (staff, maintenance, and overheads)	13.3 EUR/kWp
Annual production	8.55 GWh
Energy price	105 EUR/MWh

[1] 2025 values.

A real after-tax WACC of 1.88% is applied as the discount rate. Consequently, all projected cash flows are expressed in real euros (with 2025 being the benchmark), i.e., excluding inflation effects.

This ensures internal consistency between the discount rate and the monetary streams being discounted. It also reduces reliance on long-term inflation assumptions for individual cost and revenue items, which are inherently uncertain and can introduce avoidable variability into the results over a multi-decade project horizon.

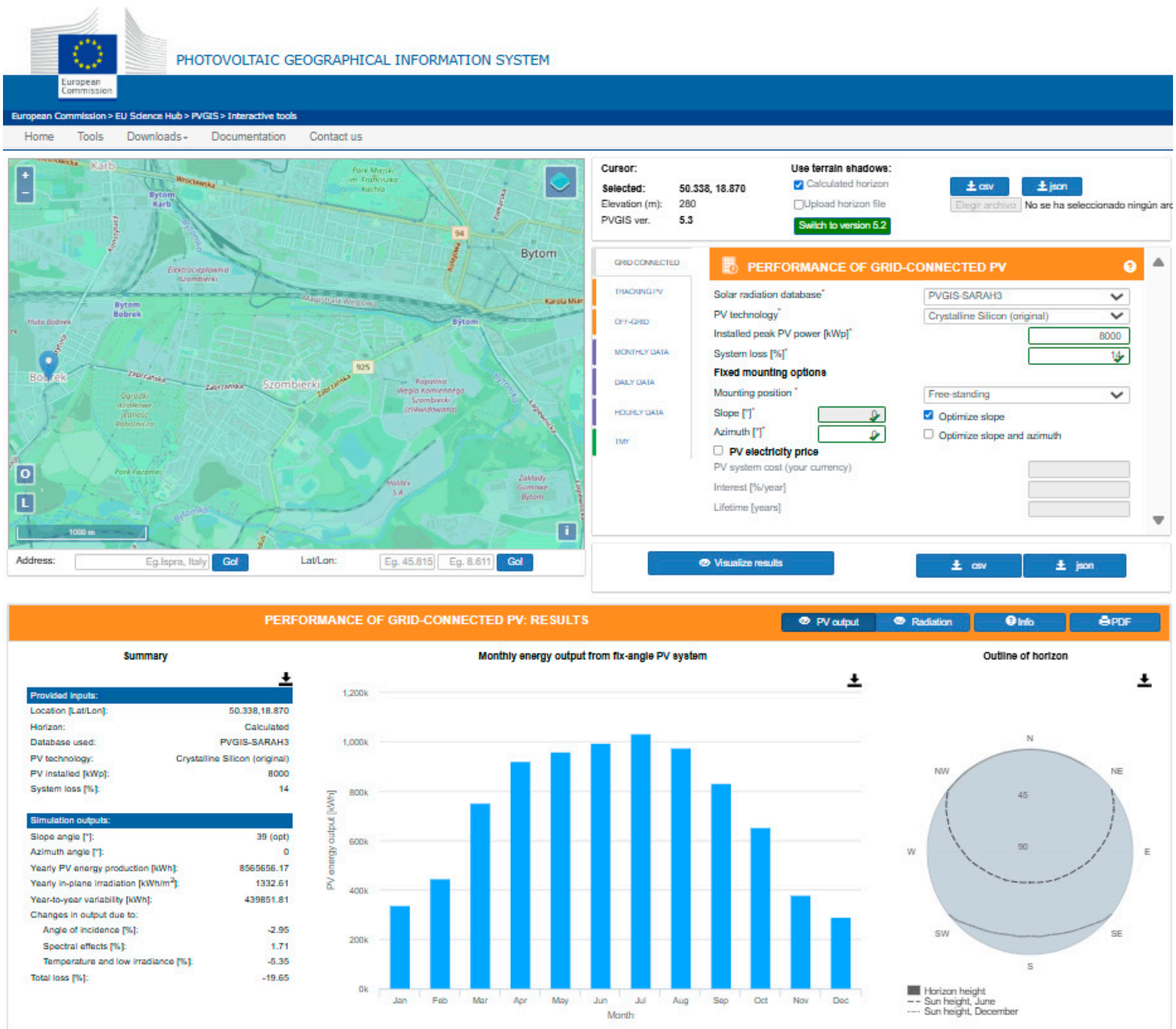

Figure 7. Estimated solar electricity generation at the Bobrek coal stockpile area.

Adopting a real framework is particularly suitable for the types of infrastructure investments considered at Bobrek, where the purpose is to evaluate the intrinsic economic performance of the proposed installations rather than outcomes driven by macroeconomic price escalation.

Discounting constant-price cash flows at a real after-tax WACC supports a transparent, methodologically robust appraisal while limiting sensitivity to uncertain future inflation paths.

Table 7 presents the cash flow calculations for this scenario.

Table 7. Cash flow calculations for the PV scenario [1].

Item	Year 0	Year 1	Year 2–20
PV installation investment	(5,120,000)		
Electricity incomes		897,750	897,750
Annual expenditure		(106,400)	(106,400)
Total	(5,120,000)	791,350	791,350

[1] Expressed in real EUR, with 2025 being the benchmark.

The net present value (NPV) would be

$$\mathrm{NPV} = -5.12 + \frac{0.79}{(1+0.0188)} + \ldots + \frac{0.79}{(1+0.0188)^{20}} = 7.97 \text{ million EUR,} \quad (1)$$

the internal rate of return (IRR) would be

$$\mathrm{IRR} = 14.41\%, \quad (2)$$

and the payback period would be

$$\mathrm{PP} = 8 \text{ years.} \quad (3)$$

After developing the sensitivity analysis of the PV scenario using the TopRank 7.5 programme [31], the results indicate that the net present value (NPV) is primarily driven by two variables, annual electricity production (MWh) and the energy price (EUR/MWh), as illustrated in Figure 8.

These two parameters exert the greatest influence on NPV variability, clearly outweighing the impact of other technical and economic inputs considered in the model. On this basis, the subsequent step of the analysis consists of representing both variables through appropriate probability distribution functions, which enables the propagation of uncertainty in a consistent manner.

This modelling choice serves as the basis for the subsequent Monte Carlo analysis, enabling the combined effect of production-level and electricity price variability on the project's economic performance to be assessed probabilistically.

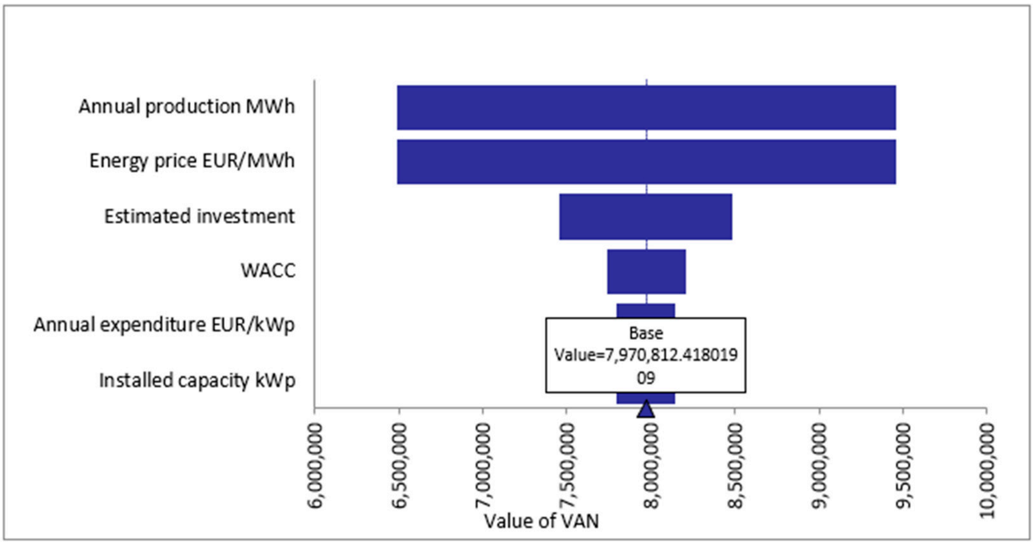

Figure 8. Tornado graph of PV scenario NPV.

To model PV electricity generation within the uncertainty analysis that is developed using the @Risk program [32], as it is bounded (cannot be negative) and typically varies within a reasonable range around a forecast, it is possible to represent it probabilistically using a Beta distribution, which is well-suited to variables that are strictly bounded and potentially asymmetric (Figure 9).

For modelling energy prices, a lognormal distribution is adopted. This choice reflects the fact that electricity prices are strictly positive, cannot take negative values, and are typically right-skewed, with occasional high-price events driven by market stress, fuel price shocks, regulatory interventions, or supply–demand imbalances.

Moreover, electricity prices are subject to multiplicative rather than additive sources of uncertainty, consistent with the lognormal distribution's statistical properties.

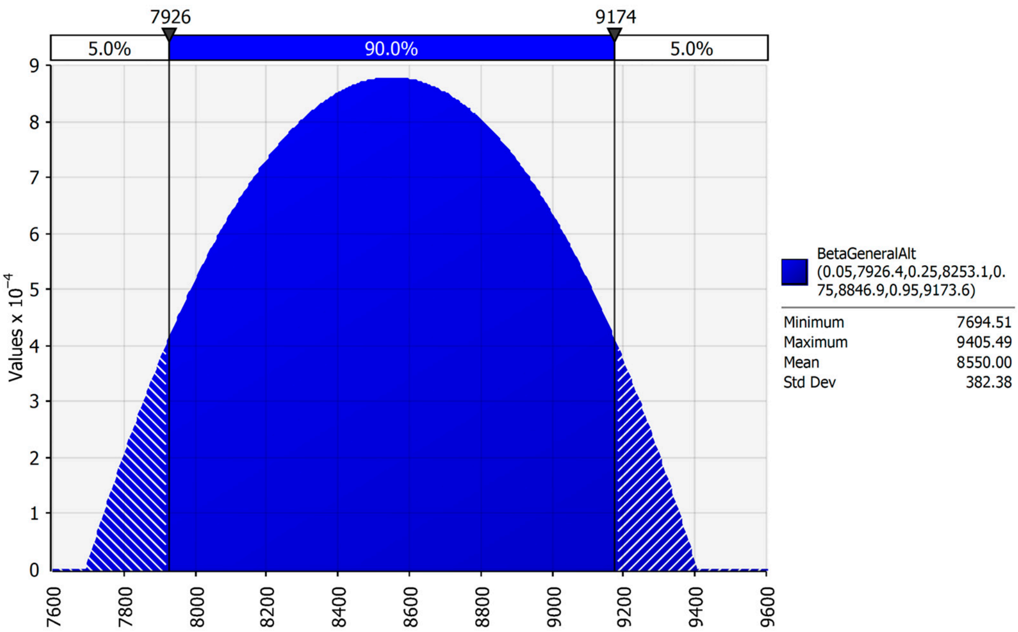

Figure 9. Beta distribution of annual electricity production.

Using a lognormal representation allows extreme but plausible price outcomes to be captured while preserving realistic central tendencies, making it well-suited for Monte Carlo-based economic analysis (Figure 10).

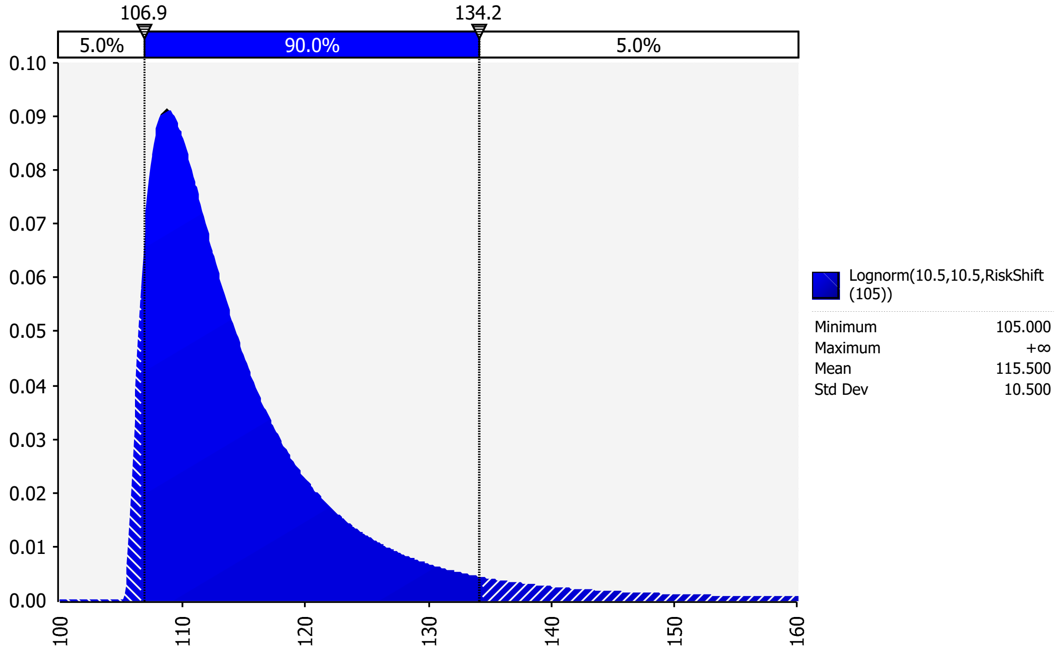

Figure 10. Lognormal distribution of energy price.

Figure 11 presents the NPV distribution obtained from the Monte Carlo simulation, illustrating the combined effect of uncertainty in the key economic drivers. The results show that plausible variations in energy prices lead to a significant upward shift in the NPV distribution, indicating a strong sensitivity of the financial outcome to market conditions. This probabilistic assessment demonstrates that across a wide range of realistic scenarios, the PV option delivers robust economic performance.

Consequently, the analysis confirms that the PV scenario is a financially attractive investment for the Bobrek mine, particularly in contexts where electricity prices remain elevated or continue to rise over time.

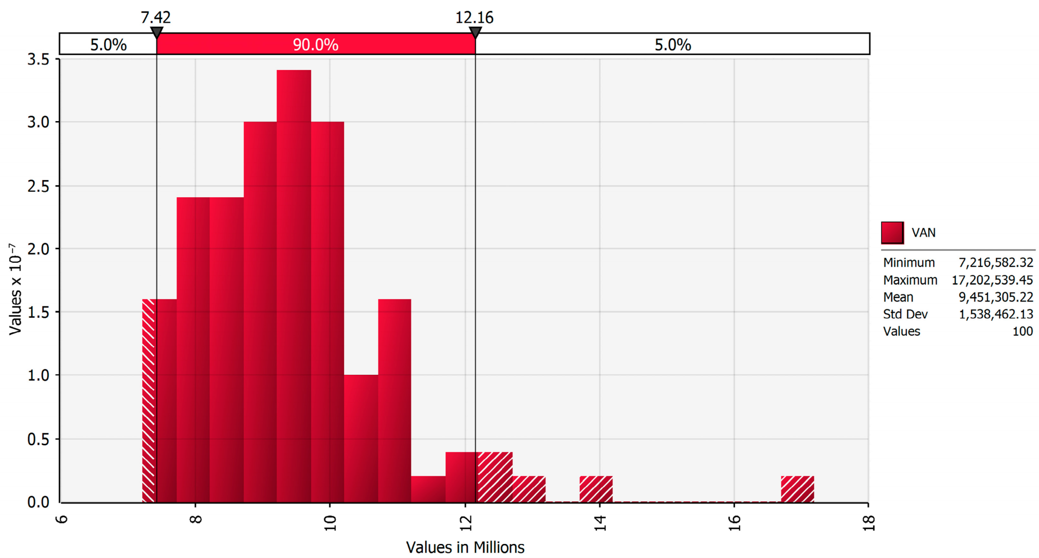

Figure 11. NPV distribution after Monte Carlo simulation.

The assessment of wind energy potential at the Bobrek site (Figure 12) focuses on evaluating local wind resource conditions, the technical feasibility of turbine deployment, and associated energy yield expectations.

To support this analysis, advanced assessment tools such as the Global Wind Atlas [33] are employed to characterise wind availability and to estimate potential capacity and performance, thereby providing a robust basis for informed decision making regarding future wind energy development.

Figure 12. Infographic of a dual-wing turbine site close to the Ignacy shaft of the Bobrek mine.

The analysis is based on two generic 4.5 MW wind turbines classified as IEC Class III, with a hub height of 100 m and a rotor diameter of 150 m. These turbines represent modern onshore designs optimised for low-wind inland conditions, rather than exposed coastal or mountainous environments.

They are used as benchmark reference models to estimate energy production and to assess the technical feasibility of wind deployment at the site. They are commonly considered suitable for inland European locations, including post-industrial and former mining areas.

The turbines are specifically designed to maximise energy capture under low-wind regimes (up to 7.5 m/s), which corresponds well with the wind conditions identified at Bobrek. In particular, the mean wind speed for the 14% windiest areas of the site is approximately 6.01 m/s (Figure 13).

Under these conditions, the expected annual electricity generation is estimated at approximately 0.27 GWh per turbine (Figure 14).

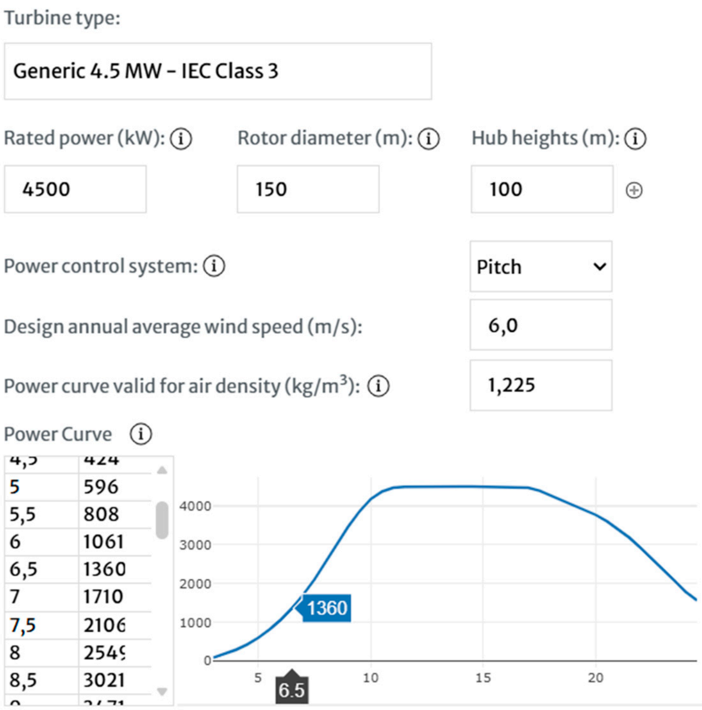

Figure 13. Wind turbines' design characteristics.

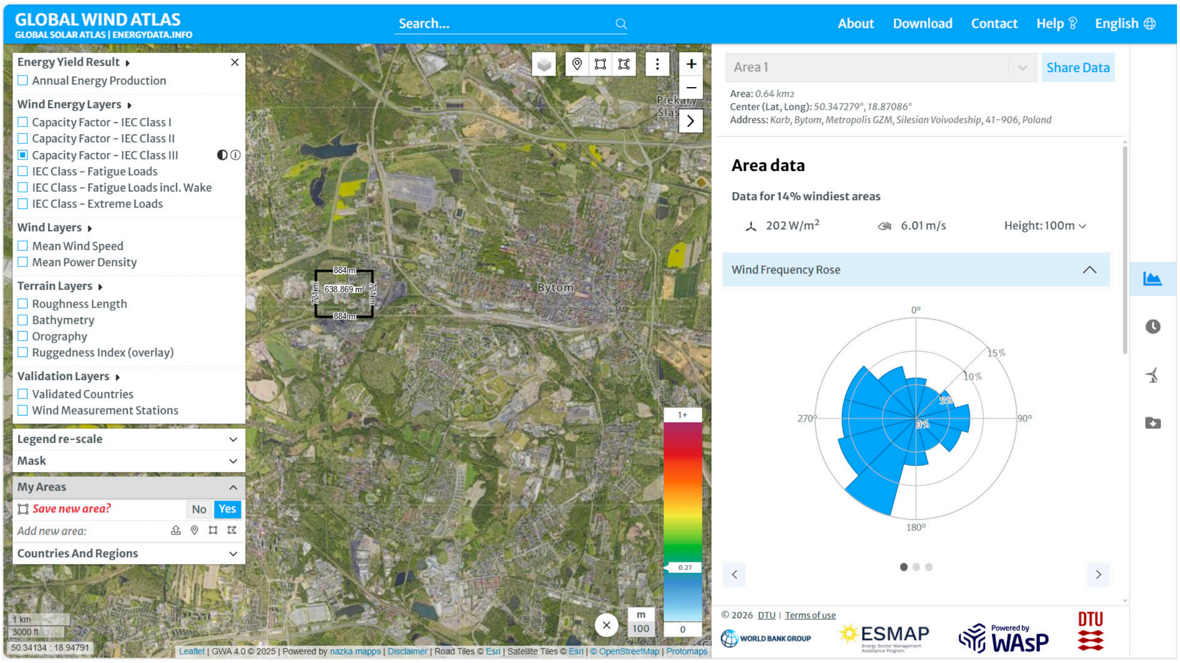

Figure 14. Estimated energy generation according to the Global Wind Atlas.

For generic onshore wind turbines (IEC Class III, ~4–5 MW class) in Europe, a reasonable current assumption is ≈850–950 EUR/kW, with ~890 EUR/kW being a representative central estimate consistent with recent International Renewable Energy Agency (IRENA) benchmarks for total installed onshore wind costs in 2024–2025 [34].

So, a reasonable single-point estimate is ~8 million EUR total CAPEX for 2 × 4.5 MW onshore turbines (excluding any site-specific grid reinforcement, permitting/compensation, or unusual civil works). Considering the OPEX, Fraunhofer ISE uses fixed OPEX for onshore wind of 39 EUR/kW per year plus a variable OPEX of 0.008 EUR/kWh (i.e., €8/MWh) [35].

Table 8 summarises the deployment parameters of the wind energy installation at Bobrek.

Table 8. Wind energy deployment parameters [1].

Parameter	Value
Installed capacity	9 MW
Estimated investment (20 years)	8 MEUR
Annual expenditure (staff, maintenance, and overheads)	39 EUR/kW
Annual production	0.54 GWh
Energy price	105 EUR/MWh

[1] 2025 values.

Table 9 presents the cash flow calculations for this scenario.

Table 9. Cash flow calculations for the wind energy deployment scenario [1].

Item	Year 0	Year 1	Year 2–20
Wind energy installation investment	(8,000,000)		
Electricity incomes		56,700	56,700
Annual expenditure		(351,000)	(351,000)
Total	(8,000,000)	(294,300)	(294,300)

[1] Expressed in real EUR, with 2025 being the benchmark.It is redundant

The net present value (NPV) would be:

$$NPV = -8.00 - \frac{0.29}{(1+0.0188)} - \ldots - \frac{0.29}{(1+0.0188)^{20}} = -12.87\ million\ EUR, \quad (4)$$

Based on these results, wind energy deployment at the Bobrek site is not economically viable under current conditions. The local wind regime yields limited annual electricity production, approximately 0.54 GWh, which is insufficient to offset the associated capital investment, even under scenarios assuming substantially higher electricity prices.

If we nonetheless conduct a sensitivity analysis, the results for the wind energy scenario indicate that the NPV is primarily driven by cost-related parameters rather than by resource variability. In particular, the variable with the greatest influence on NPV is the estimated investment cost (CAPEX), followed by annual OPEX and installed capacity.

By contrast, parameters associated with the local wind regime exhibit a comparatively minor impact on the financial outcome. This indicates that within the range of conditions analysed, even substantial variations in wind resource availability are insufficient to materially alter the economic results, and that the viability of the wind option is primarily constrained by capital intensity and fixed operating costs rather than by wind variability (Figure 15).

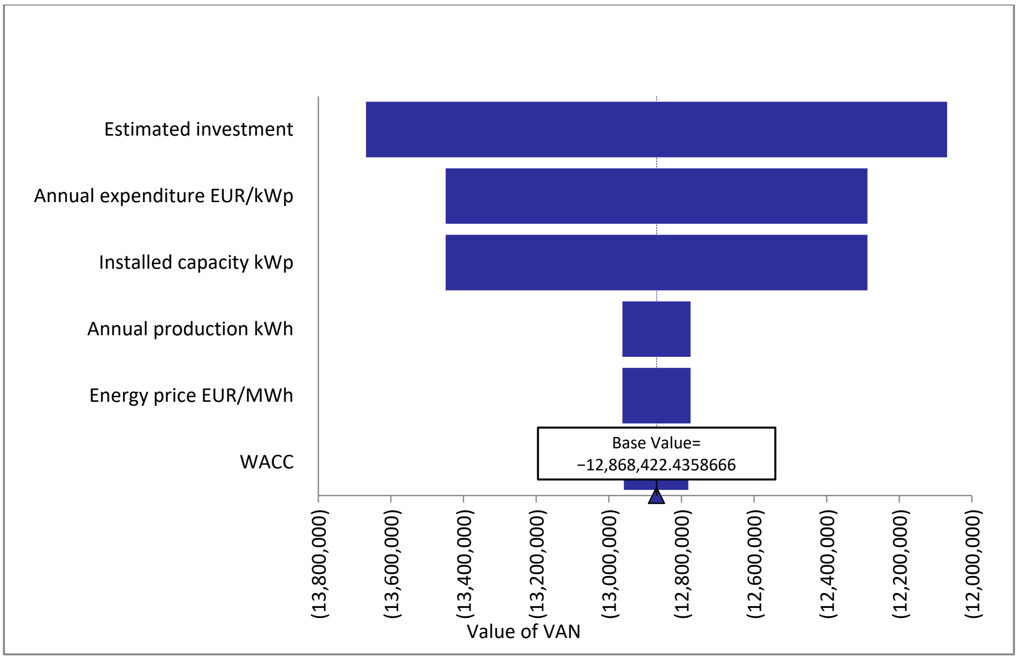

Figure 15. Tornado graph of wind energy scenario NPV.

Finally, the utilisation of mine water as a renewable geothermal heat source is identified as a key component of the VPP concept proposed for the Bobrek mine. Heat recovery from flooded underground workings provides a stable and predictable thermal resource, with mine-water temperatures of approximately 29 °C, enabling the continuous operation of high-efficiency heat pumps.

This configuration supports the development of a reliable, low-emission heat supply for the post-mining redevelopment area. The arrangement of the surface infrastructure and the main assumptions underpinning the underground circulation system are illustrated in Figure 16.

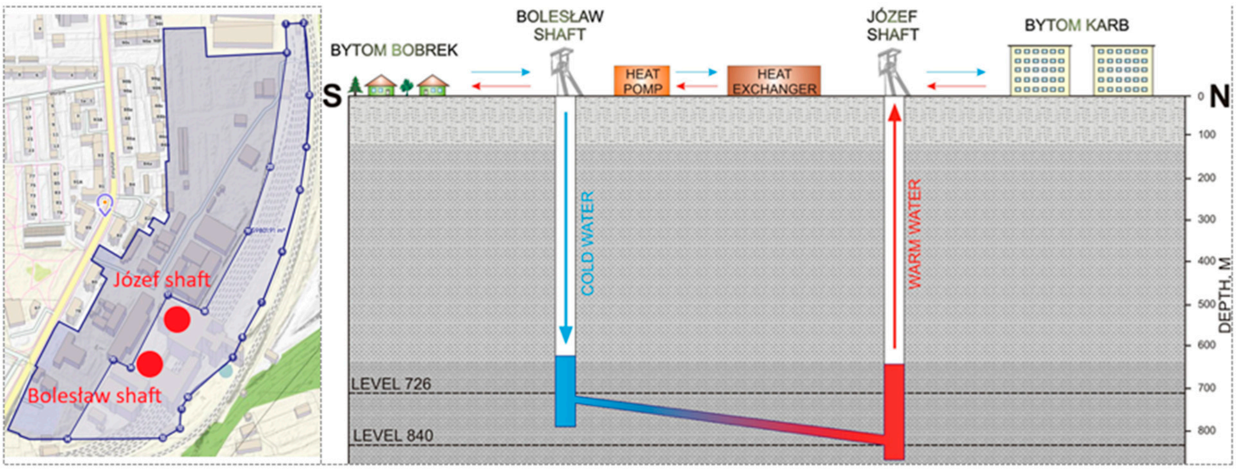

Figure 16. Surface infrastructures and mine-water circulation system.

The spatial configuration indicates that the Bobrek mine is embedded in a densely urbanised and highly industrialised setting, characterised by short transport distances, shared utility corridors and readily available technical infrastructure that can be repurposed for new functions.

This proximity of energy users and existing networks further supports the feasibility of developing a mine-water geothermal installation, enabling the recovery and distribution of heat and cold within the post-mining area.

The heating/cooling system is conceived as a closed-loop configuration linking the surface heat-pump station with the deeper sections of the mine. In this arrangement, the Józef and Bolesław shafts provide the vertical circulation route between the underground reservoir and the surface installations.

A sealed water reservoir at approximately 840 m depth acts as a thermally stable buffer, maintaining a nearly constant mine-water temperature year round. Mine water is lifted to the surface, where heat is recovered via heat exchangers and heat pumps, and is then reinjected into the underground level.

This closed-circuit design eliminates any discharge of mine water to the environment and supports the long-term thermal stability and sustainability of the system.

Based on an average mine-water flow rate of approximately 5 m^3/min and the daily pumping regimes at the different underground levels, the proposed configuration enables the deployment of a geothermal heating and cooling plant with an estimated capacity of around 9 MWth.

Preliminary district-heating assessments for the area indicate a total heat supply of approximately 11.5 MWhth and a cool supply of roughly 6 MWhcool. The system is designed to serve buildings in the Bytom–Karb residential district and facilities within the Bobrek post-mining area, thereby supporting the provision of low-emission thermal energy to local users.

Published European benchmarks for mine-water geothermal applications delivered via large-scale heat-pump plants suggest specific investment costs typically in the order of 0.5–1.1 million EUR per MWth, with variability driven primarily by plant scale, heat-source characteristics and site-specific integration requirements.

In particular, Pieper et al. report indicative ranges of 0.5–0.8 million EUR per MWth (2014) and 0.8–1.1 million EUR per MWth (2017) for Danish district-heating heat-pump projects with capacities of up to approximately 10 MW [18]. On this basis, and to remain within a defensible yet cautious assumption set, a CAPEX value of 0.8 million EUR per MWth is adopted for the subsequent calculations.

Regarding the OPEX, for European low-temperature geothermal heat schemes coupled with large heat pumps (a good proxy for mine-water geothermal district-heating/cooling plants), the Joint Research Centre (JRC) techno-economic dataset reports fixed operations and maintenance (O&M) of ~29,000 EUR·$MWth^{-1}$·$year^{-1}$ for 2020, with an indicative uncertainty band of ~20,000–40,000 EUR·$MWth^{-1}$·$year^{-1}$ [36].

For district heating, a reasonable "Europe-wide" central assumption consistent with these benchmarks for heat/cooling price is ~100 EUR/MWhth for heat and ~40 EUR/MWhcool for cooling [37].

Table 10 summarises the deployment parameters of the geothermal energy installation at Bobrek.

Table 10. Geothermal energy deployment parameters [1].

Parameter	Value
Installed capacity	9 MWth
Estimated investment (plant life: 20 years)	7.2 MEUR
Annual expenditure	29 EUR/kWth
Annual production heating	11.5 GWhth
Annual production cooling	6 GWhcool
Energy price heating	100 EUR/MWhth
Energy price cooling	40 EUR/MWhcool

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[1] 2025 values.

Table 11 presents the cash flow calculations for this scenario.

Table 11. Cash flow calculations for the geothermal scenario [1].

Item	Year 0	Year 1	Year 2–20
Geothermal installation investment	(7,200,000)		
Electricity incomes		1,390,000	1,390,000
Annual expenditure		(261,000)	(261,000)
Total	(7,200,000)	1,129,000	1,129,000

[1] Expressed in real EUR, with 2025 being the benchmark.

The net present value (NPV) would be

$$NPV = -7.20 + \frac{1.13}{(1 + 0.0188)} + \ldots + \frac{1.13}{(1 + 0.0188)^{20}} = 11.48\ million\ EUR, \quad (5)$$

the internal rate of return (IRR) would be

$$IRR = 14.66\%, \quad (6)$$

and the payback period would be

$$PP = 8 \text{ years}. \quad (7)$$

Finally, in the geothermal energy scenario, the financial indicators are almost identical to those obtained for the PV scenario. The sensitivity analysis indicates that NPV is primarily driven by annual heating energy production and the heating energy price, which clearly dominate the results' variability. By contrast, the variables associated with cooling energy production and cooling energy prices have negligible effects on the NPV.

This finding reflects the limited contribution of cooling revenues in the analysed configuration. It confirms that the economic performance of the geothermal option is mainly determined by the scale and valuation of the heat supply (Figure 17).

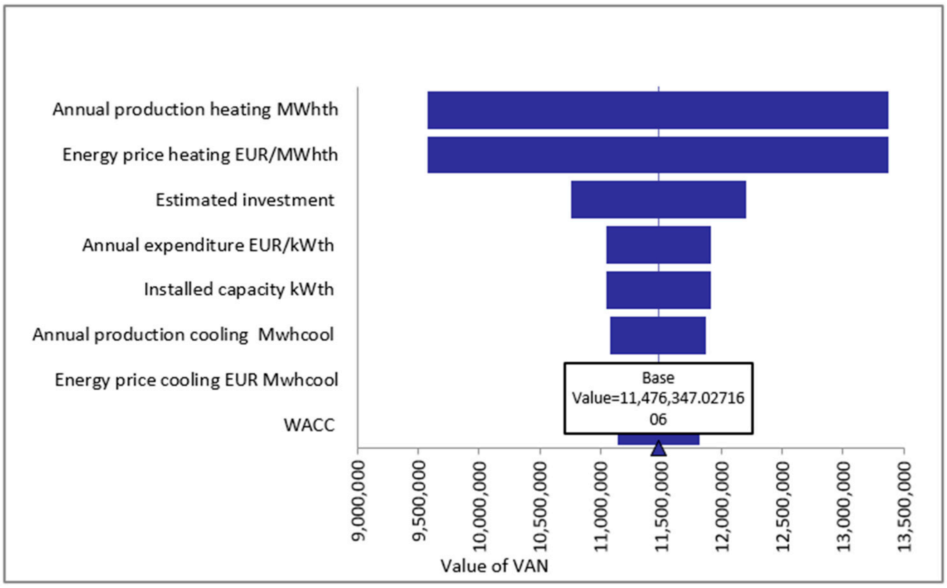

Figure 17. Tornado graph of wind energy scenario NPV.

4. Discussion

This study demonstrates how a post-mining site can be repositioned from a single-purpose extractive landscape into a multi-functional industrial platform by combining (i) an eco-industrial park anchored in circular-economy activities and (ii) a virtual power plant (VPP) that consolidates local renewable energy assets and supports low-emission operations.

Beyond the selection of individual technologies, the main contribution is the integrated redevelopment logic: local energy generation is treated not as an isolated "add-on" but as an enabling service that increases the feasibility and resilience of new economic functions at the former mine site.

The proposed eco-industrial park concept directly responds to the spatial and socio-territorial realities of the Bobrek mine. The site is embedded in a dense urban–industrial fabric, where redevelopment must be compatible with neighbouring communities and where potential "customers" (industrial and municipal) for energy and services exist in proximity.

The eco-industrial park model, multi-tenant, operationally integrated, and structured around shared logistics and utilities, offers a practical mechanism to reduce transport demand, concentrate impacts, and operationalise circular-economy principles. Importantly, the multicriteria screening process also highlighted that not all decarbonisation pathways are equally appropriate at the site level: options that may score well conceptually can be constrained by local conditions (e.g., water-quality requirements for hydrogen or social acceptability issues for certain waste-processing activities).

The selected pathway illustrates a broader implication for mine closure planning: redevelopment should prioritise options that remain feasible under local technical, social, and infrastructural constraints, rather than those that are only attractive in generic transition narratives.

The VPP complements this logic by providing a coordinating layer for decentralised generation assets and by strengthening local energy self-sufficiency. For a multi-tenant eco-park, this is particularly relevant: energy can become a shared service, potentially improving operating economics, reducing exposure to market volatility for some users, and supporting the low-emission profile of circular-economy processes.

Even where individual assets (e.g., small wind turbines) are not dominant contributors, the aggregation and management function remains valuable, especially when the redevelopment is conceived as a portfolio rather than a single investment.

The techno-economic assessments indicate that photovoltaic (PV) and mine-water geothermal deployments are the most robust energy-related components in the Bobrek configuration, whereas the wind scenario is not economically attractive under the local resource conditions and assumptions used in this study.

The PV scenario shows favourable financial performance within the assumed boundary conditions, with a payback period of approximately 8 years. The sensitivity and uncertainty analyses reinforce that the economic outcome is primarily driven by two factors: annual electricity production and the selling price of electricity.

This has practical implications for implementation. First, accurate resource estimation and conservative performance assumptions are critical at the feasibility stage, particularly for post-mining land where geotechnical conditions, shading, and layout constraints can influence output. Second, financial risk management becomes central because revenue is price-exposed.

In practice, this supports phased development and/or the pursuit of revenue-stabilisation mechanisms (e.g., long-term offtake arrangements, internal consumption by eco-park tenants, or hybrid sales strategies), rather than relying entirely on spot market conditions.

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The mine-water geothermal scenario (designed around shafts and a closed-loop configuration) also yields a payback period of approximately 8 years, with financial indicators comparable to those of the PV case.

The sensitivity analysis identifies the heating component—specifically heat production and heat price—as the dominant drivers of project viability, while the cooling revenue plays a secondary role. This highlights an important implementation implication: mine-water geothermal is most transferable and bankable when it can be linked to stable, sufficiently large heat demand (district heating, industrial heat use, or clustered public buildings) with predictable tariff structures.

In addition, the chosen closed-loop approach offers an environmental co-benefit by enabling discharge minimisation, which is a relevant consideration in post-mining water-management strategies.

In contrast, the wind scenario is not economically viable in the analysed configuration, primarily because of the limited annual electricity generation under the assumed local wind conditions.

In practical terms, the result illustrates a wider point about transferability: wind deployment on post-mining sites is highly sensitive to local wind regimes and site-specific constraints (including geotechnical conditions on reclaimed ground and social acceptance in urbanised settings). For Bobrek, wind is better interpreted as an optional or demonstration-scale component rather than a core economic pillar.

Overall, the renewable energy results point to a portfolio approach that emphasises PV as a scalable electricity source on reclaimed land and mine-water geothermal as a stable thermal backbone to secure heat customers.

This combination can also reduce the intermittency-related limitations of PV when the overall redevelopment is evaluated at the system level (eco-park loads + energy supply), rather than as isolated energy projects.

A key outcome of the eco-industrial park assessment is that the different circular-economy lines play different roles in the redevelopment logic. The PV end-of-life treatment line is retained as a strategic and environmentally justified option, but the analysis indicates that it is not currently a robust standalone business line under "business-as-usual" market conditions. The primary reasons are the combination of high capital requirements and substantial operating costs relative to expected revenues, resulting in negative or marginal financial indicators and long payback periods.

The implication is not that PV-panel recycling is irrelevant; on the contrary, it aligns strongly with circular-economy priorities, but it may require targeted external support and/or technological and operational step changes (notably automation and reduced energy intensity) to become investable under realistic conditions.

From an implementation perspective, this supports a phased strategy: PV recycling may be positioned as a second-stage investment once the eco-park is operational, market conditions evolve, or programme-based co-financing can be secured.

By contrast, the e-waste and household refrigeration-appliance recycling lines emerge as candidates for the economic "anchor" of the eco-park, given their comparatively strong financial performance indicators (high internal rates of return and short payback periods in the analysed variants).

This is a critical finding for Just Transition planning because it suggests a plausible mechanism for sustained economic activity at the site beyond energy generation alone.

At the same time, this study also clarifies the main risk condition: the success of these lines depends on reliable waste-stream supply and market access for recovered fractions, with competition and the ability to secure input streams identified as decisive sensitivity factors. In other words, circular-economy activity is not automatically guaranteed by infrastructure availability; it requires commercial structuring (supply contracts, logistics planning, and market positioning) comparable in importance to technical feasibility.

A major implication of the Bobrek case is that redevelopment feasibility can be constrained as much by "enabling infrastructure" and social acceptance as by the technical parameters of energy systems.

The analysis identifies a critical last-mile bottleneck: although the site benefits from rail proximity and broader regional accessibility, direct access is constrained by reliance on a single local road connection and an overburdened overpass that requires repair.

This affects more than operational convenience; it directly influences whether new industrial functions can be introduced and, by extension, the eco-park's job-creation capacity. In this sense, the internal logistics node is not an auxiliary element but a core condition for implementation, as it aggregates transport impacts, enhances operational safety, and supports multimodal handling via the railway siding.

For transferability, this underscores that post-mining redevelopment should evaluate logistics as an early-stage "go/no-go" variable, not as a downstream design detail.

The stakeholder screening process further demonstrates that social licence is site-specific. Candidate activities such as biomass processing and refuse-derived fuel (RDF) preparation were flagged as socially contentious due to the risk of odours and nuisance in an area characterised by residential neighbourhoods.

Conversely, e-waste recycling is viewed as comparatively more acceptable and as offering clearer pathways for industrial reuse of existing infrastructure and workforce retraining. The broader implication is that technology portfolios for mine closure must be aligned with local community tolerance thresholds, particularly in dense urban settings, and should be iteratively refined through stakeholder dialogue rather than finalised exclusively through technical optimisation.

The Bobrek redevelopment pathway is transferable primarily as an approach, whereas the individual technological and circular-economy components are transferable to different degrees and only under clearly defined boundary conditions.

Two complementary dimensions of transferability can be distinguished. First, the methodological transferability is high; the combined use of structured variable analysis, scenario building, multicriteria screening, and subsequent techno-economic assessment constitutes a replicable workflow that can be applied to other post-mining sites. This is particularly relevant because mine-closure contexts are heterogeneous: the same portfolio of technology "candidates" will not be feasible everywhere, yet the same decision logic can be reused to identify locally robust options and to transparently justify why certain pathways are discarded. Second, the transferability of the solutions themselves depends on site-specific constraints and enabling conditions, which determine whether the selected configuration can be replicated with comparable performance and risk.

Regarding the solutions, photovoltaic deployment is broadly transferable to end-of-life mines that offer reclaimed land or suitable brownfield areas (and/or rooftops), with feasible grid connection and manageable geotechnical constraints.

Its value as a scalable electricity source is strongest where a substantial share of local consumption (e.g., industrial tenants and municipal services) can be supplied, thereby reducing exposure to electricity price volatility.

Mine-water geothermal is transferable where mine-water resources can be accessed and managed reliably and where heat consumers exist within a feasible connection distance; its viability increases when redevelopment can be integrated into a district-heating context or an industrial heat-demand cluster.

In addition, site-specific water chemistry and the applicable legal and permitting frameworks for other mine-water uses, such as green hydrogen production, should be addressed early, as these factors can materially affect both costs and implementability.

Wind deployment is only weakly transferable as a default component and instead requires strict site-by-site validation, because adequate wind resource, sufficient spatial buffers, geotechnical suitability of reclaimed ground, and social acceptance are all necessary preconditions; where these are not met, wind should be treated as a non-core or optional element rather than a central pillar.

Finally, circular-economy recycling lines are transferable where there is reliable access to relevant waste streams, adequate logistics and permitting conditions, repurposable industrial buildings and infrastructure, and market access for recovered fractions. The Bobrek case suggests that e-waste and refrigeration processing can act as robust anchors when these conditions are satisfied, whereas PV-panel recycling may require programme support and/or substantial process innovation to become investable in the near term.

The Bobrek case points to a broader replication insight: integrated eco-park concepts are most promising in regions where post-mining sites are not isolated but embedded in wider industrial and municipal systems (energy demand, waste flows, and transport infrastructure). In more remote contexts, the same approach may remain valid, but the technology mix and the viable business models may shift.

Beyond Bobrek, the GreenJOBS project applied the same screening logic to two further post-mining contexts in Western and Central Europe, thereby helping contextualise transferability.

In Asturias (Aller–Barredo–Figaredo), mine-water geothermal energy is already implemented in phased form and connected to urban heat users, with pumped mine water providing a stable low-temperature resource and supporting the progressive expansion of district heating/cooling; the regional portfolio also considers PV on reclaimed waste heaps and renewable-powered hydrogen as an additional pathway.

In Slovenia (Velenje), the transition challenge is shaped by the presence of a large, established district-heating system supplying approximately 40,000 customers; geothermal integration is framed as a strategic replacement for coal-based heat, while the extensive subsidence-lake system creates a distinct opportunity for floating PV alongside conventional PV siting.

Compared with these cases, Bobrek is a compact, densely urban underground mine site, where the most immediate advantage is the proximity of diverse electricity and heat consumers and the feasibility of coupling distributed renewables with circular-economy activities, hence the emphasis on an eco-industrial park whose loads and generators can be coordinated through a VPP layer.

The presented results should be interpreted as a pre-feasibility-level assessment that supports strategic decision making and prioritisation. Several limitations follow from this scope. First, financial outcomes depend on key assumptions (prices, production estimates, and cost structures), and while sensitivity and uncertainty analyses were used for the energy scenarios, comparable uncertainty treatment has not been fully developed across all eco-park business lines. Second, implementation feasibility will ultimately require detailed engineering design, permitting assessments, environmental liability evaluations, and confirmation of grid and transport upgrades. Third, the value of an integrated eco-park plus VPP pathway depends on governance and commercial structuring, tenant attraction, contractual arrangements for waste-stream supply, and long-term offtake, issues that are not fully resolved in a techno-economic scenario analysis.

Addressing these aspects in follow-up work would strengthen the bankability and practical implementation readiness of the proposed redevelopment.

Socio-economic risks—such as skills mismatches in workforce transition, uneven distribution of local benefits, and community acceptance of new energy infrastructure—may affect implementation and require dedicated stakeholder engagement and Just Transition measures beyond the scope of this pre-feasibility study.

Finally, for clarity, the environmental benefit claims in this paper are interpreted against a conservative counterfactual that assumes minimal post-closure management (site safety and monitoring, basic water management where required, and land stewardship), without new energy conversion or circular-economy activities.

Within this concept-stage assessment, a full lifecycle study of the eco-industrial park is outside the scope, as it would require detailed, site-specific inventories (e.g., future waste-stream volumes, logistics, process yields, substitution and allocation assumptions).

Nevertheless, an indicative, screening-level comparison can be provided by expressing the proposed energy services as avoided emissions through substitution. For electricity, the annual PV generation reported in Section 3 (8.55 GWh/year) can be translated into avoided operational global warming potential (GWP) using the national electricity emission factor for final consumption (553 kg CO_2/MWh for 2024).

For heat, the mine-water geothermal option (11.5 GWhth/year) can be expressed as avoided combustion emissions using International Plant Protection Convention (IPCC) default factors for natural gas, net of the electricity required by the heat pump over a conservative Coefficient of Performance (COP) range.

This high-level comparison indicates that the redevelopment pathway provides a material climate benefit already from the energy components alone, while the recycling business lines are expected to further reduce upstream burdens (through material recovery and refrigerant management) but require a dedicated life cycle assessment (LCA) once reliable mass-flow and market data are available.

5. Conclusions

This paper proposes and assesses an integrated redevelopment pathway for the end-of-life Bobrek coal mine that combines an eco-industrial park with a virtual power plant (VPP), positioning closure as a starting point for low-emission industrial activity and circular-economy value creation.

The techno-economic analyses indicate that (i) photovoltaic deployment and (ii) mine-water geothermal heating/cooling are the most robust renewable energy components in the proposed portfolio, each yielding a payback period of approximately eight years under the study assumptions, while (iii) the analysed wind option is not economically viable under local resource conditions.

For the eco-industrial park, the assessment distinguishes between circular-economy lines that are strategically relevant and those that can serve as financial anchors. PV-panel end-of-life treatment is environmentally justified but not a robust standalone business under business-as-usual conditions, whereas e-waste and household refrigeration-appliance recycling show strong investment potential provided that a stable waste-stream supply and markets for recovered fractions can be secured.

Transferability of the approach lies in the replicable workflow (scenario building, multicriteria screening, and techno-economic assessment), while transferability of specific solutions depends on local boundary conditions—especially heat-demand proximity for geothermal, reliable logistics and waste-stream access for recycling lines, and site-validated wind resources where wind is considered.

Overall, the results support integrated, place-based mine closure planning that treats energy, the circular economy, logistics, and social acceptance as interdependent determinants of a credible Just Transition pathway.

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Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
RFCS	Research Fund for Coal and Steel
VPP	Virtual Power Plant
SCADA	Supervisory Control and Data Acquisition
WEEE	Waste Electrical and Electronic Equipment
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
DCF	Discounted Cash Flow
NPV	Net Present Value
IRR	Internal Rate of Return
PP	Payback Period
AMM	Abandoned Mine Methane
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
WACC	Weighted Average Cost of Capital
GIG	Central Mining Institute
HUNOSA	Hulleras del Norte, S.A.
UNIOVI	University of Oviedo
RDF	Refuse-Derived Fuel
PPA	Power Purchasing Agreement
IRENA	International Renewable Energy Agency

TGE	Towarowa Giełda Energii
DAM	Day-Ahead Market
JRC	Joint Research Centre
O&M	Operations and Maintenance
GWP	Global Warming Potential
IPPC	International Plant Protection Convention
COP	Coefficient of Performance
LCA	Life Cycle Assessment

Appendix A

Table A1. Description of the 38 technical variables used for Bobrek.

N°	Key Variable	Short Definition
(i) Technical variables adopted for the underground part of the hard coal mine (16)		
1	Depth of mine	The variable determines the maximum depth of the mine (deepest exploitation level/workings), which conditions feasible underground re-use options.
2	Ground movement	The variable determines the possible rock-mass movement influencing underground workings/shafts and surface infrastructure after closure (with or without flooding).
3	Geological singularities of the mine	The variable refers to the presence/absence of geological disturbances (e.g., faults and impermeable strata) that affect containment and re-use potential.
4	Methane surface emissions	The variable determines expected concentration/flow of Abandoned Mine Methane emissions and their potential management or recovery implications.
5	Methane resources	The variable reflects the potential quantity/availability of methane resources in the coal measures relevant for post-mining utilisation.
6	Coal spontaneous ignition	The variable determines the likelihood of spontaneous combustion affecting underground safety and feasibility of re-use measures.
7	Volume of pumped water	The variable determines the volume/flow of mine water that can be abstracted (or is required to be pumped), affecting geothermal and water-management options.
8	Pumped water chemistry/quality	The variable characterises mine-water quality (major ions, salinity, and pollutants) relevant to utilisation pathways and treatment needs.
9	Hazardous substances in mine water	The variable determines the presence of hazardous constituents that constrain discharge, reuse, or require additional treatment.
10	Depth of the shafts	The variable determines shaft depth and hence technical feasibility/cost of shaft-based uses (access, ventilation, lifting, geothermal, etc.).
11	Shaft diameter	The variable determines shaft cross-section, conditioning technical feasibility of retrofitting, conveyance, and installation options.
12	Shaft technical condition	The variable determines the structural integrity of shafts and their suitability for continued use after closure.
13	Function/status of shaft	The variable defines whether shafts remain operational and for what purpose, influencing feasible redevelopment options.
14	Water inflow	The variable determines inflow rates to the mine workings, affecting pumping requirements and geothermal/water-based options.
15	Pumped water temperature	The variable determines mine-water temperature, which conditions the recoverable low-temperature geothermal potential.
16	Flooding status of the mine	The variable determines whether workings are flooded (and to what extent), influencing accessibility, safety and geothermal feasibility.
(ii) Technical variables adopted for the surface part of the hard coal mine (8)		
17	Coal-processing-plant capacity	The variable determines the capacity/scale and repurposing potential of existing surface processing infrastructure (or constraints for its removal).
18	Area of waste heap	The variable determines available waste-heap surface area, influencing siting potential and reclamation scope.

19	Height of waste heap	The variable determines heap elevation and potential constraints/opportunities (stability, visibility, and wind exposure).
20	Angle of slopes of waste heap	The variable determines slope gradients affecting stability, safety and constructability for any surface installation.
21	Geometry of waste heap	The variable describes heap shape/layout relevant to land-use efficiency and engineering constraints.
22	Material type deposited on waste heap	The variable characterises deposited material (granulometry and composition) influencing stability, drainage and reclamation measures.
23	Geotechnical stability of waste heap	The variable determines slope stability and geotechnical risk, conditioning allowable redevelopment intensity.
24	Status of reclamation of waste heap	The variable determines the extent of prior reclamation (cover, vegetation, and drainage), affecting readiness and cost of redevelopment.
(iii) Technical variables adopted for the synergy of the mine with its surroundings (14)		
25	Neighbourhood density	The variable characterises the density of nearby residential/urban fabric, influencing acceptability, siting constraints and demand proximity.
26	Existence of historic or singular buildings	The variable refers to protected/heritage structures that may constrain redevelopment or enable cultural/educational re-use components.
27	Land-use restrictions	The variable captures zoning, planning and environmental restrictions limiting allowable land uses and facility siting.
28	Connection capacity of mine to grid	The variable determines available electrical grid connection capacity/voltage at or near the site, affecting renewable integration potential.
29	Available space for new technologies/projects	The variable determines the physically available brownfield area for new installations after closure and remediation constraints.
30	Character of local area	The variable describes the dominant land-use character (residential/industrial/mixed), influencing compatibility of proposed activities.
31	Neighbourhood and proximity to the nearest urban/industry	The variable determines proximity to potential energy/material consumers and workforce catchment.
32	Access/proximity to road infrastructure	The variable determines road accessibility relevant for logistics of construction, waste-stream supply and product shipment.
33	Access/proximity to railway infrastructure	The variable determines rail accessibility relevant for bulk logistics and industrial-scale material movements.
34	Access/proximity to water reservoir	The variable determines proximity to surface water reservoirs relevant for water management and specific technology needs.
35	Access/proximity to gas pipeline network connections	The variable determines proximity to gas network connections relevant for energy-system integration options.
36	Proximity to industries	The variable determines proximity to industrial partners/offtakers enabling industrial symbiosis and shared utility solutions.
37	Electro-intensive industries	The variable captures the presence of high-electricity-demand industries nearby, which is relevant for local balancing/offtake potential.
38	Constant-energy-consumption industries	The variable captures nearby baseload demand that can stabilise utilisation of local generation and flexibility services.

Appendix B

This appendix provides a simplified example to illustrate the scoring and weighting procedure used in the MULTIPOL assessment. Consider two hypothetical scenarios (S1 and S2) evaluated against three criteria (C1–C3) under one policy axis (e.g., Climate policy). Experts assign a performance score on a bounded ordinal scale (e.g., 0–20, where 0 =

very poor and 20 = excellent). Criterion weights reflect relative importance and sum to 1 within the policy axis:

- Step A1: Define criteria and weights (example):
  a. C1: GHG mitigation potential, with weight $w_1 = 0.50$.
  b. C2: Renewable energy integration, with weight $w_2 = 0.30$.
  c. C3: Resource circularity contribution, with weight $w_3 = 0.20$ with $w_1 + w_2 + w_3 = 1.00$.
- Step A2: Score each scenario against each criterion (example):
  a. Scenario S1: (C1 = 16), (C2 = 12), (C3 = 10).
  b. Scenario S2: (C1 = 14), (C2 = 16), (C3 = 15).
- Step A3: Compute weighted policy score.

  The weighted score for a scenario under the policy axis is computed as:

$$Score(S) = \sum_{j=1}^{3} w_j \cdot s_j(S)$$

  Thus:

- Score(S1) = 0.50×16 + 0.30×12 + 0.20×10 = 8.0 + 3.6 + 2.0 = 13.6.
- Score(S2) = 0.50×14 + 0.30×16 + 0.20×15 = 7.0 + 4.8 + 3.0 = 14.8.

In this illustrative case, S2 performs better under the selected policy axis because its stronger performance in renewable integration and circularity offsets a slightly lower GHG score. In the full assessment, the same procedure is applied across all criteria and policy axes; scenario profiles are then reported as weighted scores by criterion and aggregated by policy axis to support transparent comparison and selection.

Where multiple experts provide scores, the criterion score (S) is obtained by aggregating expert ratings (e.g., mean/median), consistent with the expert elicitation approach adopted in this study.

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