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PLANNING POST-MINING REUSE OF UNDERGROUND WORKINGS: A STRUCTURED REVIEW AND STAGE-GATED DECISION FRAMEWORK

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Abstract: Underground mine closure is usually treated as a process of decommissioning, sealing, flooding and long-term environmental control. However, selected underground workings and infrastructure may retain substantial technical value. This structured critical review synthesises European evidence on post-mining underground reuse, supplemented by selected international cases, and develops a stage-gated framework for deciding when continued access is justified. The review distinguishes mature operational uses from emerging and site-specific concepts and identifies the conditions associated with durable reuse. The proposed framework separates non-compensatory safety acceptance from comparative suitability. Legal status and liability are verified first, followed by exclusion screening, use-case matching, critical-hazard assessment, life-cycle and governance evaluation, staged validation and adaptive monitoring. Seven gates determine whether a site should proceed, be redirected, reassessed or closed. The analysis shows that reuse is most credible when considered before irreversible closure, when preservation is limited to a defined and maintainable core, and when long-term demand, ownership, financing and second-closure responsibility are explicit. Post-mining reuse should therefore be treated as a selective closure option rather than a universal alternative to conventional closure.

Keywords*: *mine closure, post-mining reuse, underground space, circular economy, just transition

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1. INTRODUCTION

Mine closure is increasingly an infrastructure and regional-development challenge rather than a terminal engineering event. Classical closure research emphasises decommissioning, environmental control, financial assurance and responsible transfer of long-term liabilities, while later work also highlights the social consequences and wider sustainability performance of mining regions (Laurence 2006; Peck and Sinding 2009; Bainton and Holcombe 2018; Tost et al. 2018). In underground mines, this challenge extends to shafts, chambers, transport routes, drainage, ventilation, power, communication and monitoring systems that may be lost after closure. The reuse question is therefore not simply *"Whether such infrastructure can be kept open?"*, but *"Whether retaining selected assets creates more durable value than conventional closure?"*. This question is becoming increasingly relevant as the European mining sector undergoes a substantial transition. However, no harmonised European inventory consistently separates underground from surface mines by operating status and closure horizon. The JRC coal-transition baseline and Eurostat trend data document regional exposure and historically low coal production and consumption, but they should not be interpreted as counts of underground mines (Alves Dias et al., 2018; Eurostat, 2025; Rueda Cantuche et al., 2025). Consequently, the scale and timing of underground reuse opportunities must be established from verified site-level records rather than sector-wide enterprise or employment totals.

For reuse planning, however, a key limitation is that many underground assets are approaching closure while RMIS and EGDI still emphasise mineral occurrence, commodity and broad site status rather than reuse readiness (RMIS 2021; EGDI 2026). This is increasingly important as selected workings are considered for research, testing, education, heritage, mine-water energy and other secondary functions. Yet the relevant circular-economy principle is preservation of useful function, not preservation for its own sake. Post-mining studies show that reuse must be assessed against environmental, social and land-use alternatives and against the risk of transferring new liabilities to future owners or communities (Mert 2019; Cui et al. 2020a; 2020b; Lèbre et al. 2020; Pavloudakis et al. 2020; Keenan and Holcombe 2021; Pactwa et al. 2021a; 2021b). Reuse should therefore be compared with a technically credible conventional-closure counterfactual over the same time horizon. The main post-mining underground reuse pathways considered in this review are summarised in Fig. 1.

A recent decision-support system ranks post-closure reutilisation alternatives by integrating technical and socioeconomic constraints (Deutschmann et al. 2026). This advances transparent comparison of feasible options, but ranking alone does not determine whether legal, access and decision-critical safety conditions are acceptable. The present review therefore treats criteria-based ranking as a later comparative step within a gate sequence that first establishes admissibility.

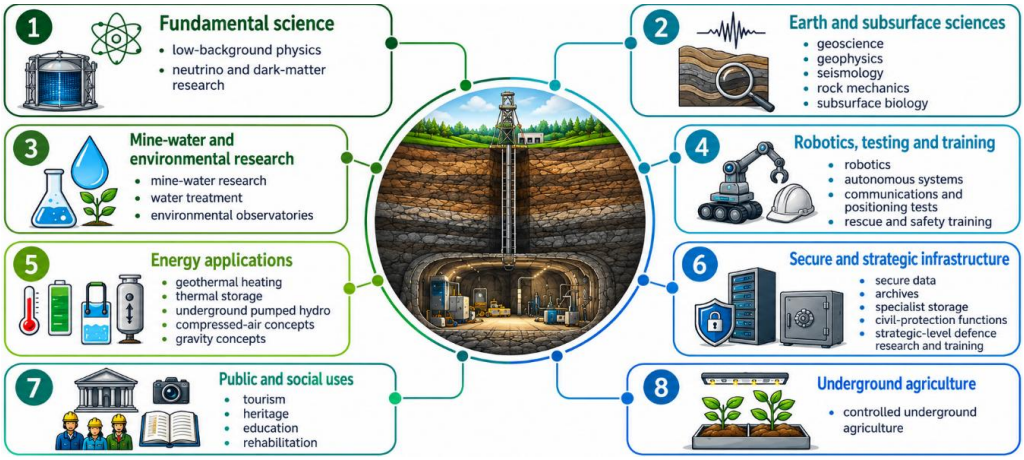


Fig. 1. Main classes of potential post-mining underground reuse considered in the review

Existing pathways differ sharply in maturity. Low-background laboratories, teaching and test mines, heritage attractions and selected mine-water heating systems have operational precedents. Robotics, environmental observatories and multi-user engineering facilities are emerging, whereas underground pumped hydropower, gravity storage and related energy concepts remain more site-specific. Reviews and case studies of closed-mine energy applications show that geometry, hydrogeology, shaft or reservoir condition and the surface energy system are decisive (Menéndez et al. 2019a; 2019b; Lyu et al. 2022; Krzemień et al. 2023). Feasibility studies, funded demonstrations and operational services should therefore be distinguished as separate maturity states.

This distinction is important because preserving access creates immediate obligations. Pumping, ventilation, hoisting, inspections, emergency readiness and support maintenance continue after production stops, while a prospective user may arrive years later or not at all. Reuse screening must therefore begin early enough to influence closure design, while rejecting weak scenarios before temporary preservation becomes an unfunded liability. The objective is not to maximise conversions, but to identify sites where continued access provides demonstrable long-term value.

Accordingly, this article addresses three questions: (1) Which post-mining underground reuse pathways have credible operational evidence? (2) How can technical suitability, critical risk, life-cycle feasibility and governance be integrated without allowing benefits to compensate for unacceptable hazards? (3) Which conditions distinguish durable facilities from stalled projects? Building on earlier work on second-life infrastructure and the conversion of workings into underground laboratories, the principal contribution is a compact stage-gated framework linking legal status, exclusion screening, use-case matching, critical-hazard acceptance, comparative sustainability and governance, staged validation and adaptive monitoring (Konieczna-Fuławka et al. 2023). The

methodological advancement lies in the decision architecture rather than in claiming that each constituent assessment tool is new. The framework sequence has been presented in Fig. 2. This sequence defines when comparative ranking is legitimate and when missing evidence or unacceptable risk must stop it.

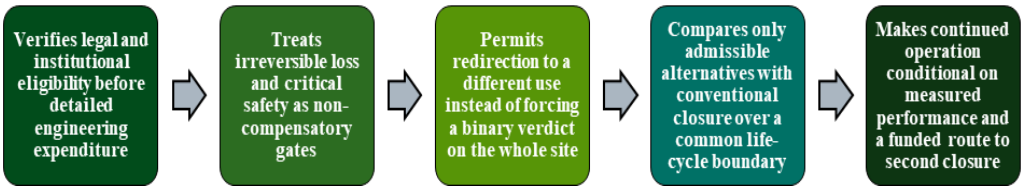


Fig. 2. Steps for determining when comparative ranking is justified and when missing evidence or unacceptable risk should preclude it

2. REVIEW METHODOLOGY

The study was designed as a structured critical review. PRISMA 2020 and PRISMA-ScR principles guided source identification, eligibility and transparent reporting (Tricco et al. 2018; Page et al. 2021). The work is not presented as a formal systematic review because the early exploratory searches and backward and forward citation checks were not logged at record level. The geographic focus was Europe. Non-European cases were retained only when they supplied transferable evidence on conversion, governance, risk control or long-term operation.

The search covered records available from database inception to 17 July 2026 and was last updated in July 2026. Searches covered Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar and were supplemented by European and national repositories, project databases and official facility, operator and regulator sources. Syntax was adapted to each platform. Representative combinations were: (“underground mine” OR “closed mine” OR “abandoned mine”) AND (reuse OR repurpos* OR “post-mining”) AND (laborator* OR test* OR robotic* OR tourism OR heritage OR “mine water” OR geothermal OR “energy storage”); and (“mine closure” OR post-closure) AND (risk OR suitability OR governance OR liability OR “life cycle” OR decision*). Sources were eligible when they addressed underground assets, reuse options, closure decisions, site selection, hazards, governance, costs or documented outcomes. Screening progressed from titles, abstracts or executive summaries to full texts. Sources were retained if they supported an extraction field or verified a time-sensitive site status. Exclusions covered duplicates, promotional material, surface-only applications without transferable underground evidence, concepts lacking a defined underground setting and unverifiable status claims. As the exploratory phase was not logged at record level, initial and deduplicated counts cannot be reliably reconstructed;

therefore, no PRISMA flow is reported. The final auditable evidence base comprises 124 sources: 78 scholarly publications and 46 regulatory, standards, project, database, operator or institutional sources. Searching stopped when further queries yielded no new reuse pathways, decision domains or independently verifiable case outcomes. Each case was assessed for site status, underground function, geometry, access, utilities, flooding, reuse, hazards, governance, financing and outcomes. Quantitative values were retained only with explicit sources, units and reference years; incompatible database definitions remained separate. Time-sensitive claims were cross-checked against the latest available operator, regulator or project sources. Evidence was synthesised across asset condition, use requirements, hazards, life-cycle sustainability, governance and operational maturity (Fig. 3).

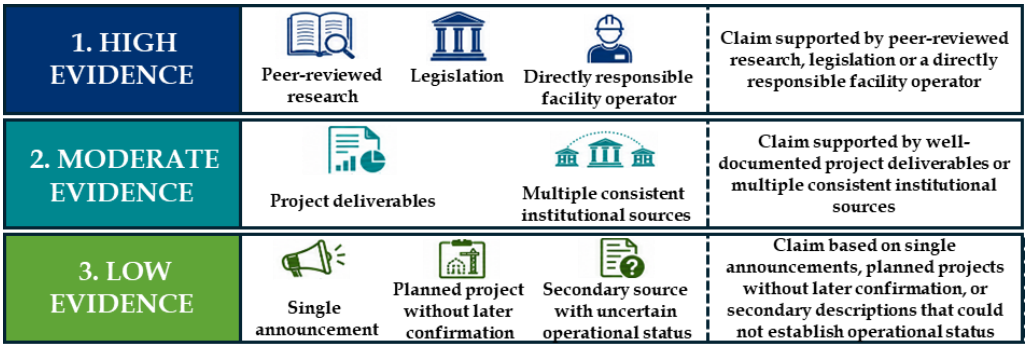


Fig. 3. Claim-specific evidence-confidence logic used to distinguish technical evidence, institutional documentation and unverified announcements

Claim confidence was assessed using four criteria: relevance to the claim, independence from the promoted project, recency for time-sensitive information, and source authority or traceability. Peer-reviewed studies were preferred for technical performance. Current operator, regulator or project sources were used to verify access, commissioning, closure status and governance. Evidence was assessed across six domains:

- Asset condition and access;
- Requirements of the intended use;
- Underground hazards;
- Life-cycle sustainability;
- Governance and liability;
- Operational maturity.

At the same time Pathways were classified as:

- Mature: Full-scale or service operation beyond a one-off demonstration, with an identifiable operator and maintained access;

- Emerging: Commissioned pilots, repeated controlled tests or limited multi-user services, but insufficient evidence of lasting, transferable operation;
- Speculative: Models, concepts, feasibility studies or announcements without verified commissioning;
- Where evidence differed between sites, the more cautious classification was used, with site-specific exceptions noted.

Robotics and multi-user testing were classified as emerging because repeated tests and facility services exist, while long-term operating models remain limited. Pumped-hydro and gravity concepts remained speculative where evidence was limited to feasibility studies or uncommissioned pilots.

3. LANDSCAPE OF POST-MINING UNDERGROUND REUSE

3.1. EUROPEAN INFORMATION SYSTEMS AND NETWORKS

European initiatives address complementary parts of the reuse problem rather than providing one decision-ready inventory. RMIS and EGDI support continental identification of locations, commodities and broad status, while REMINDNET and PoMHaZ add mining-district governance and post-mining hazard perspectives (RMIS 2021; EGDI 2026; PoMHaZ Consortium 2026; REMINDNET 2026). Technology projects have explored underwater or robotic access to difficult deposits and flooded workings (European Commission 2018; 2020; EIT RawMaterials 2022; European Commission 2023). Other programmes address regional business models, heritage and energy reuse (POTENTIALS Consortium 2023; Underground4Value 2023; ATLANTIS Consortium 2024; GreenJOBS Consortium 2025). BSUIN, the EUL project and the European Underground Laboratories Association focus more directly on transnational access, services and user cooperation (BSUIN Consortium 2020; EUL Project 2022; European Underground Laboratories Association 2026). The result is a discovery ecosystem, not yet a harmonised reuse-readiness system. A practical reuse inventory should therefore link public spatial information with owner-controlled technical records. A minimum screening layer would contain verified status, planned closure date, depth, principal access, flooding state and broad infrastructure availability. Restricted layers could hold support condition, ventilation, emergency routes, utilities, hazard zones, ownership, liability and commercially sensitive information. Such a system should accelerate screening, not automatically rank sites.

3.2. OPERATIONAL MATURITY AND REPRESENTATIVE FACILITIES

The evidence-based maturity classification of the principal reuse pathways is summarised in Table 1.

Table 1. Operational maturity and representative facilities

Reuse pathway	Maturity	Representative evidence	Principal conditions
Research/teaching	Mature	Callio Lab; Reiche Zeche; SURF; active-mine laboratories	Safe access, stable institutional mandate, recurring users, OPEX coverage
Multi-user testing / robotics / observatories	Emerging	Commissioned robotic campaigns and multi-user test services; limited evidence of sustained cross-site operation	Suitable geometry, recoverable test areas, data quality, operational support
Heritage/tourism/ education	Mature	Wieliczka and other professionally operated visitor routes	Evacuation capacity, conservation, public access, stable demand
Mine-water heating/cooling	Mature	Heerlen Minewater; other operating flooded-mine heat schemes	Hydrochemistry, local demand, network integration
Pumped hydro / gravity storage	Speculative	Feasibility studies, announced pilots and projects without independently verified commissioning	Geometry, water conditions, shaft condition, operator and finance continuity
Secure infrastructure/ agriculture	Speculative	Site-specific concepts	Security, environmental control, regulation, business case

Underground laboratories show that successful reuse depends not only on physical conditions but also on the institutional model. Deep-underground science has long used active and former mines, transport tunnels and purpose-built rock laboratories (Bettini 2014). Callio Lab is a relevant transition case. The former Pyhäsalmi mine supports physics, geoscience, robotics and technology testing while access and infrastructure evolve after mining (Joutsenvaara et al. 2021; Joutsenvaara et al. 2024; Callio Lab 2026). Its scientific value is supported by measurements of natural radiation and low-background conditions as well as detector-development work (Gostilo et al. 2020; Pohuliai et al. 2020; Polaczek-Grelik et al. 2020; Trzaska et al. 2022). Reiche Zeche represents a different model based on a stable university teaching and research mandate (TU Bergakademie Freiberg 2026).

The wider range of underground facilities also shows that depth alone does not determine research value. SNOLAB and Boulby use active-mine access, while SURF occupies a former mine. Gran Sasso, Äspö, Mont Terri and Hagerbach operate as dedicated research or test environments, whereas Canfranc and Modane use tunnel infrastructure. Across these models, shielding, access and environmental control determine the suitability for specialised research (Duncan et al., 2010; Piquemal, 2012; Bandac et al. 2017; Äspö Hard Rock Laboratory 2026; Boulby Underground Laboratory 2026;

Canfranc Underground Laboratory 2026; Gran Sasso National Laboratory 2026; Hagerbach Test Gallery 2026; Modane Underground Laboratory 2026; Mont Terri Project 2026; Sanford Underground Research Facility 2026; SNOLAB 2026).

Energy reuse follows a similarly site-specific logic. Mine-water heating and cooling have the strongest operational record among energy-related options. The Heerlen system shows how flooded workings can provide a thermal resource when they are linked to local demand and surface networks (Verhoeven et al. 2014; Walls et al. 2021).

Experience from Pyhäsalmi also highlights the value of diversification. The proposed LAGUNA/LBNO neutrino programme was not constructed, yet other scientific and industrial uses of Callio continued (Trzaska et al. 2011; Tonazzo 2015; Trzaska et al. 2018). This broader multi-user approach is supported by international cooperation through the Polish UL-PL initiative and DULIA-Bio activities, which complement the earlier BSUIN/EUL networking model (Polish Underground Laboratory Consortium 2025; DULIA-Bio 2026).

4. INTEGRATED ASSESSMENT AND STAGE-GATED FRAMEWORK

4.1. USE-CASE MATCHING AND NON-COMPENSATORY RISK

Reuse assessment should start from the intended function because requirements are not interchangeable. Low-background research needs sufficient overburden and controlled radiological conditions, robotics testing needs suitable geometry and recoverable areas while tourism requires public access and evacuation. In turn, mine-water energy depends on hydrogeology and nearby demand. Initial screening should therefore verify ownership, liability, access and closure obligations before detailed technical work (ICMM 2019; Konieczna-Fuławka et al. 2023; Pagouni et al. 2024). Broader post-mining frameworks also show the value of clear land-use definitions, stakeholder input and spatially explicit criteria (Kivinen 2017; Kaźmierczak et al. 2017; Kivinen et al. 2018; Morales and de Vries 2021; Arratia-Solar et al. 2022; Worden et al. 2024).

Technical and regional alternatives can be compared with GIS, AHP, fuzzy methods, TOPSIS or outranking approaches, but method choice and uncertainty must be explicit. Post-mining applications range from mined-land suitability and outranking to fuzzy, network and geospatial models (Soltanmohammadi et al. 2008; 2009; 2010; Behzadian et al. 2012; Roy and Słowiński 2013; Masoumi et al. 2014; Mardani et al. 2015; Haddad and Sanders 2018; Bakhtavar et al. 2019; Amaro et al. 2021; Amirshenava and Osanloo 2021; Amaro et al. 2022; Amirshenava and Osanloo 2022; Mhlongo 2023; Servou et al. 2023). Deutschmann et al. (2026) provide a criteria-based ranking that integrates technical and socioeconomic constraints for post-closure mine reutilisation. In the present framework, this type of model is positioned within G4: it compares alternatives only after G0–G3 have confirmed that the site, use and residual critical

risks are admissible. These tools are useful for transparent comparison, but only after non-negotiable legal and safety constraints have been satisfied. A preliminary weighted suitability score can be expressed as:

$$S_i = \sum_{j=1}^{m} w_j r_{ij}, \quad \sum_{j=1}^{m} w_j = 1, \tag{1}$$

where r_{ij} is the normalised performance of alternative i against criterion j and w_j is its documented weight.

The score is comparative, dataset-dependent and should be sensitivity-tested. It is not a safety certificate. Critical hazard k for alternative i must instead satisfy a separate acceptance condition $R_{(k,i)} \leq R_{\mathrm{acc}(k)}$ after credited controls. Only alternatives passing every critical threshold may enter broader feasibility ranking. It is important that G4 weights should be set through a documented process, such as expert consultation or stakeholder workshops. Safety thresholds must remain separate from weights. Analysts should report the base weights, test equal weights and alternative scenarios, and identify rank changes. An option is robust only if it ranks highly across plausible scenarios; otherwise, competing alternatives should be presented.

Underground hazards are coupled because failures of ventilation, power, pumping or communication may disable several barriers at once. Risk identification in underground facilities should therefore consider multiple interacting hazards and their potential consequences rather than treating individual hazards in isolation (Pytel et al. 2020). Legacy-workings studies emphasise geological and mining controls on storage or reuse, while mine-water literature highlights persistent hydrochemical liabilities (Acharya and Kharel 2020; Wang et al. 2021; Colas et al. 2023; 2025). Rock-mass assessment should combine inherited classifications with explicit treatment of uncertainty rather than relying on one deterministic safety factor (Barton et al. 1974; Hoek and Brown 1997; Phoon and Kulhawy 1999a; 1999b; Griffiths and Fenton 2004). HAZID, FMEA and bow-tie methods can structure critical scenarios (de Ruijter and Guldenmund 2016), while ISO 31000, IEC 60812 and IEC 31010 provide general principles for risk assessment and failure analysis (IEC 2018; ISO 2018; IEC 2019). Site-specific acceptance thresholds must nevertheless be defined by the responsible owner, operator and regulator.

4.2. STAGE-GATED DECISION LOGIC

The proposed decision process contains seven gates (G0–G6). Each gate description with minimum evidence and permitted outcome are presented in Fig. 4 and Table 2.

The sequence deliberately front-loads low-cost evidence and prevents premature design investment. The seven gates, their minimum evidence requirements and permitted outcomes are summarised in Table 2.

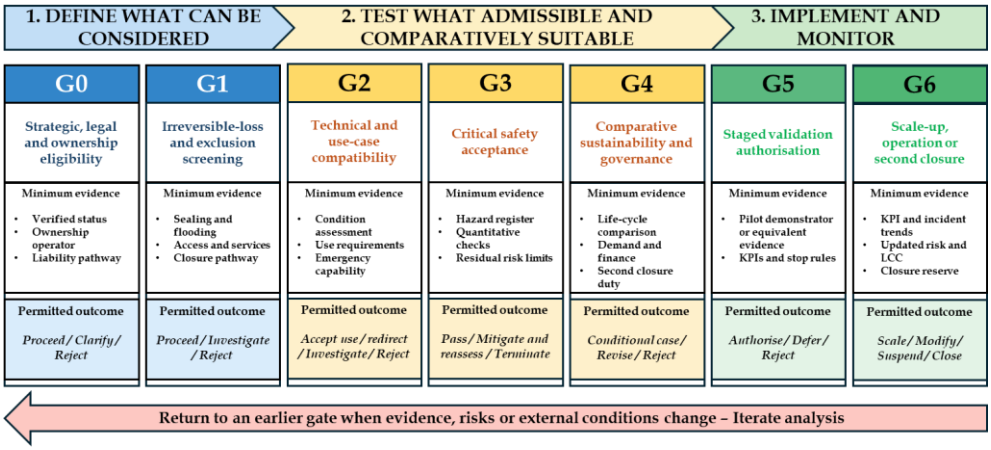


Fig. 4. Stage-gated decision framework for sustainable reuse of closed and closing underground mines

Table 2. Formal decision gates in the proposed framework

Gate	Decision	Minimum evidence	Permitted outcome
G0	Strategic, legal and ownership eligibility	Verified site status; ownership, operator and liability pathway	Proceed/clarify/reject
G1	Irreversible-loss and exclusion screening	Sealing, flooding, access and irreversible infrastructure-loss record	Proceed/investigate/ reject
G2	Technical and use-case compatibility	Condition assessment; use-requirement matrix; preliminary emergency concept	Accept use/redirect/ investigate/reject
G3	Critical safety acceptance	Hazard register; quantitative checks; pre-agreed residual-risk thresholds	Pass/mitigate and reassess/terminate
G4	Comparative sustainability and governance	Life-cycle cost and environment; demand; finance; second-closure responsibility	Conditional business case/revise/reject
G5	Staged validation authorisation	Pilot, demonstrator or equivalent staged validation selected for site constraints; KPIs; stop rules; contingency and exit strategy	Authorise/defer/reject
G6	Scale-up, operation or second closure	KPI and incident trends; updated risk and life-cycle analysis; closure reserve	Scale/modify/suspend/ close

The proposed staged approach assumes that G0 checks whether reuse is legally and institutionally feasible. G1 identifies closure conflicts and reasons to stop early. G2 checks whether the site suits the intended use. G3 requires all critical risks to meet agreed safety criteria before G4 compares costs, environmental impacts, demand and governance with conventional closure. G5 allows staged testing, with clear stop criteria and an exit plan where reversal is impossible. G6 permits continued operation or expansion only while

performance remains acceptable and funds for eventual closure are secured (Głowacki and Milczarek 2013). **Nevertheless, failure at a gate does not always eliminate a site.** A public heritage concept may fail G2 because evacuation capacity is insufficient, while a restricted research use may remain feasible in a retained core. A dry-access concept may fail after flooding, while mine-water energy becomes more attractive. The feedback loop therefore allows a site to return to an earlier stage when new evidence changes the use case, provided that legal and safety requirements remain satisfied.

5. LESSONS FROM REPRESENTATIVE CASES

Table 3 summarises lessons from representative operating, stalled and discontinued initiatives. The cases show that geology alone does not determine successful reuse. Long-term viability also depends on retained access, institutional responsibility, stable demand, secure financing and the capacity to fund maintenance and eventual closure.

Table 3. Transferable lessons from representative operational and stalled initiatives

Site/initiative	Status	Dominant challenge	Transferable lesson
Callio Lab, Finland	Operating research/testing during mine transition	Changing access and fixed infrastructure cost	Diversify users; retain only a maintainable core
SURF/ Homestake, USA	Mature former-mine research facility	High long-term maintenance and infrastructure costs	Clear ownership and durable multi-source funding
Heerlen Minewater, Netherlands	Operational heating/cooling network	Network integration and water management	Match underground resource to nearby demand
LAGUNA/LBNO at Pyhäsalmi	Large detector not constructed; other Callio uses continued (Trzaska et al. 2011; Tonazzo 2015)	Dependence on a single megaproject	Preserve alternative functions and avoid single-user dependence
GraviStore at Pyhäsalmi	Announced pilot not documented as commissioned before developer liquidation (Tisheva 2024; Green 2026)	Technology-provider and finance continuity	Treat announcements as proposals until commissioning and operator continuity are verified
Reiche Zeche, Germany	Operating teaching and research mine	Continuous maintenance and safety management	A stable institutional mandate can sustain selective preservation
Wieliczka, Poland	Mature heritage/visitor operation (Wieliczka Salt Mine 2026)	Conservation, evacuation and visitor safety	Professional operation and stable demand are decisive

Project history further shows that failure of one concept does not necessarily eliminate the value of a site. At Homestake, the original DUSEL pathway was discontinued, but the site was later successfully developed as SURF (Cho 2011; Sanford Underground Research Facility 2026). Similarly, LAGUNA/LBNO was not constructed at Pyhäsalmi, while other Callio activities continued (Trzaska et al. 2011; Tonazzo 2015; Trzaska et al. 2018). In contrast, the GraviStore pilot was announced but not documented as commissioned before the developer entered liquidation (Tisheva 2024; Green 2026). Wieliczka provides a mature heritage benchmark, where professional operation, conservation and visitor safety support long-term use (Wieliczka Salt Mine 2026).

5.1. RETROSPECTIVE QUALITATIVE APPLICATION TO CALLIO LAB

Table 4 demonstrates how the framework can be used without converting incomplete public information into a false numerical precision. The assessment uses only evidence cited in this review and treats an undocumented requirement as uncertain rather than passed.

Table 4. Retrospective qualitative application of G0–G6 to Callio Lab

Gate	Evidence available in the reviewed record	Assessment and remaining uncertainty	Indicative outcome
G0	Callio Lab operates during the Pyhäsalmi transition and has an identifiable facility organisation and current service information.	Operational status is documented; the complete contractual allocation of residual liability and second closure is not public.	Clarify, then proceed
G1	Underground access and selected infrastructure have remained available while mining activities and access arrangements evolve.	No irreversible loss prevents current research uses; future access changes must be treated as a reopening trigger.	Proceed/ investigate changes
G2	Physics, geoscience, robotics and technology-testing activities document functional compatibility for defined retained areas.	Compatibility is use-specific; public-access or incompatible high-disturbance uses require separate matrices and may need redirection.	Accept defined uses/ redirect others
G3	Published environmental and radiation measurements support characterisation; facility operation implies active safety management.	Public sources do not replace the operator's hazard register, emergency case or regulator-approved residual-risk thresholds.	Indicative assessment only

Table 4 continued

G4	A diversified research and testing portfolio reduces single-project dependence, but shaft access and fixed underground services create continuing OPEX.	Demand, financing, governance and second-closure funding must be reviewed together against conventional closure.	Conditional business case
G5	Controlled research campaigns and incremental service development provide staged operational evidence rather than one universally reversible pilot.	KPIs, stop criteria, interface controls and contingency arrangements should be specified for each new use.	Authorise by use/ defer if evidence is weak
G6	Continued activity and diversification support operation while access, performance and finance remain acceptable.	Long-term operation remains conditional on monitored trends, accountable ownership and a maintained closure reserve.	Operate/modify/ close as triggered

The presented case shows the intended separation between documented suitability and unresolved acceptance evidence. Callio Lab has strong evidence for defined research and testing uses, but the framework still exposes contractual liability, future access, critical-risk acceptance and second-closure finance as items that cannot be inferred from scientific success. The G3 result should be interpreted as an indicative assessment only. The available public information does not provide sufficient evidence to establish formal safety acceptance or confirm that all required safety controls and acceptance thresholds have been met. Therefore, the indicative outcome should not be interpreted as a formal pass of the G3 safety gate. The retrospective application demonstrates the framework's applicability but does not constitute regulatory certification or verification of the facility's safety status.

5.2. CROSS-CASE LESSONS

The strongest transferable lesson is to assess reuse before access is lost. Retaining a shaft, pumping station or ventilation route during closure may preserve future options at relatively low incremental cost. Reopening sealed or flooded workings may later be prohibitive. Preservation should therefore be selective. A well-documented core can be retained, while remote, unstable or environmentally problematic areas are isolated. Accurate surveys, support records, mine-water data and closure-stage monitoring reduce uncertainty and strengthen G1–G3 decisions.

Long-term viability also depends on diversified users and funding. Reliance on a single experiment, investor or technology provider exposes fixed access and maintenance costs to cancellation or market change. Multi-user operation can spread these costs, but it requires clear governance of vibration, contamination, security, scheduling and emergency requirements. Regional value is also important. Research, education and heritage

can preserve specialist skills and technical identity, but they should not be treated as a direct replacement for mining employment. Durable reuse therefore requires recurring demand, stable financing, a viable service portfolio and a credible exit strategy. These conditions, together with those associated with stalled or unsustainable initiatives, are summarised in Fig. 5.

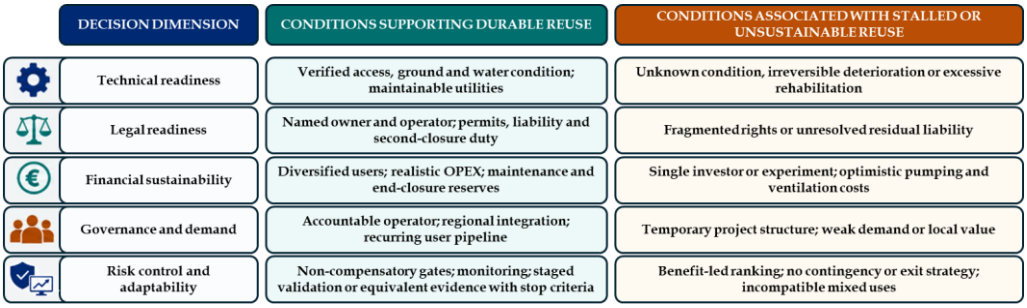


Fig. 5. Conditions associated with durable reuse versus cancelled, stalled or unsustainable initiatives

6. DISCUSSION

Effective reuse of underground workings is a problem of managing irreversible decisions under uncertainty. Classical closure approaches focus on safe decommissioning, financial assurance and long-term liability (Laurence 2006; Peck and Sinding 2009; ICMM 2019). Post-mining planning shifts attention toward future land use, stakeholder needs and spatial suitability (Kivinen 2017; Arratia-Solar et al. 2022; Worden et al. 2024). Both perspectives are necessary. Closure defines what must be made safe, while reuse planning determines which underground assets are worth keeping accessible and for how long. The key decision is therefore not how much infrastructure can be preserved, but which parts justify the cost and responsibility of continued access.

Decision methods also differ in how they address this problem. Multi-criteria approaches provide transparent comparison of alternatives (Soltanmohammadi et al. 2008; 2009; 2010; Amaro et al. 2021; 2022). Their limitation is that weighted scores may allow benefits in one criterion to compensate for unacceptable performance in another (underground hazards. Risk-centred approaches instead separate Roy and Słowiński 2013; Haddad and Sanders 2018). This logic is unsuitable for critical acceptance from preference (Cui et al. 2020a; Pytel et al. 2020). The framework proposed here combines these logics in sequence: feasibility first, non-compensatory safety acceptance second, and life-cycle comparison only after critical thresholds are met. This prevents an attractive future use from justifying retention of an asset that cannot be operated safely or reliably.

Relative to post-mining land-use suitability frameworks and the criteria-based decision-support system of Deutschmann et al. (2026), the proposed framework is not another compensatory scoring model. Its advancement is to govern the sequence in which existing tools may be used: legal and irreversible exclusions first, use compatibility second, non-compensatory critical-risk acceptance third, and only then comparative sustainability and socioeconomic ranking. The final stages add use-specific staged validation, monitored operating triggers and explicit responsibility for second closure. The approach therefore complements criteria-based ranking by defining its admissible decision space.

Reuse should also not be equated with sustainability. Retaining underground assets may avoid new excavation and preserve existing infrastructure, but it creates continuing costs for access, maintenance, water control, monitoring and second closure (Tost et al. 2018; Pactwa et al. 2021a). Technical studies show that long-term performance remains site-dependent and sensitive to geometry, hydrogeology, infrastructure condition, system integration and economics (Hall et al. 2011; Burnside et al. 2016; Madlener and Specht 2020; Menéndez et al. 2020; Saigustia and Robak 2021; Walls et al. 2021; Matas-Escamilla et al. 2023; Weber et al. 2024). Reuse and conventional closure should therefore be assessed over the same system boundary and time horizon. The sustainability dimensions are summarised in Table 5.

Table 5. Sustainability dimensions for comparing reuse with conventional closure

Dimension	Potential benefit	Burden/counterfactual	Example indicators
Environmental/ energy	Avoided excavation, land take and possible heat recovery	Pumping, ventilation, hoisting, water treatment and second closure	Life-cycle energy/GHG; water balance; material flows
Economic/ financial	Reused capital assets and avoided new construction	Rehabilitation CAPEX, fixed OPEX, insurance and uncertain demand	Discounted LCC/NPV; OPEX coverage; closure reserve
Social/ regional	Employment, skills, education, heritage and visibility	Limited job scale, access restrictions and uneven benefit distribution	Jobs; training; accessibility; stakeholder distribution
Governance/ liability	Shared infrastructure and multi-user cooperation	Fragmented rights, latent defects and unclear final-closure duty	Named owner/operator; permits; insurance; decision rights
Safety/ adaptability	Monitored use of a characterised underground environment	Instability, flooding, gas, fire, access loss and common-cause failures	Residual-risk thresholds; redundancy; triggers; exit plan

Governance is part of engineering feasibility. A retained asset requires a named owner, an accountable operator and clear responsibility for safety, maintenance, finance and

final closure. European policy can support transition but cannot replace a viable site-level case (European Parliament and Council 2006; Council of the European Union 2021; Endl et al. 2021; European Parliament and Council 2021a; 2021b; 2021c; European Parliament and Council 2024; European Commission 2026a; 2026b). Cooperation can reduce duplicated effort and improve access to comparable information. BSUIN, EUL, UL-PL, DULIA-Bio and the European Underground Laboratories Association illustrate this role (BSUIN Consortium 2020; EUL Project 2022; Polish Underground Laboratory Consortium 2025; DULIA-Bio 2026; European Underground Laboratories Association 2026). Such coordination should support screening rather than transfer site responsibility. Figure 6 illustrates this multi-level architecture.

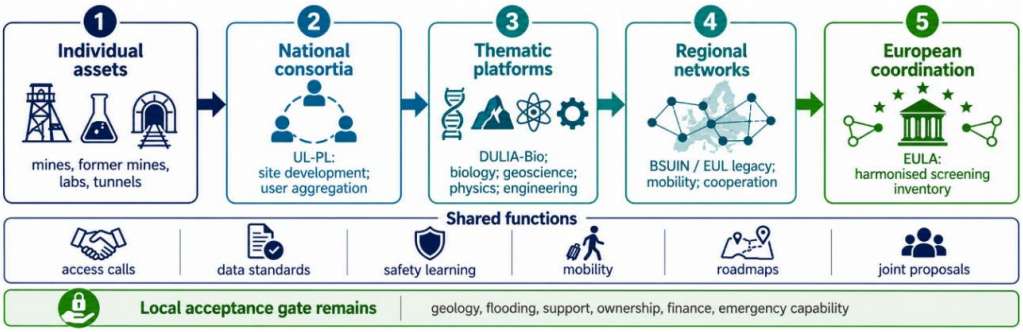


Fig. 6. Multi-level coordination architecture from individual underground assets to European cooperation, while site-specific acceptance remains local

Several limitations remain. The review and evidence appraisal were conducted by the author, and record-level counts from the early exploratory phase cannot be reconstructed. Operational status can change rapidly. The Callio Lab application demonstrates the logic retrospectively but does not certify the facility or establish predictive performance, and the framework has not yet been prospectively validated across multiple closures. Future work should pre-register the evidence protocol, apply common gate records at contrasting sites and test whether early screening reduces unnecessary preservation without causing premature loss of valuable underground assets.

7. CONCLUSIONS

Post-mining underground reuse is a credible but selective component of mine closure. The strongest operational evidence concerns research, teaching and testing facilities, heritage functions, and mine-water heating and cooling. Other pathways remain emerging or strongly site-dependent. Existing European databases can support initial site identification, but they rarely provide the technical, legal and operational information re-

quired for reuse decisions. The proposed stage-gated framework addresses this gap by separating eligibility, exclusion screening, technical compatibility and critical safety acceptance from later life-cycle and governance assessment. Its central principle is non-compensation: scientific, economic or regional benefits cannot offset unacceptable instability, flooding, fire, gas or evacuation risk. Only options that meet critical safety thresholds should proceed to comparative assessment. The practical implication is that reuse should be considered before irreversible closure, while access should be retained only for a defined and maintainable core. Continued preservation should depend on evidence, recurring demand, accountable ownership, stable financing, monitoring and a funded route to second closure. The key question is therefore not whether underground reuse is technically possible, but whether preserving a specific asset remains safe, justified and sustainable over its full life cycle.

Operationally, the framework should be used as a documented decision record rather than as an automatic score. G2 requires evidence for every mandatory use requirement, G3 prevents unacceptable critical risks from being compensated, G4 reports weight and scenario sensitivity, and G5 permits a pilot (reversible where feasible), demonstrator or other bounded staged validation appropriate to the site. These rules make the framework reproducible while preserving the site-specific authority of owners, operators and regulators.

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DECLARATION ON THE USE OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

OpenAI ChatGPT was used as an assistive tool for language editing and generation of Figs. 1 and 6. All literature sources, methodological decisions, classifications, numerical information and figure content were checked and approved by the author, who takes full responsibility for the content of the manuscript.

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