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Article

Challenges Related to the Transformation of Post-Mining Underground Workings into Underground Laboratories

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Abstract: Underground mines are a vital part of the European raw material industry. The subsurface mining process is related to the large-scale development of underground structures like tunnels, chambers, workings, etc. These structures are abandoned or liquidated during the process of exploitation or after the termination of works. Still, due to the unique environment, post-mining facilities may be adopted for different purposes. There are few examples of implementations of this capacity in practical terms such as underground laboratories (ULs), energy storages, landfills of dangerous wastes, or food production plants. Unfortunately, the unique environment offered by underground space is also related to the occurrence of exceptional hazards, like seismicity and ground control problems, gases, floods, the lack of natural ventilation, and high temperatures. This results in low interest in investing in such facilities. Within this paper, some ways to repurpose underground mines have been presented, and possible challenges that need to be faced have been described. An extensive database of threats to post-mining repurposing and ways to mitigate them has been prepared based on surveys and interviews conducted with representatives of currently existing Uls and mining companies and a literature review. Finally, this manuscript provides a general look at post-mining infrastructure in Europe's current situation and in the future.

Keywords: underground facilities; post-mining repurposing; sustainable development

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1. Introduction

The objectives of sustainable development concern harmonised relations between humans and natural environments. Policy in this matter was officially discussed at the United Nations (UN) forum and focused on the wide scope of issues related to human well-being and the health of the planet [1]. As a result, the United Nations prepared guidelines in the form of 17 Sustainable Development Goals (SDGs). The function of the goals is to stimulate action in areas of critical importance to humankind and the planet. The goals are global and universal [2]. The achievement of the SDGs is strongly supported by the European Union. All aspects of the SDGs were implemented in long-term European policy, which was reflected in European treaties, core projects, and sectoral strategies. One of the objectives listed in the SDGs is related to industry, innovation, and infrastructure. Part of these initiatives is industrial development, which positively impacts the improvement of living standards [3]. Thanks to this policy, the EU supports activity in the field of research and development as a source of innovations. This strategy also involves the mining sector, a significant part of European industries and economies.

Different industries and industrial operators commit to the UN SDGs in their operations and operational practices. However, the potential of the established infrastructure is often forgotten after the end of its original use. In the case of the mining industry, the established infrastructure is not limited to surface infrastructure but can consist of quarries, open pits, and a vast network of underground tunnels, galleries, and workings. Many of these facilities could be beneficial for non-mining activities, but in reality, most of them become abandoned during or after the end of the mining activities. Still, as pointed out by the authors of [4], these underground constructions are well fitted to hosting earth science and astroparticle and particle physics experiments [5], which in the long term, could be profitable as well. One of the most utilised properties of the underground environment is its natural shielding and even isolation from surface factors, including seasonal and weather changes, electromagnetic waves, and cosmic radiation [6]. All these aspects create many chances to adopt these available spaces for different types of activities, which can create benefits in various branches of science, industry, education, tourism, or even agriculture [6–9]. Additionally, facilities located deep underground may be well suited for long-term or permanent storing of mining and post-flotation [10], chemical [11], or radioactive wastes [12,13], which may bring positive effects on local society and the environment. For example, underground nuclear waste storages are safer than surface storage places.

The extension of the use and the life cycle of infrastructure that has already been heavily invested in is important for economic and social sustainability. Concerning mines, investments both before and during operations in the supporting civil infrastructure, the surface facilities, and the actual underground infrastructures have faced enormous investment costs, which are much greater than in other industries. The investment cost is spread over many years of mineral exploitation, and the first profits appear after many years of operation. Moreover, mining investments are subject to technical and market uncertainty [14,15]. Repurposing some parts, or the whole mine site, and having different businesses after the termination of excavation means a more efficient return of investment for local societies, mining companies, or other infrastructure operators managing the site. Using a site for a longer period, even if for a different type of operation, benefits the local communities and societies in mitigating the negative effects that ending mining operations has on employment, taxation, and, eventually, accessibility to services. Such a way of improving typical mining activity will help develop other branches of science and industries and should help change the public perception of the mining industry. Furthermore, in the process of transforming the region, it will protect against its degradation (mainly economic and spatial management).

The reuse of mine infrastructures fits into both the SDGs and the principles of a circular economy [16]. Therefore, post-mining site reuse is significant as long as the risks associated with the closure of the mine have been identified [17].

Additionally, the underground environment, despite having visible advantages, is also affected by the harsh and hazardous environment. The biggest challenges in repurposing underground workings into laboratories, tourist routes, etc., are strongly connected with safety. According to a report [18,19], underground mining is characterised by the highest accident rate among all industrial branches. As pointed out by Lööw et al. [20], the underground environment creates many different hazards, including physical, chemical, and ergonomic hazards, which may cause health problems connected with musculoskeletal disorders, hearing loss, and respiratory system diseases [20,21]. Considering the EU's policy concerning safety [22] and observed trends in mining companies in recent years, one may conclude that safety must be prioritised in mine reuse, beginning with initial plans [23]. This means that dealing with risks is currently the most significant challenge jeopardising new projects.

In this manuscript, the current status of underground mining in Europe has been analysed, and mines that are planned to be closed in the near future were identified. Then, data regarding potential risks and challenges related to underground environment repurposing have been collected and analysed based on a literature review and surveys and interviews conducted with representatives of universities, mining companies, and research facilities. Finally, the most impactful challenges have been linked to particular methods of underground space repurposing aimed at creating an underground laboratory.

2. Underground Mines in Europe and Potential Ways of Their Repurposing

The mining industry, including underground projects, has a solid base across Europe, despite unfavourable conditions that enterprises must deal with, e.g., society's resistance, energy prices, and green deal requirements. There is still pressure from the social and political side to limit activities in this field due to the negative impact on the environment. This is evident in the case of coal underground mines, many of which are in the middle of closure processes across Europe. The pressure is connected to energy transformation into carbon-neutral energy, and critics hope that by 2050 there will be no energy or steaming coal mines in the present form in any EU countries. Only coking coal mines will still be open after EU energy transition. This is related to, among other things, the goals of the European Green Deal to have zero greenhouse gas emissions by 2050 and the decoupling of economic growth from natural resources [24]. On the other hand, mines excavating critical raw materials are strongly supported by the EU in order to achieve independence from global raw material dynamics and supply chain challenges [25]. According to United States Geological Survey data, there are more than 100 active underground mines in the EU, shown in Table 1.

Table 1. Number of main active underground mines in the EU [25].

No.	Country	Number of Mines	Minerals
1	Austria	3	graphite, magnesite, and wolfram
2	Bulgaria	6	copper, gold, lead, and manganese, silver and zinc
3	Czech Republic	3	coal
4	Estonia	2	oil shale
5	Finland	5	chromium, gold, and silver
6	France	1	salt
7	Germany	10	barite, fluorite, potash, and salt
8	Greece	8	bauxite, copper, gold, lead, magnesite, and zinc
9	Ireland	3	gypsum, lead, salt, and zinc
10	Italy	4	potash, salt, and marble
11	Norway	3	coal, dolomite, and iron
12	Poland	26	coal, copper, silver, gypsum, and salt
13	Portugal	2	copper, tin, silver, and wolfram
14	Romania	6	coal, copper, salt, and silver
15	Slovakia	6	gold, magnesite, and talc
16	Slovenia	1	coal
17	Spain	10	coal, copper, fluorite, gold, lead, and magnesite, potash, tin, zinc, and wolfram
18	Sweden	8	copper, gold, iron, lead, and zinc
19	United Kingdom	5	barite, fluorite, potash, salt, and tin

Note: There are no significant underground mines in the remaining EU countries.

As one may conclude, underground mines still exist in most European countries. This kind of exploitation is most prevalent in Poland and Serbia. This is because of the significant number of coal mines in these countries. Due to the European green transition process, most of these mines will be closed in the coming years, especially in Poland. This means that there will be potential possibilities to transform part of these underground infrastructures for different purposes instead of liquidation, which means, in many cases, permanent and irreversible destruction of infrastructure. Considering the number of active underground mines in Europe, these issues will appear relatively often. Therefore, communities should highlight the potential of repurposing available underground workings.

One of the possible uses of closed mines is as deep underground laboratories (DULs). The definition of deep is related to having access to a depth of more than 1000 m below the surface level. The main activity that DULs are currently used for is high-energy astroparticle physics. The locations of DUL facilities in Europe is shown in Figure 1. However, some mines that are soon to be closing, closed, or even operating, e.g., the copper mine Neves Covro in Portugal and the coal mine Zinkgrovan in Sweden, in Europe could become DULs. It could mean new possibilities in terms of mine reuse in Europe.

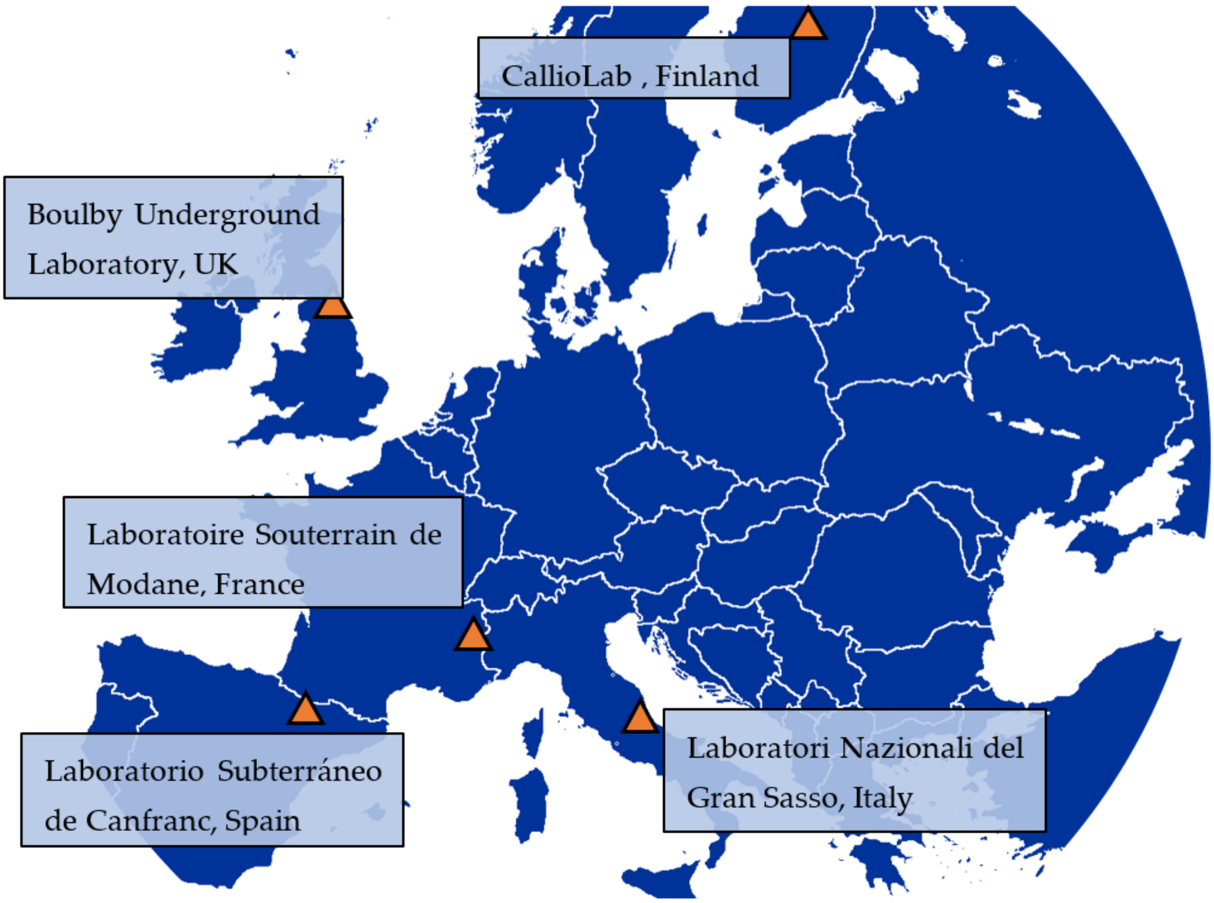

Figure 1. Location of deep underground laboratories in Europe [25].

As recent experiences show, physics is not the only field of science that can be explored in underground laboratories [26]. A new area of research is connected with experiments in astrobiology and biology in extreme conditions [27], space research (planetary or lunar analogue environments) [28], underground food production [29,30], education [31], tourism [32] and the development of more efficient and environmentally friendly mining technologies [27]. There are also multipurpose facilities that allow performing various activities in different areas of the mine. Still, repurposing underground space is challenging due to the unique environment and the number of hazards observed in underground conditions. Thus, in most cases, there is no interest in taking actions aimed at the further development of mines after the termination of excavation activities among society, investors, and other stakeholders. Moreover, the involvement of these groups is a complex and demanding task [33]. One of the recent initiatives to develop the reuse of underground sites is the European Underground Laboratories Association (EUL), which gathers underground research, science, and tourism facilities and promotes this approach to underground mine repurposing. The underground sites belonging to the EUL association are presented in Figure 2.

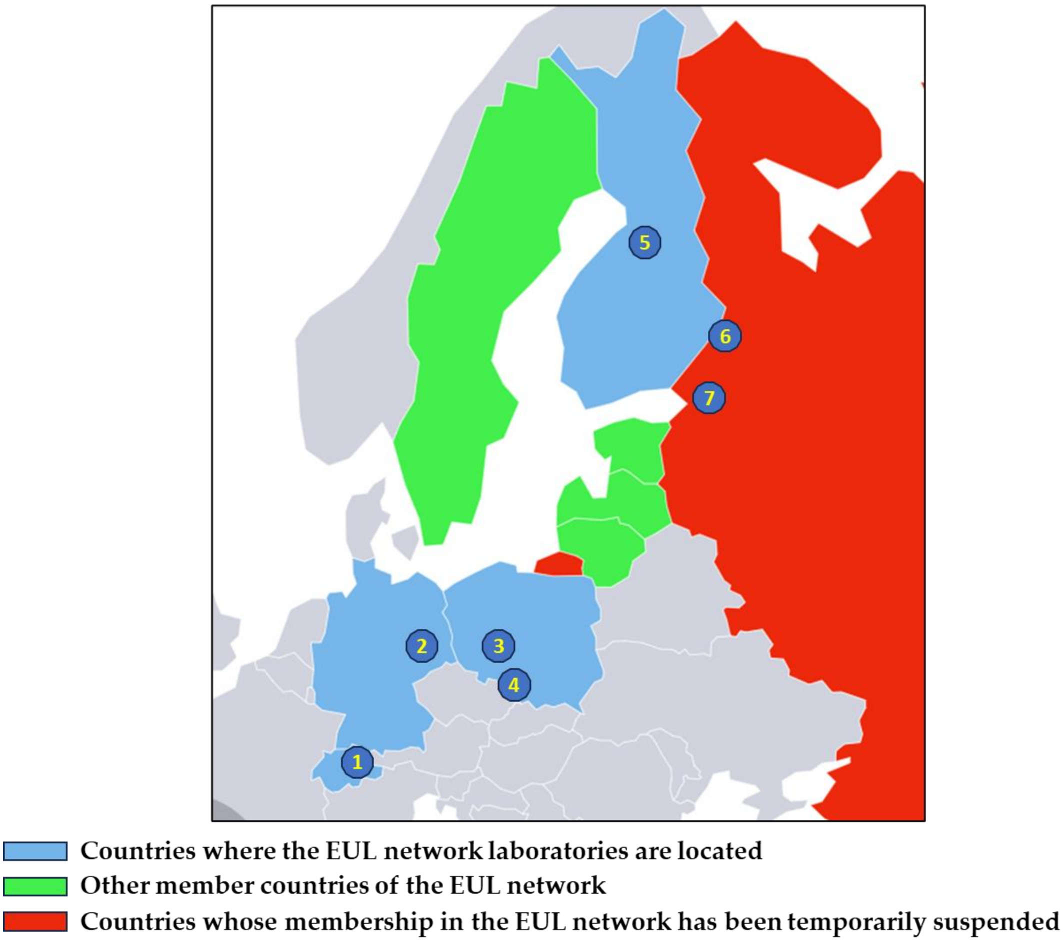

Figure 2. Underground Laboratories of the EUL association. 1—Hagerbach Test Gallery; 2—Reiche Zeche; 3—Lab Development by KGHM CUPRUM; 4—GIG Experimental Mine "Barbara"; 5—Callio Lab; 6—Ruskeala; 7—Khlopinh.

Types of Underground Activities

One of the prospective examples of underground lab applications for post-mining areas is physics laboratories, which are needed for studying, e.g., astroparticle physics and dark matter, or conducting low background measurements on material radiopurity [26,34,35]. Examples of such transitions are Boulby Mine in the UK [36], the Homestake Mine in South Dakota, USA [37], and Pyhäsalmi Mine in Finland [38], the latter of which started as the Centre for Underground Physics in Pyhäsalmi. The aforementioned sites have since turned to be or given access to more multidisciplinary, providing facilities for various fields of science and engineering.

For the experiments conducted at deep underground laboratories, a common requirement is good shielding against the cosmic-ray background, and adequate shielding is reached with an overburden of more than 1000 m of rock [5]. The experiments are also increasing in size (e.g., DUNE: four halls of 69.9 m × 27.4 m × 19.8 m [39] with plans of detectors systems with up to a 100 m scale. The requirements for the overburden and the hall sizes put enormous pressure on rock mechanical engineers to mitigate the risks coming from the shared rock mass-induced gravitational pressure and any horizontal pressures (see, e.g., [40]).

Another perspective for underground mine reuse is multi- and transdisciplinary research mines. These facilities are not developed solely for one kind of activity but work as suitable places for any projects that may benefit from different underground environments. Currently, in the EU, there are few facilities of that type. Some examples include the Äspö Hard Rock Laboratory, Sweden; Experimental Mine Barbara, Poland; Callio Lab, Finland; and Reiche Zeche, Germany.

As pointed out by Pactwa et al. [16], underground space is also suitable for sustainable food production. Selected methods for underground space repurposing are presented in Figure 3.

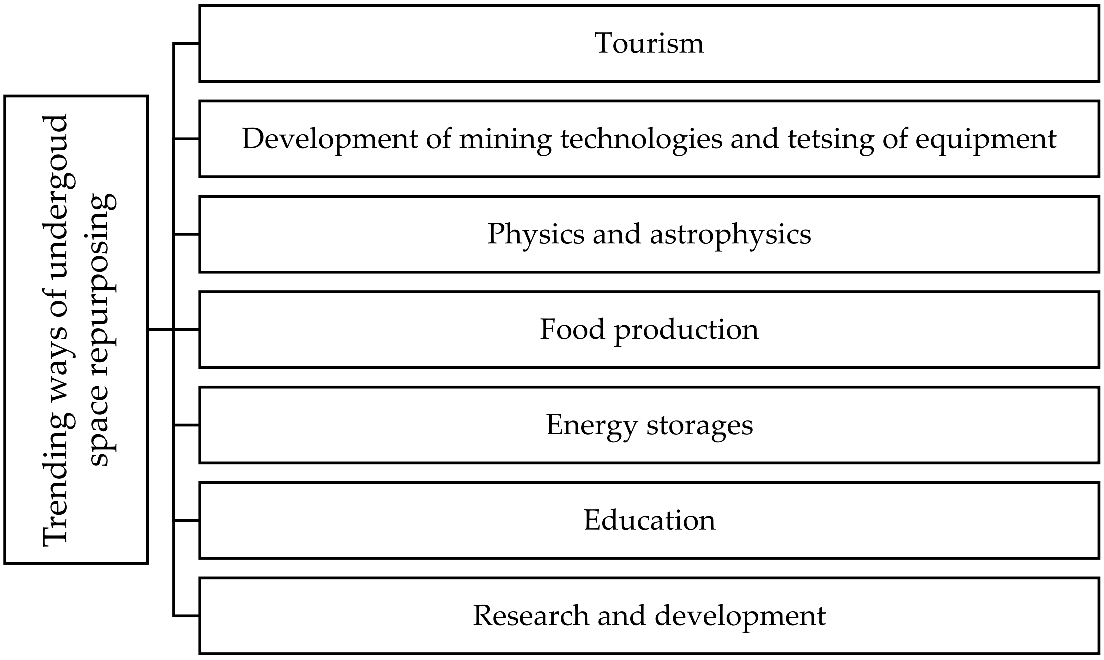

Figure 3. Methods for underground space repurposing [27,30–32,41–48].

It is also worth mentioning that, in the light of the EU policy of greenhouse gas emission reduction, there is also the potential to achieve this target by means of using underground space as energy storage. Many different technologies can be considered like underground gas storage (UGS), hydrogen storage (HS), compressed air energy storage (CAES), underground pumped hydro storage (UPHS), and thermal energy storage (TES) [49].

3. Materials and Methods

The analysis presented herein was based on a literature review, surveys, workshops, and webinars performed within the following international projects:

- Baltic Sea Underground Innovation Network (BSUIN);
- Empowering Underground Laboratories Network Usage (EUL).

3.1. Data Collection and Identification of Challenges

Information about obstacles and challenges that must be faced during underground space repurposing has been collected during international webinars and workshops (i.e., [50]). In the whole data collection process, the representatives of ULs in Europe, mining companies, and scientists were involved. Chosen entities that took part in the preparation of this research are presented in Figure 4.

Figure 4. Underground labs from which representatives took part in the data preparation process.

What is worth mentioning is that the above presented underground laboratories have been developed for different purposes. Experimental Mine Barbara, Hagerbach Test Gallery, and Reiche Zeche are facilities that are directly related to R&D activities. Ruskeala Underground Lab works as an underground tourism route. Khlopin Low Background Lab focuses on environmental radiation, while Äspö HRL is used as a test site for different technologies and practices related to underground nuclear waste storage. There are also multipurpose facilities such as Callio Lab, which reuses built or excavated mining-related infrastructures as research, testing, and validation environments. There is no underground lab in its standard form in KGHM copper mines. However, numerous international and national research projects are still performed that progress the exploitation of copper ore.

3.2. Preliminary Risk Evaluation

Safety is the crucial parameter for any field of activity or industry, whether evaluated on the surface, in the air, or underground. However, many of the threats in underground environments are not typical for other industries or research fields and, therefore, are not fully recognised [19]. Thus, a detailed process of risk identification has been performed. Surveys and workshops were conducted with experts from the underground mining industry and users of underground laboratories in Europe. In total, 106 unwanted threats were identified in a risk identification worksheet, and a list of analysed hazards may be found in [51]. These threats were classified into four groups and 18 hazard categories (Figure 5).

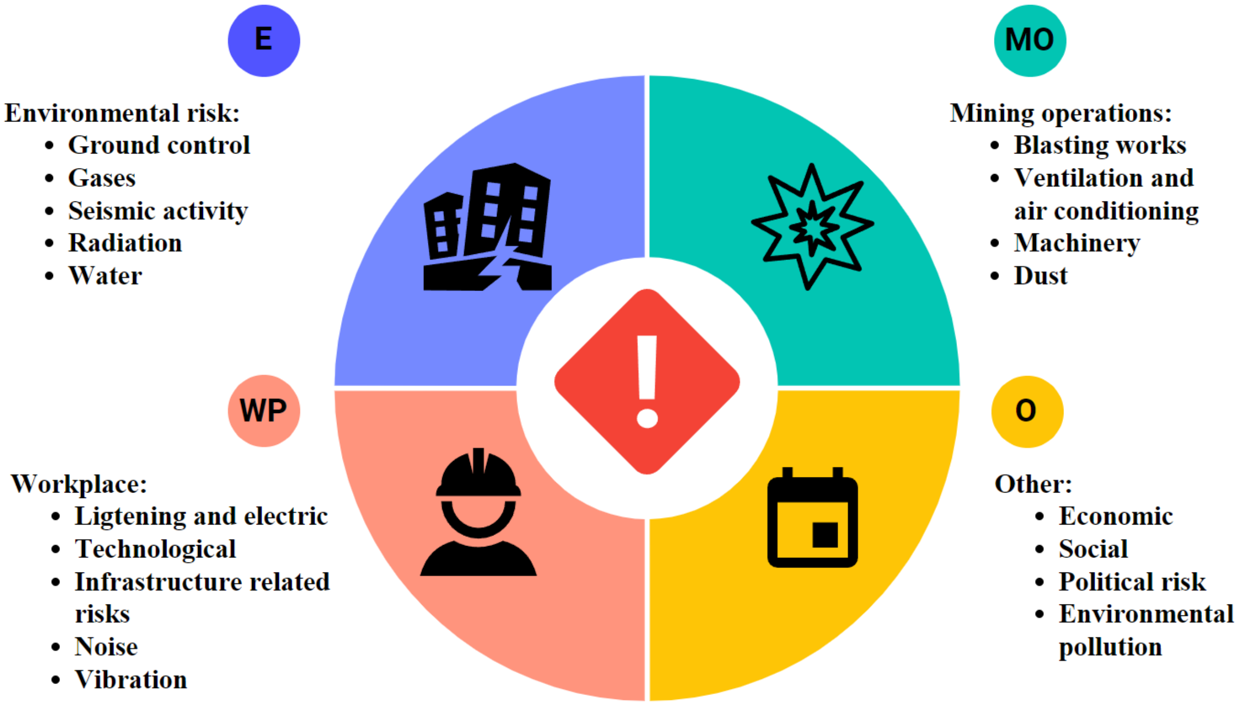

Figure 5. Groups and categories of risks identified in underground conditions.

Then, each risk was analysed qualitatively using the risk matrix method. As pointed out in [19], the risk matrix method is one of the most commonly utilised approaches in establishing risk severity. There are many types of risk matrixes, but the so-called two-dimensional risk matrix is most commonly used due to the ease of its preparation and in interpreting its results. Such an approach allows not only to determine the impact of each event but also to identify the risk's probability or consequence. This information is of high importance during the process of mitigation procedure development. The risk assessment method based on a risk matrix for ULs can be applied as early as the design stage of a given facility. Still, it is crucial that evaluation is carried out exclusively by specialists in a particular field to achieve reliable results. The greatest advantage of the proposed approach is the possible implementation of appropriate risk prevention and minimisation measures at the design stage and just after preliminary evaluation. At the same time, there are no technical limitations to using it as the basic method of classifying selected events as part of the periodic risk assessment of the operation of underground facilities throughout their entire life cycle.

For the purpose of this analysis, the risk evaluation worksheet was developed and sent to researchers, scientists, and UL users. In the risk matrix method, the risk may be defined according to the following formula:

$$RISK = R_p \times R_i \quad (1)$$

where:

R_p—the probability of unwanted event occurrence;
R_i—expected/predicted consequences of the event.

Such an approach is suitable for preliminary analysis and allows for a general point of view for hazards in a particular facility. The exemplary worksheet for evaluating risks related to ground control in underground facilities is presented in Figure 6.

No.	Ground Control	Probability	Impact	Risk
1.	GEOLOGIC DISCONTINUITIES OCCURRENCE	MODERATE	SEVERE	MEDIUM
2.	UNSUPPORTED ROOF	LOW	CATASTROPHIC	SERIOUS / HIGH
3.	SPALLING OF WALL	MODERATE	MODERATE	MEDIUM
4.	ROOF FAILURES	LOW	CATASTROPHIC	SERIOUS / HIGH
5.	WORKINGS INSTABILITY	LOW	CATASTROPHIC	SERIOUS / HIGH
6.	OVERBURDEN CAVING	EXTREMELY SMALL	CATASTROPHIC	MEDIUM
7.	LONG TERM CREEP EFFECT	MODERATE	MODERATE	MEDIUM
8.	TOO HIGH IN-SITU STRESS	LOW	SEVERE	MEDIUM
9.	GROUND MOVEMENT	LOW	CATASTROPHIC	SERIOUS / HIGH
10.	COLLAPSE OF SURFACE	EXTREMELY SMALL	CATASTROPHIC	MEDIUM
11.	MINE COLLAPSE	EXTREMELY SMALL	CATASTROPHIC	MEDIUM
12.	LACK OF MONITORING DEVICES OF WORKINGS STABILITY	LOW	SMALL	LOW
13.	CAVE-IN	EXTREMELY SMALL	SEVERE	LOW
14.	SWELLING	MODERATE	SMALL	LOW
15.	SQUEEZING	MODERATE	SMALL	LOW
16.	….			

Figure 6. Qualitative evaluation of ground control risk using the risk matric method.

A risk evaluation worksheet with a list of all 106 risks and a detailed report [52] may be found on the following webpage: https://bsuin.eu/2021/01/08/bsuin-final-reports/ (accessed on 20 September 2022) [52]. It must be highlighted here that the risk matrix method is a very general approach and should be used to determine risk categories that have to be evaluated in a more detailed (quantitative) way. For example, in the case of roof falls, risk may be analysed with the use of numerical methods or with a systematic approach, as presented, respectively, by Ghasemi et al. in [53] or by Sakhno et al. in [54]. In the case of more general analyses that are not focused on only one group of hazards, a hierarchical analysis may be performed, as presented by Siahuei et al. [55].

4. Results and Discussion

Within this research, 29 surveys were completed by representatives of ULs and underground mines, scientists, and UL users. The ULs within these surveys are unique in their usage (R&D, tourism, education, and excavation), environmental conditions (physical depth and rock overburden, geomechanics, hydrogeology, seismic, and social acceptance), and local threats. The most significant challenges related to the readaptation of underground workings into non-mining facilities are presented in Figure 7.

After analysing all surveys and issues pointed out by the respondents, it was concluded that safety issues (13.43%) and legal obstacles (12.50%) were most often mentioned. While the safety aspects may be limited at the user level, the problems of national legal regulations in most cases are beyond the influence of the users of underground laboratories. Still, as Paat and Joutsenvaara [54] pointed out in the report "Underground laboratories working environment, a common standard", underground laboratories work under the same laws and regulations as mining companies in most EU countries. In such a case, the revitalisation of underground workings or transition from the mining company to the UL site may be smooth. Responsibilities and liabilities between the different parties need to be agreed upon for the transition's planning.

By involving the local experts from the mining industry, the activities and management of the revitalised mining environment can be performed in safe and sustainable ways and according to local laws and regulations. Contacting the mining authority may be helpful as well.

The next group of challenges is related to the economic aspects of underground laboratory management. Many respondents pointed out that the investment costs (9.72%) may exceed the incomes (6.48%). Moreover, there are significant doubts in terms of the business (11.11%) model, which could attract stakeholders and investors (7.87%) in the long term, providing efficient and stable profits during the whole life cycle of the underground facility (8.80%).

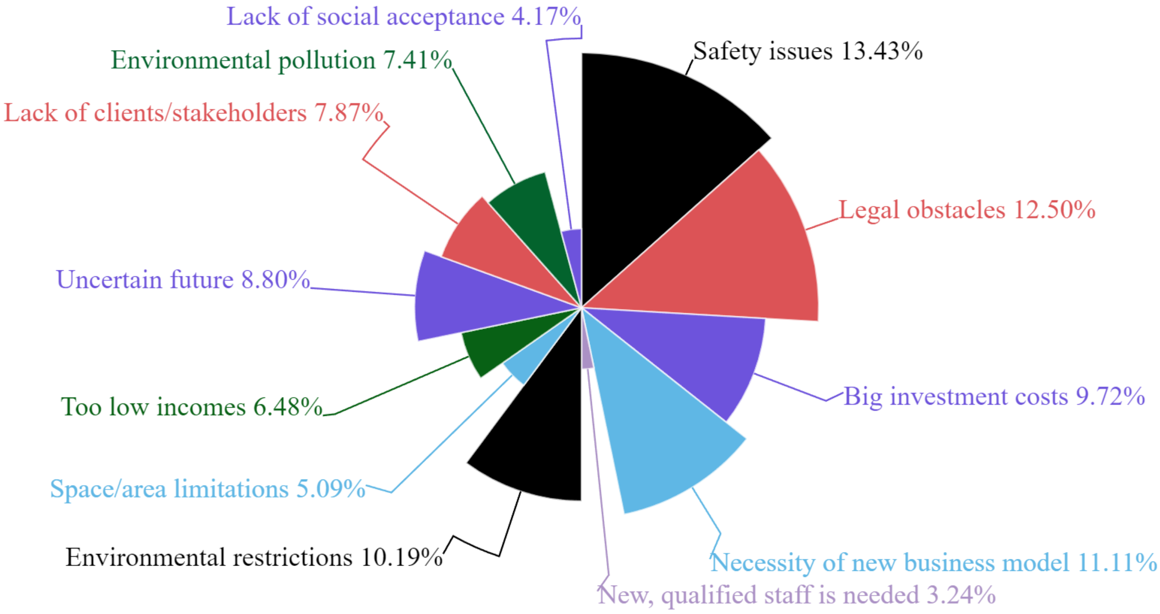

Figure 7. The biggest challenges related to setting up new underground non-mining facilities.

According to surveys and workshops, environmental issues are also significant when considering underground space repurposing. Over 10.19% of all answers were related to environmental restrictions of underground workings such as the lack of natural ventilation, lack of natural light, high humidity, etc. Also, space limitations were mentioned by respondents. In this case, 5.09% of votes pointed out that space limitations may be challenging, especially in the case of ventures that could be potentially developed in the future.

Surprisingly, the issues related to a lack of social acceptance (4.17%) and lack of qualified staff (3.24%) were mentioned the least. This could be justified by the social awareness of advantages and disadvantages related to underground activities in the mining and post-mining regions.

As pointed out in numerous studies, safety issues are the factors that most significantly jeopardise projects that are planned to be conducted in underground conditions. Therefore, a detailed analysis of risks and a categorisation of their significance have been performed. During the data collection, 29 representatives, including those from the mining industry and supervisors of underground laboratories, filled in the risk evaluation worksheet. They determined the probability and expected impact of each of the 106 identified risks classified into 18 groups. The results of the analysis are presented in Figure 8.

Based on the detailed analysis of the severity of risks and their listed categories, one may conclude that more hazardous events are related to ground control issues (24% of risks classified as severe) and the presence of ground vibrations induced by natural (40% of events classified as severe) and anthropogenic seismicity (31.25% of events classified as severe). This is mainly because any type of rockburst, roof fall, or spalling of the rock layers may generate significant negative consequences including fatal or serious injuries and economic losses. Particular attention should also be paid to ventilation issues. According to the risk evaluation surveys, the most dangerous events in this group are related to the possibility of fire occurrence. Thus, safety chambers or at least self-rescue breathing apparatuses should be available on site.

Extensive preventive measures should also be undertaken in case of technological aspects and accidents related to machinery movement in underground conditions. Periodical testing of ground support performance and proper traffic organisation could significantly minimise these hazard levels. Noise (9.1%) and lightning (8.0%) issues were also classified as severe. In the case of these events, expected consequences are not very high, but the probability and intensity of these events are relatively high and affect all people working in underground conditions.

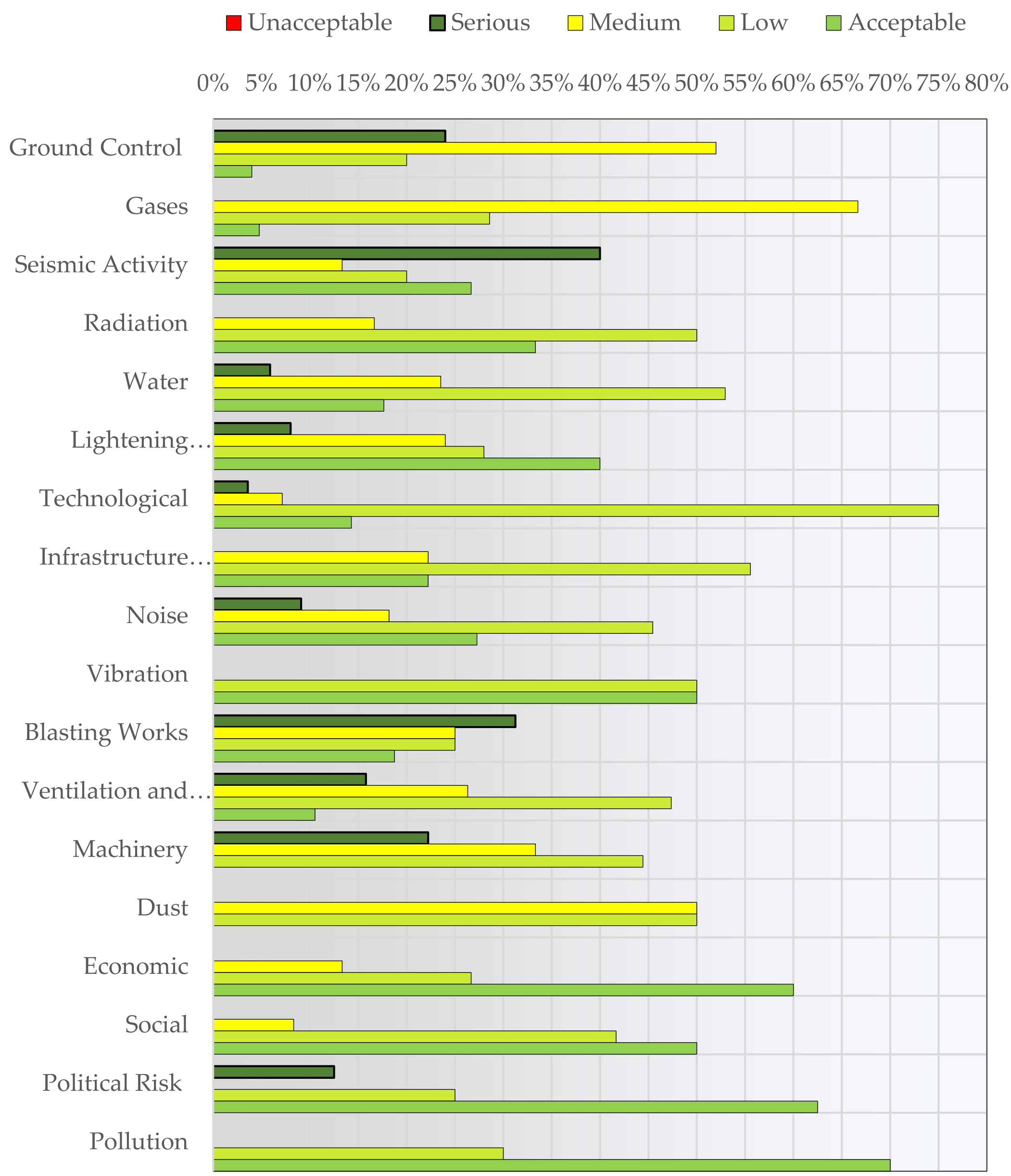

Figure 8. Preliminary analysis of the severity of risks classified in each of the identified groups.

The last group of risks classified as severe is related to political aspects such as local laws and regulations, which may considerably constrain the activities of the underground facility.

It is worth mentioning that there were no events in which risk was classified as unacceptable. In turn, most of the evaluated risks were categorised as acceptable or low, which stands for their low impact on the project's feasibility.

5. Conclusions

This paper analyses the challenges and threats related to setting up an underground laboratory in post-mining areas. An analysis has been performed with experts from the mining industry, scientists, and representatives of underground laboratories that operate successfully in Europe and the Baltic Sea region. Safety issues are of the highest importance and should be analysed and possibly mitigated first. Also, imprecise local law regulations, the lack of awareness of stakeholders, and financing problems of the whole venture may be problematic and affect the project's feasibility.

Still, as recent experiences have shown, the scope of activities that may be successfully performed in underground conditions is very extensive and covers many aspects of tourism, education, science, R&D or mining technology, and extraction method development.

Repurposing may be greatly facilitated by experiences gathered by other underground laboratories that already operate. Analyses of business models, a SWOT analysis of different UL operations, or detailed risk evaluations may familiarize users with not only possible threats but also opportunities. Extended advice on this topic may be found on the open web platform of the European Underground Laboratories Association, where numerous reports from international projects BSUIN and EUL are freely accessible. These reports may be found at the following webpage: https://undergroundlabs.network/ (accessed on 15 July 2022).

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