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Article

Second Life of Post-Mining Infrastructure in Light of the Circular Economy and Sustainable Development—Recent Advances and Perspectives

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Abstract: Current EU policy will force a significant reduction of hard coal mines in the near future due to environmental restrictions. There are also numerous non-coal underground mines that will be excavated in the next few years. Taking the above into consideration, it is worth starting to plan further steps in terms of reclamation of these facilities. Within this manuscript, both recently used and novel approaches to underground space reclamation have been reviewed. Selected methods of reclamation were analyzed in terms of their strengths and weaknesses, and the results were compared with the effect of a commonly used approaches (i.e., filling or flooding of underground space after mine termination). The analysis has been performed in the scope of sustainable development. Taking into account the opinion of many stakeholder groups and underground facilities, reuse was considered as an action aimed at fulfilling sustainable development goals and the circular economy concept. Based on numerous surveys, the challenges and opportunities have been determined as well. Finally, most perspectives concerning underground mine reclamation, including environmental impact, social acceptance, and profitability have been proposed and described.

Keywords: underground laboratory; new ways of mine reclamation; sustainability; circular economy

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1. Introduction

The worldwide trend of the substitution of fossil energy by atomic and renewable energy sources has had a significant impact on the demand for raw mineral materials [1]. As a result, there are numerous mining projects and initiatives aimed at exploring and excavating new resources of mineral raw materials [2,3]. Growing needs in the field of renewable energy and electric mobility are related to the high importance of critical raw materials (CRMs) [4]. In turn, due to EU environmental policy and lack of competitiveness [5], most underground hard coal mines will be closed down over the next 15–20 years. Between 2014 and 2017 alone, 27 coal mines in Poland, Germany, the Czech Republic, Hungary, Romania, Slovakia, Slovenia, and the United Kingdom were closed [6]. Furthermore, considering the efficiency of underground coal mining it is expected that most coal regions will be subjected to termination by 2030, which poses a great risk of local economic crisis and numerous job losses in these areas. The map of potential job losses related to coal mine closure in the EU is presented in Figure 1.

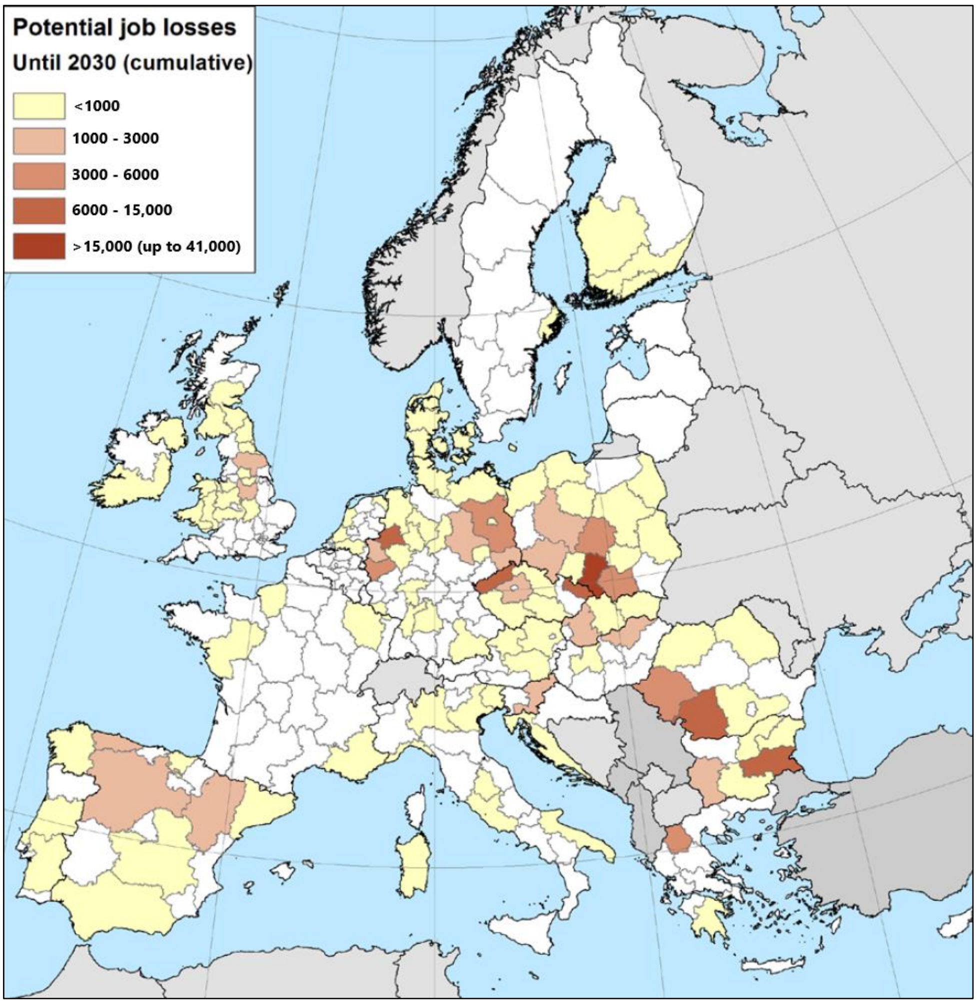

Figure 1. Potential job losses caused by the closure of coal mines in the EU [6].

The consequences of closing mines will also be felt by employees of mining-related enterprises (i.e., companies operating due to the existence of mines). This applies both to entities supplying products (mining machinery and equipment, specialized materials) and services, as well as those using minerals as the basic raw material for their production. As research [7] shows, some of them are not preparing for a mining shutdown scenario.

As past experiences showed, the unplanned and sudden transformation of mining areas has a negative impact on the economy [5,8] and environmental sustainability [9–14]. One of the inglorious examples of such an impact was the rapid termination of underground hard coal mining in the Lower Silesian Coal Basin (LSCB) in Poland, at the end of the 20th century. According to [15] after mines liquidation, the local unemployment increased from 15% in 1997 up to 32% in 2002. The consequences of the liquidation of industries are best illustrated by the data over the years. In the former Wałbrzych Voivodeship, employment in industry (in total) amounted to 148.5 thousand in 1980, 99.1 thousand in 1990 (the year when the decision to close the Wałbrzych mines was made), and 70.1 thousand in 1996 [16]. At the same time, in 1996, the last coal cart was excavated at the "Thorez" mine. Employment in the Wałbrzych Voivodeship for two decades is shown in Figure 2.

Figure 2. Employment in the Wałbrzych Voivodeship in the years between 1976 and 1996 (own study based on [16]).

Considering the numbers of closed mines and those which are planned to be set up, it may be concluded that even with the rapid development of new mining projects, most workers will stay unemployed. At the same time, post-mining underground space, in most cases, has not been considered as a suitable place for activities other than mining and are often filled with rocks and water to prevent its further effect on the local environment [17–19]. In general, widely considered methods of underground mines reclamation aim to utilize the most cost-effective and efficient way of backfilling to prevent further ground subsidence after mine closure [20].

A lack of other forms of underground space reclamation may be related to the harsh and dangerous environment [21,22] and limitations in the scope of national regulations [23]. Still, as it was pointed out in a paper [24], "*Each revitalization project should be performed with consideration of the social, economic, and environmental aspects*". Therefore, it is important to develop solutions for post-mining underground workings reclamation which will at least partially ensure social and economic sustainability after the end of resources exploitation to achieve sustainable development (SD) and circular economy (CE) goals. Here, the circular economy is understood not in the classical sense [25], but in a broader sense—by planning the use of remnants (land, facilities, machines, etc.) after the completed mining activities. A second life for mines is, due to the variety of opportunities, a second life also for communities, landscapes, and/or science.

The authors [26] notice a growing need for post-mining space development, which is dictated, firstly, by the increased demand for space, and secondly by the need to use this space effectively in order to achieve the goals of sustainable development. It should be noted that the re-use of the exploited underground space does not have to be limited to one method of development.

Choosing how to reuse underground post-mining spaces becomes a challenge. There are few generally accepted practices or patterns for the redevelopment of closed mines' resources in the literature. The research conducted so far focuses mainly on individual case studies and does not give a diagnosis towards the correct choice of the method of reuse. This paper [27] presents an innovative solution and provides a universal framework for the development of abandoned mines. However, such an approach has still not been taken into consideration by most of the mining companies.

The aim of the article is to analyze alternative methods of underground working use and their possible impact on local and regional sustainability and the circular economy. The analysis was performed based on a literature review and surveys conducted with representatives of chosen underground facilities located in the EU.

2. Recently Utilized Alternative Ways of Mining Reclamation

When analyzing the potential ways of repurposing or revitalizing underground workings, one may conclude that the most popular and easy to implement method involves setting up underground tourist routes within the stable areas of old mines [28,29]. According to [30], in Poland there are over 200 underground touristic routes with over 1500 employees. As it was pointed out in research [31], such a method of mine reclamation provides numerous short-, medium-, and long-term advantages for the local society, environment, and regional economy after mine closure. Moreover, according to the World Travel and Tourism Council's estimations [32], tourism was the fastest growing industry worldwide until the COVID-19 pandemic. Examples of underground, profitable tourist routes in Europe are, among others, Wieliczka salt Mine in Poland [33], Zollverein Coal Mine Industrial Complex, Germany [34], Iwami Ginzan Silver Mine in Japan [35], and the Ruskeala Mining Park [17]. Still, considering the involvement of the mining industry in local budgets, there is no possibility to fill this gap only with a simple transformation into the tourism industry [35]. One of the infamous examples of "tourism after mining" may be the Hokkaido coal-mining region in Japan, where after a mine closure in Yubari City, even with strong support of local administration and high investment into tourism, the local community suffered bankruptcy and the population in the town shrank from 12,000 to 500 people [36]. Therefore, a sustainable strategy aimed at competitive advantages of each region is a key element during the process of transformation into "tourism cities".

The latest experiences during the pandemic have drawn attention to digital solutions that allow visitors to contact tourist facilities remotely [37]. Examples include the provision of materials by the Coal Mining Museum in Zabrze in the form of short virtual walks [38]. The materials available on Google Arts and Culture include, among others, photos from the Museum of Mines of Mercury Monte Amiata [39]. Digital technologies are used to provide information before visiting tourist sites. They can maintain the continuity of the tourism industry. They are useful for older people or with disabilities [37]. They can be described as consistent with the idea of SD.

On the other hand, post-mining underground spaces, due to their unique environment, offers several opportunities in the field of science, research, and education. As a result, continued growth in the use of underground space for research purposes can be observed within the past several years [40,41]. Rapid development is visible mainly in the scope of advanced physical measurements deep under the ground surface [42]. This is due to the presence of natural coverage that provides a significant reduction of cosmic ray flux or flux of neutrons when compared to the surface. As a result, numerous underground laboratories aimed strictly at astrophysical measurements have been set up during the last twenty years. Examples of such underground facilities may be Laboratory for Underground Nuclear Astrophysics (Luna), Italy [43,44], Jiangmen Underground Neutrino Observatory, (JUNO), China [45], Sudbury Neutrino Observatory (SNO), Canada [46], and Pyhasalmi mine, Finland [47,48].

Distinctive environmental conditions also affect the possibility of the development of new technologies for the mining industry. The simultaneous effect of such factors as high humidity, dust, lack of light, and problems with the ground control cause great difficulties in mapping the mine environment in laboratory conditions. Therefore, facilities located deep underground designed exclusively for the needs of technology development are strongly desired in the whole mining industry. Such a method of reclamation fits also into current EU policy and highlights the necessity of safe and more efficient mineral raw materials exploitation. Research performed in a real underground mining environments potentially allows one to develop and implement more reliable and economically effective products. Facilities of that type may be found in Sweden (e.g., Äspö Hard Rock Laboratory) where research on smart integrated test environments for the mining industry was performed [49]; Germany (e.g., Reiche Zeche) where, for example, methods of bioleaching are under development [50,51]; or Poland (e.g., Experimental Mine "Barbara"), where research on coal gasification [52], safety in the underground environment [53], and blasting technology [54,55] were performed recently.

An interesting and sustainable solution is the use of abandoned mines as energy storage. There are several technological solutions in this area [56]. They represent a way to deal with the problem of integrating the share of renewable energy sources with energy systems. An example is the project of storing excess heat from solar power plants using post-mining infrastructure in the Ruhr region [57]. Menendez et al. [58] and Li et al. [59] also wrote about solutions leading to the use of the potential of mines in a pro-ecological manner.

Furthermore, growing interest in underground farming and food production inside old post-mining areas can be observed in the last few years. As it was pointed out by GreenForges [60], underground spaces permit creating stable environmental conditions where food may be grown in a constant, predictable, and sustainable way. Such kinds of facilities have been set up in London [61] and in the Pyhasalmi mine, where a project related to industrial-scale insects and food production is under development [62].

It has to be highlighted that the underground space which may be repurposed after the termination of mining works in most cases is big enough to consider not only one way of underground site adaptation, but the setting up of a number of smaller facilities which may work independently. The example of a multipurpose experimental site, the ÄSPÖ HRL, has been presented in Figure 3.

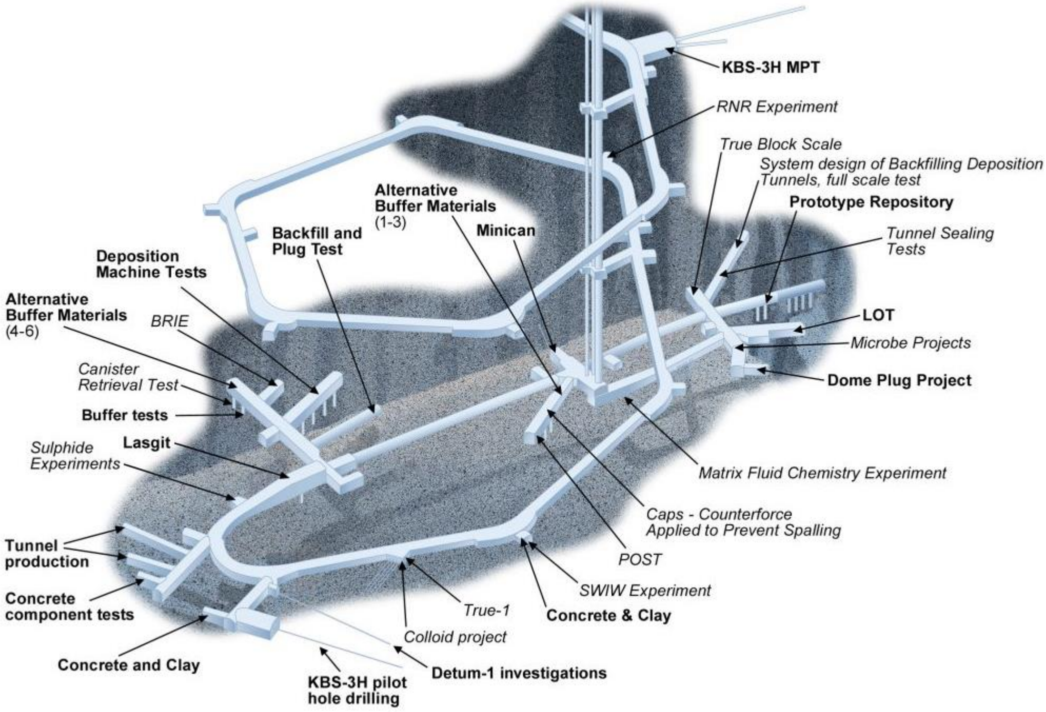

Figure 3. Allocation of experiments at Äspö HRL [57]. Reprint with permission of Äspö HRL, 2021, https://www.skbinternational.se.

However, it must be borne in mind that such a method of mine reclamation, in the case of deeply located underground workings, may not generate enough profits to maintain this type of facility by itself. Therefore, when analyzing the possibility of mine workings, a detailed business model should be developed.

3. Material and Methods

The possibility of effective underground space re-development is strongly dependent on the properly developed business model, quality of value proposition, method and effectiveness of service design, and the presence of stakeholders who are essential in the process of implementing and exploiting new ideas. The whole process of mining reclamation should be preceded by SWOT analyses which could highlight the most efficient way of further underground space development. All methods, surveys, and analyses have been performed within EU donated Baltic Sea Underground Innovation (BSUIN) and Empowering Underground Laboratories Network Usage (EUL) projects.

3.1. Development of the Business Model

A business model describes the logic of how a company intends to maintain its business lucrative, as well as the rationale of how a company or an organization creates, delivers, and captures value [63]. A business can be described with a business model canvas. Here, the business model canvas consists of nine building blocks: customer segments, value proposition, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure. One of its key benefits is bringing clarity to the core aims of an organization while identifying its strengths, weaknesses, and priorities. The example of the Canvas survey worksheet developed for conceptual laboratory which is considered to set up in one of KGHM mines in future is presented in Figure 4.

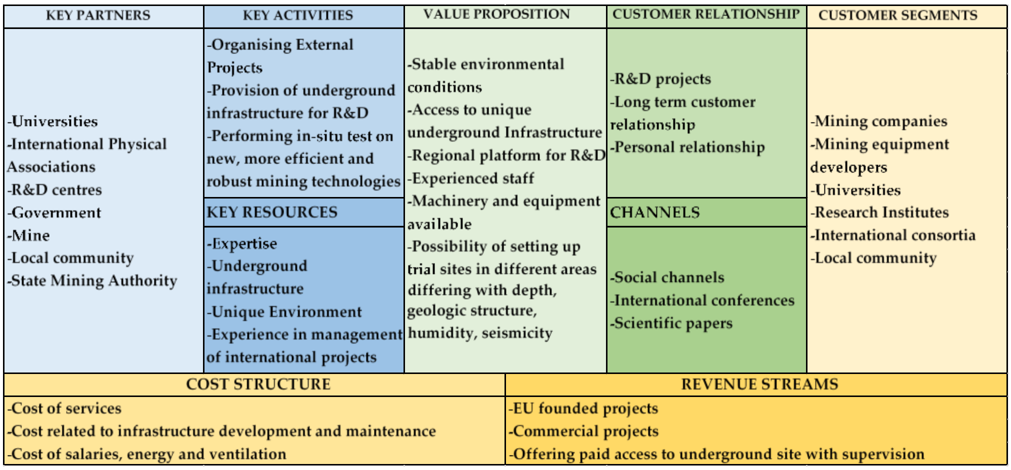

Figure 4. The general structure of the canvas business model worksheet for facility set up for development of new mining technologies.

3.2. Process of Service Development

Service design is an approach that uses design thinking to create new or improve existing services so that they are more desirable and useful by and for customers, as well as efficient and effective for service providers [64]. The following are the main principles of service design [65] that should be considered during the entire service design process, which includes the following stages: exploration, creation, reflection and implementation [66]:

- *Human-centered*: denoting the need to fully understand the impressions and experiences of all people affected by the service;
- *Collaborative*: meaning the need to integrate different points of view by involving different stakeholders in the service design process;
- *Iterative*: explaining that service design is an iterative process consisting of: exploration, adaptation, experimentation and implementation;
- *Sequencing*: meaning that the entire service process should be viewed as a sequence of interrelated activities;
- *Real*: about the fact that the customer needs research and concept prototyping should be real;
- *Holistic in nature*: emphasizing the need to have a broad perspective and considering the entire service environment. The service development process for underground

workings also has been described based on interviews with representatives of BSR underground laboratories in Figure 5.

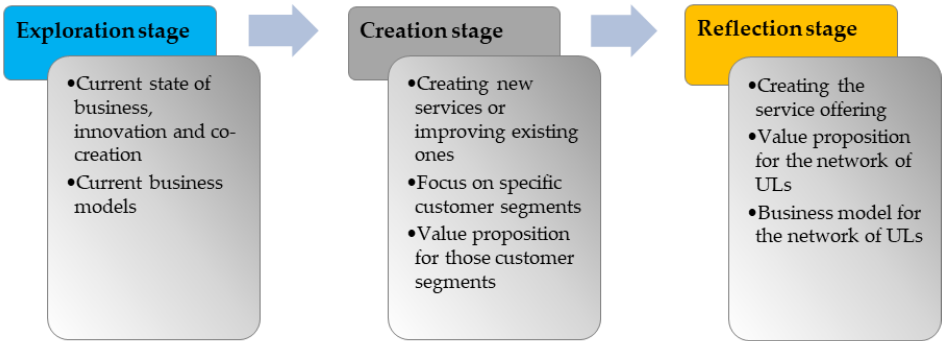

Figure 5. Stages of underground facility service development process.

3.3. Surveys with Stakeholders

The identification of stakeholders' opinions was based on interviews conducted with representatives of underground mines, state mining authorities, mining universities, research and development centers, and underground laboratories in BSR. The data collection questionnaires have been sent to the participant of the EUL project, from BSR countries. The structure of the questionnaire has been presented in Figure 6.

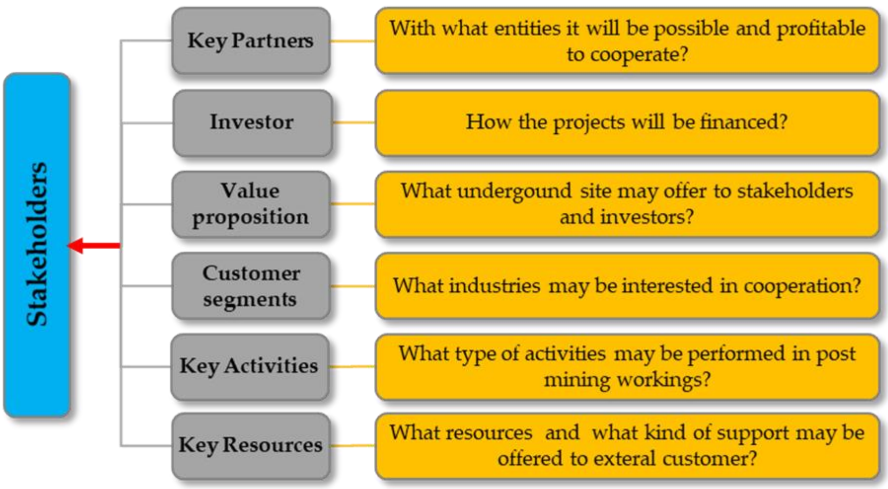

Figure 6. The topics which need to be solved during the identification of stakeholders.

3.4. The SWOT Analysis

Knowing the potential business model development, service design approach and stakeholders some, methods of underground mine reclamation may be determined. Still, in order to determine which idea is most feasible, a SWOT analysis has to be conducted. Such an approach is easy to implement and allows one to obtain all strengths, weaknesses, opportunities, and threats of each proposed solution. The details about SWOT analysis have been described in [67].

All abovementioned data have been collected among specialists and researchers representing underground facilities from Sweden, Germany and Switzerland, Poland, Finland and Russia who were involved in the process of data collection. Moreover, the analysis presented herein has been supported by representatives of KGHM copper mines, Poland, representatives of R&D centers, and universities from the European Underground Laboratories Association. As a result, a number of questionnaires have been collected. These data were used for determining what kind of repurpose are utilized in EU mines and what are the perspective ways concerning the business models, service design process, possible stakeholders, and SWOT.

4. Results and Discussion

Based on 29 questionnaires which were filled up by representatives of R&D centers, underground labs, universities, and representatives of state mining authorities the ways of underground workings readaptation were described and analyzed. The whole process of choosing the type of reclamation need to be supported by the development of the business model, service development, identification of stakeholders, and finally an analysis of strengths and weaknesses (Figure 7).

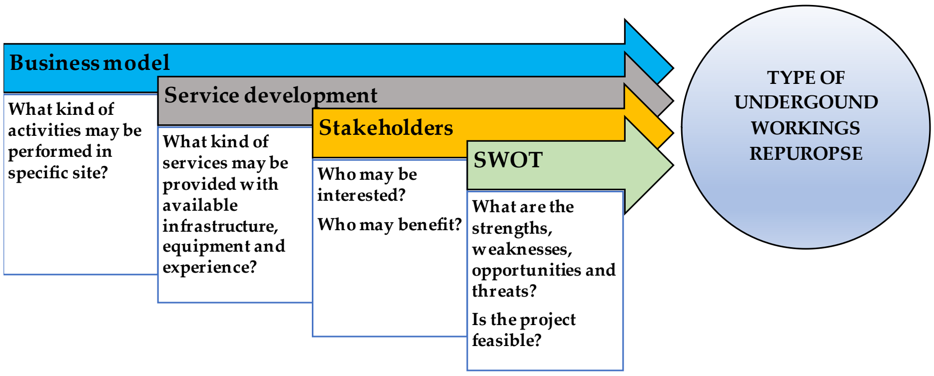

Figure 7. The topics which need to be solved during the identification of stakeholders.

Depending on the content analysis of present ways of underground laboratories functioning in BSR—on the basis of their business models, it may be concluded that the methods of underground space reclamation are in different stages of service business development due to the different nature of their contexts, the geomechanical conditions of surrounding rockmass, and location. Still, the actions aimed at repurposing of post-mining underground workings may be divided into three main groups. The first group gathers activities that lead to the permanent filling and liquidation of empty underground space, while the second is aimed at further exploitation of the unique environment. The last group is the multipurpose facility, combining different ways of workings adaptation. The classification of ways of underground mines reclamation is presented in Figure 8.

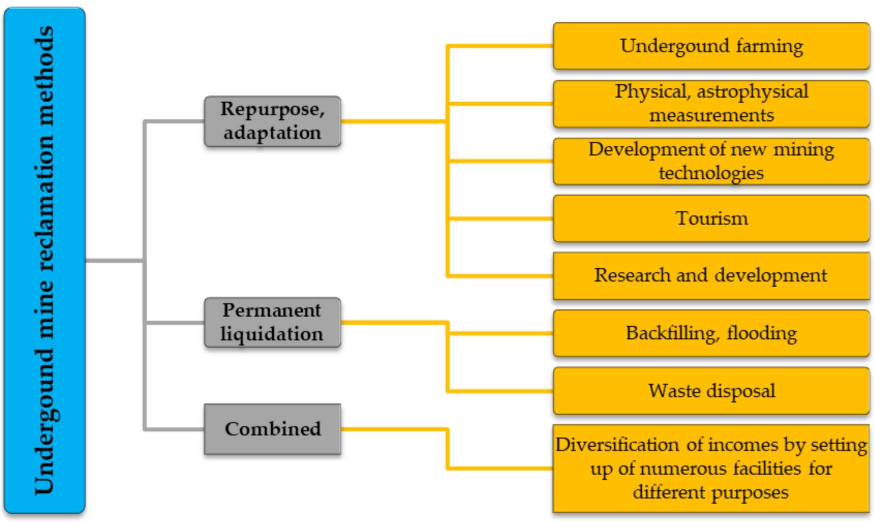

Figure 8. Prospective methods of underground workings repurposing according to surveys performed within the scope of EUL project.

All the above-presented methods, after detailed planning, may be economically justified and have a potential for further development. At the same time, all approaches have some strengths and weaknesses. A detailed analysis may be found in Supplementary Materials.

It is worth mentioning that according to SWOT analysis, the biggest strength of underground spaces is that they provide access to a unique environment with stable environmental conditions in terms of temperature, humidity, and natural background radiation. In turn, these unique conditions, are also related to unique hazards which are not observed in other facilities located on the surface. Therefore, numerous hazards and safety issues are mentioned as the biggest weakness in most of the analyses. Such a situation also affects the potential threats. Namely, hazardous environment, and high accident rates in the mining industry, turn into a lack of potential investors, which may be one of the biggest challenges during the running up of new venture. Subsidies by local governments or EU funds may be the solution, while according to current EU policy, the extended research and actions aimed into sustainable development, green technologies and development of new effective exploitation methods are strongly required. This may be a great opportunity.

In order to summarize the collected data, the quantitative results of SWOT analysis have been presented in Figures 9–11.

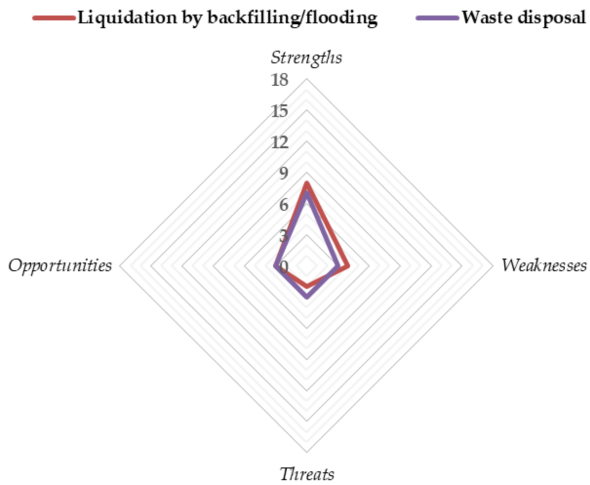

Figure 9. The quantitative results of SWOT analysis for reclamation methods aimed at permanent liquidation of underground workings.

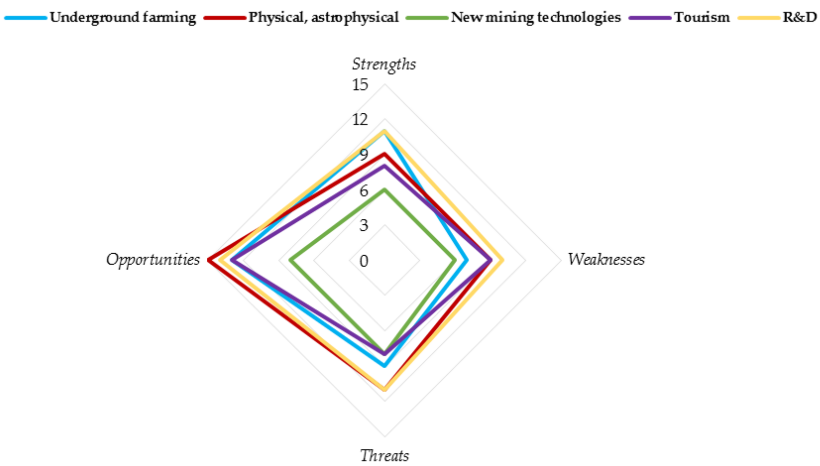

Figure 10. The quantitative results of SWOT analysis for reclamation methods aimed at adaptation and repurpose of underground workings.

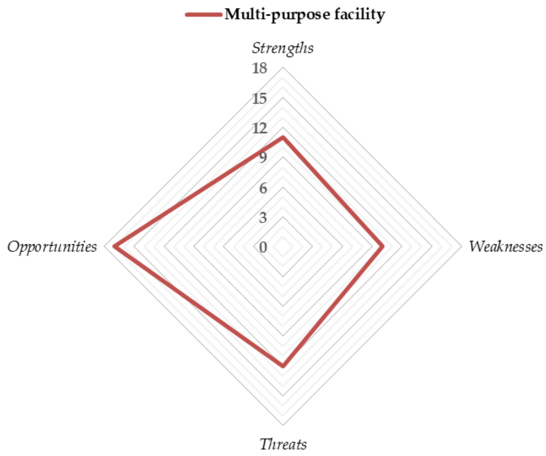

Figure 11. The quantitative results of SWOT analysis for reclamation methods aimed at combined/multidisciplinary repurposing of underground workings.

According to performed analyses, one may conclude that the most commonly used approach, based on permanent liquidation of underground workings in general, is the safest solution due to the low number of threats and weaknesses (Figure 9). Such an approach does not require further investments, and therefore is preferably utilized by most of the mining companies. However, more sophisticated solutions aimed at further exploitation of underground spaces may bring numerous advantages to local society as well as the science and mining industry. In fact, strengths and opportunities in analyzed cases are distributed parallel to weaknesses and threats related to each type of venture. As it may be noticed in analyzing Figure 10, the most promising facilities are those which are focused on astrophysical and physical measurements and those which are strictly related to performing R&D activities. At the same time, these approaches are burdened with the highest risk of project implementation. In turn, faculty dedicated solely for the development of new mining technologies is expected to provide the lowest incomes and is characterized by a low number of opportunities, and simultaneously is not characterized by many weaknesses and threats.

The best rate of opportunities and strengths in comparison to weaknesses and threats may be achieved by the setting up of numerous multidisciplinary facilities in the area of abandoned mines (Figure 11). Such a solution allows for the diversification of incomes. Moreover, as it may be concluded when analyzing the case study from Pyhäsalmi Mine, Finland, such approaches are proved to be economically efficient. However, what is worth mentioning is the fact that representatives of the mine and cooperating universities have started the marketing campaign a few years before mine closure. Such an approach would allow one to perform a smooth transition between an excavation-based business model to a research/science business model.

When analyzing the general challenges related to the transition from mining activities to science, tourism, and R&D, it must be borne in mind that most of the threats and weaknesses of such facilities are related to their hazardous environment and unfriendly conditions [21]. As a result, the way of perceiving this issue by potential investors is rather negative. Thus, much more attention has to be paid to marketing and the development of proper service design and business models.

After examining the service design and business models of currently working underground laboratories in Europe, it was concluded that in order to develop an economically justified service business, the managers of underground mines need to attract more investors and perform more proactive marketing communication. According to our analyses, the most important customer segments at the moment are universities and research institutes which gather funding mostly from international projects performed within large framework programs such as Horizon 2020, Horizon Europe, Interreg BSR, and EIT Raw

Materials. Still, these founding sources are temporary, and without commercialization of performed activities, the revenue streams are not substantial enough for the future. Moreover, the financial resources are generally scarce in many of the ULs, while their fixed costs are significant.

5. Conclusions

In this manuscript, the currently used and prospective methods of underground space reclamation have been reviewed and analyzed. The advantages and weaknesses of the selected methods of post-mining space repurposing have been examined in terms of their strengths and weaknesses. As our analysis showed, there a few methods of development of post-mining workings which will act as a base for achieving goals of sustainable development and circular economy, and the commonly used method of mine filling with water and wastes may be successfully replaced by more economically justified projects, which at the same time may support local communities in terms of both generated incomes, as well as in terms of maintenance of workplaces.

The detailed review of recent advances in that matter proved that use of post-mining underground space may be profitable not only in the scope of tourism but may also be a great accelerator of technology and science development.

Unfortunately, there are some challenges and further work aimed at broadening public awareness, and the awareness of investors is still needed. The heavy cost structure required is also a big challenge. A coherent vision and strategy for the future is a good starting point, as it would help to find new business opportunities and to attract new customer segments. Further, the organizational structure of the underground laboratories is quite complicated for many reasons. This can be tackled by good communication and organizational efforts by the underground laboratories, and they should also consider customer relationship management practices. On the other hand, there are unique strengths of such facilities lying with their human, intellectual, and environmental resources not present in other branches of industry.

Moreover, there is a high possibility that novel approaches to mine reclamation will gather social acceptance due to clearly visible profits for the local community. In an example, any R&D, science, or commercial activities will generate further income to the local budget. In turn, set up of the tourist route may also generate a great impact on the local tourism industry. At the same time in most cases, the environmental impact may be less than in the case of regular mining activities, which is in perfect accordance with the current EU policy and regulations.

Of course, it must be kept in mind that data presented in this manuscript do not represent universal solutions which may be implemented in every site. This is a general highlight for mine companies or potential investors of the methods of reclamation which are possible, and of which successful projects with a similar approach have been running at the moment. Therefore, each site, before implementation of any idea, should perform a detailed risk analysis, SWOT, develop a business model for the particular case, and design the offer of services which may lead a particular venture to successful finalization. Still, knowing the potential directions of development, managers of such facilities may look more broadly on their current activities, and hopefully will choose a way of further development.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14227551/s1, Table S1: Way of underground space repurposing: underground farming, Table S2: Way of underground space repurposing: physical, asrtophysical, measurements, Table S3: Way of underground space repurposing: development of new mining technologies, Table S4: Way of underground space repurposing: tourism, Table S5: Way of underground space repurposing: research and development, Table S6: Way of underground space repurposing: liquidation by backfilling/flooding, Table S7: Way of underground space repurposing: waste disposal, Table S8: Way of underground space repurposing: multi-purpose facility.

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References

1. Buchholz, P.; Brandenburg, T. Demand, Supply, and Price Trends for Mineral Raw Materials Relevant to the Renewable Energy Transition Wind Energy, Solar Photovoltaic Energy, and Energy Storage. *Chem. Ing. Tech.* **2018**, *90*, 141–153. [CrossRef]
2. Probst, L.; Frideres, L.; Cambier, B.; Hommel, S.; Luxembourg, P. *Sustainable Supply of Raw Materials—Innovative Mineral and Metallurgical Extraction and Processing*; European Commission: Luxembourg, 2016; Volume 17.
3. Sahu, H.B.; Prakash, N.; Jayanthu, S. Underground Mining for Meeting Environmental Concerns—A Strategic Approach for Sustainable Mining in Future. *Procedia Earth Planet. Sci.* **2015**, *11*, 232–241. [CrossRef]
4. Directorate-General for Internal Market, I.; Bobba, S.; Carrara, S.; Huisman, J.; Mathieux, F.; Pavel, C. *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study*; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-15336-8.
5. Kretschmann, J.; Efremenkov, A.B.; Khoreshok, A.A. From Mining to Post-Mining: The Sustainable Development Strategy of the German Hard Coal Mining Industry. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Yurga, Russian, 17–19 November 2016; IOP Publishing: Bristol, UK, 2017; Volume 50. [CrossRef]
6. Dias, P.; Kanellopoulos, K.; Medarac, H.; Kapetaki, Z.; Miranda-Barbosa, E.; Shortall, R.; Veronica, C.; Telsnig, T.; Cristina, V.-H.; Lacal Arantegui, R.; et al. *EU Coal Regions: Opportunities and Challenges Ahead*; Publications Office of the European Union: Luxembourg, 2018.
7. Ingram, T.; Bartuś, K.; Baron, M.; Bielecki, Ł. Sytuacja Przedsiębiorstw Okołogórniczych w Polsce, Ekspertyza Dotycząca Likwidacji Kopalń Węgla Kamiennego Dla Sektora Okołogórniczego Oraz Sytuacji Społeczno-Gospodarczej w Polsce, Etap I, Uniwersytet Ekonomiczny w Katowicach Na Zlecenie Górniczej Izby Przemysłowo Handlowej. 2020. Available online: http://www.giph.com.pl/files/Publikacje/Ekspertyza.pdf (accessed on 11 November 2021).
8. Kretschmann, J. Stakeholder Orientated Sustainable Land Management: The Ruhr Area as a Role Model for Urban Areas. *Vestnik* **2014**, *2*, 127–132. [CrossRef]
9. Smith, F.; Underwood, B. Mine Closure: The Environmental Challenge. *Min. Technol.* **2000**, *109*, 202–209. [CrossRef]
10. Müller, B.; Finka, M.; Lintz, G. (Eds.) The challenge of structural change for industrial cities and regions in the cee countries. In *Rise and Decline of Industry in Central and Eastern Europe: A Comparative Study of Cities and Regions in Eleven Countries*; Central and Eastern European Development Studies (CEEDES); Springer: Berlin/Heidelberg, Germany, 2005; ISBN 978-3-540-40478-1.
11. Wirth, P.; Mali, B.; Fischer, W. Problems and potentials of post-mining regions. In *Post-Mining Regions in Central Europe. Problems, Potentials, Possibilities*; OEKOM: Munich, Germany, 2012; ISBN 978-3-86581-294-0.
12. Kovalev, V.; Gerike, B.; Khoreshok, A.; Gerike, P. Preventive Maintenance of Mining Equipment Based on Identification of Its Actual Technical State. In Proceedings of the Taishan Academic Forum—Project on Mine Disaster Prevention and Control, Qingdao, China, 17–20 October 2014; pp. 184–189.
13. Tyulenev, M.; Zhironkin, S.; Litvin, O. The Low-Cost Technology of Quarry Water Purifying Using the Artificial Filters of Overburden Rock. *Pollut. Res.* **2015**, *34*, 825–830.
14. Tyulenev, M.; Gvozdkova, T.; Zhironkin, S.; Garina, E. Justification of Open Pit Mining Technology for Flat Coal Strata Processing in Relation to the Stratigraphic Positioning Rate. *Geotech. Geol. Eng.* **2016**, *35*, 203–212. [CrossRef]
15. Kosmaty, J. Wałbrzyskie tereny pogórnicze po 15 latach od zakończenia eksploatacji węgla (EN: Wałbrzych post-mining land 15 years after coal extraction was ended). *Górnictwo Geol.* **2011**, *6*, 131–148.

16. *Statistical Yearbooks of the Wałbrzych Voivodeship: 1977, R.1; 1979, R 3; 1981 R. 5; 1985 R.7; 1987 R. 9; 1991, R. 11; 1993, R. 12; 1995, R.9; 1997, R. 16*; Wojewódzki Urząd Statystyczny w Wałbrzychu (Śląska Biblioteka Cyfrowa): Wałbrzych, Poland. Available online: https://sbc.org.pl/access (accessed on 4 November 2021).
17. Shekov, V.; Ivanov, A.; Jalas, P.; Laaksoharju, M.; Horner, D. BSUIN—A Unique Innovation Programme for Underground Space Development to Be Tested in the Ruskeala Marble Quarry and Sortavala Geopark. In Proceedings of the 18th International Multidisciplinary Scientific GeoConference, Albena, Bulgaria, 2–8 July 2018.
18. Shekov, V.; Jalas, P.; Joutsenvaara, J.; Kisiel, J.; Laaksoharju, M.; Pytel, W.; Horner, D.; Mischo, H.; Giese, R.; Mockus, V.; et al. BSUIN Project as an Innovative Platform for Mining&Industrial Underground Heritage Investigation in Russia. In Proceedings of the International conference "InterCarto. InterGIS", Petrozavodsk, Russia, 19–22 July 2018; Volume 24, pp. 285–296.
19. Chugh, Y.P. Concurrent Mining and Reclamation for Underground Coal Mining Subsidence Impacts in China. *Int. J. Coal Sci. Technol.* **2018**, *5*, 18–35. [CrossRef]
20. Dodd, W.E. Evaluating Underground Mine Reclamation Projects in North Dakota. In Proceedings of the 35th Annual Conference of the National Association of Abandoned Mine Land Programs, Danields, WV, USA, 22–25 September 2013.
21. Pytel, W.; Fuławka, K.; Pałac-Walko, B.; Mertuszka, P.; Kisiel, J.; Jalas, P.; Joutsenvaara, J.; Shekov, V. Universal Approach for Risk Identification and Evaluation in Underground Facilities. *Min. Sci.* **2020**, *27*, 165–181. [CrossRef]
22. Shekov, V.; Shekov, K.; Fuławka, K.; Pytel, W. Safe Use of Mining-and-Industrial Heritage and Underground Space in Tourism Sector. In Proceedings of the 19th International Multidisciplinary Scientific GEO Conference, Vienna, Austria, 28 June–7 July 2019; SGEM WORLD SCIENCE, Technology Ltd.: Albena, Bulgaria, 2019; Volume 19, pp. 569–577.
23. Shekov, K.; Muller, T.; Fuławka, K.; Joutsenvaara, J. Legislative Control over Use of Old Mine Workings for Learning Purposes. *Gorn. Zhurnal* **2019**, *3*, 11–16. [CrossRef]
24. Pactwa, K.; Woźniak, J.; Dudek, M. Sustainable Social and Environmental Evaluation of Post-Industrial Facilities in a Closed Loop Perspective in Coal-Mining Areas in Poland. *Sustainability* **2021**, *13*, 167. [CrossRef]
25. Morseletto, P. Targets for a Circular Economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553. [CrossRef]
26. Xie, H.; Zhao, J.W.; Zhou, H.W.; Ren, S.H.; Zhang, R.X. Secondary Utilizations and Perspectives of Mined Underground Space. *Tunn. Undergr. Space Technol.* **2020**, *96*, 103129. [CrossRef]
27. Cui, C.-Q.; Wang, B.; Zhao, Y.-X.; Xue, L.-M. Waste Mine to Emerging Wealth: Innovative Solutions for Abandoned Underground Coal Mine Reutilization on a Waste Management Level. *J. Clean. Prod.* **2020**, *252*, 119748. [CrossRef]
28. Edwards, J.A.; Coit, J.C.L. Mines and Quarries: Industrial Heritage Tourism. *Ann. Tour. Res.* **1996**, *23*, 341–363. [CrossRef]
29. Olszewski, J.; Chruścielewski, W.; Jankowski, J. Radon on Underground Tourist Routes in Poland. *Int. Congr. Ser.* **2005**, *1276*, 360–361. [CrossRef]
30. Olszewski, J.; Zmyślony, M.; Wrzesień, M.; Walczak, K. Occurrence of radon in the Polish underground tourist routes. *Med. Pr.* **2015**, *66*, 557–563. [CrossRef]
31. Dos Santos Costa, S.S.; Santos, E. Mining Tourism and Geotourism: Alternatives Solutions to Mine Closure and Completion. In *24th World Mining Congress Proceedings: Sustainability in Mining*; IBRAM: Rio de Janeiro, Brazil, 2016; pp. 301–309, ISBN 978-85-61993-11-5.
32. World Travel & Tourism Council (WTTC). *Travel & Tourism Economic Impact 2021: Global Economic Impact&Trends 2021*; World Travel & Tourism Council (WTTC): London, UK, 2021.
33. Alexandrowicz, Z.; Urban, J.; Andreychouk, V. Crystal Caves in the 'Wieliczka' Salt Mine—Unique Cave Site. *Z. Geomorphol. Suppl. Issues* **2021**, *62*, 235–254. [CrossRef]
34. Ćopić, S.; Đorđevića, J.; Lukić, T.; Stojanović, V.; Đukičin, S.; Snežana, B.; Igor, S.; Aleksandar, T. Transformation of Industrial Heritage: An Example of Tourism Industry Development in the Ruhr Area (Germany). *Geogr. Pannonica* **2014**, *18*, 43–50. [CrossRef]
35. Armis, R.; Kanegae, H. The Attractiveness of a Post-Mining City as a Tourist Destination from the Perspective of Visitors: A Study of Sawahlunto Old Coal Mining Town in Indonesia. *Asia-Pac. J. Reg. Sci.* **2019**, *4*, 443–461. [CrossRef]
36. Hattori, K.; Kaido, K.; Matsuyuki, M. The Development of Urban Shrinkage Discourse and Policy Response in Japan. *Cities* **2017**, *69*, 124–132. [CrossRef]
37. Akhtar, N.; Khan, N.; Mahroof Khan, M.; Ashraf, S.; Hashmi, M.S.; Khan, M.M.; Hishan, S.S. Post-COVID 19 Tourism: Will Digital Tourism Replace Mass Tourism? *Sustainability* **2021**, *13*, 5352. [CrossRef]
38. Wycieczki Panoramiczne-Muzeum Górnictwa Węglowego w Zabrzu. Available online: https://www.ai360.pl/panoramy/609,5033 (accessed on 25 July 2021).
39. Museum of Mines of Mercury Monte Amiata, Santa Fiora, Grosseto, Włochy. Available online: https://artsandculture.google.com/incognito/partner/museo-delle-miniere-di-mercurio-del-monte-amiata (accessed on 25 July 2021).
40. Sterling, R.; Admiraal, H.; Bobylev, N.; Parker, H.; Godard, J.-P.; Vähäaho, I.; Rogers, C.D.F.; Shi, X.; Hanamura, T. Sustainability Issues for Underground Space in Urban Areas. *Proc. Inst. Civ. Eng.-Urban Des. Plan.* **2012**, *165*, 241–254. [CrossRef]
41. Bartel, S.; Janssen, G. Underground Spatial Planning—Perspectives and Current Research in Germany. *Tunn. Undergr. Space Technol.* **2015**, *55*, 112–117. [CrossRef]
42. Bettini, A. New Underground Laboratories: Europe, Asia and the Americas. *Phys. Dark Universe* **2014**, *4*, 36–40. [CrossRef]
43. Best, A.; Caciolli, A.; Fülöp, Z.; Gyürky, G.; Laubenstein, M.; Napolitani, E.; Rigato, V.; Roca, V.; Szücs, T. Underground Nuclear Astrophysics: Why and How. *Eur. Phys. J. A* **2016**, *52*, 72. [CrossRef]

44. Guglielmetti, A. Nuclear Astrophysics and Underground Accelerators. *Phys. Dark Universe* **2014**, *4*, 10–13. [CrossRef]
45. Cerna, C. The Jiangmen Underground Neutrino Observatory (JUNO). *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip.* **2020**, *958*, 162183. [CrossRef]
46. Bellerive, A.; Klein, J.R.; McDonald, A.B.; Noble, A.J.; Poon, A.W.P. The Sudbury Neutrino Observatory. *Nucl. Phys. B* **2016**, *908*, 30–51. [CrossRef]
47. Trzaska, W.H.; Bezrukov, L.; Enqvist, T.; Joutsenvaara, J.; Kuusiniemi, P.; Loo, K.; Lubsandorzhiev, B.; Sinev, V.; Slupecki, M. Possibilities for Underground Physics in the Pyhasalmi Mine. In Proceedings of the Thirteenth Conference on the Intersections of Particle and Nuclear Physics (CIPANP2018), Palm Springs, CA, USA, 28 May–3 June 2018.
48. Jalas, P.; Enqvist, T.; Isoherranen, V.; Joutsenvaara, J.; Kutuniva, J.; Kuusiniemi, P. Callio Lab, a New Deep Underground Laboratory in the Pyhäsalmi Mine. *J. Phys. Conf. Ser.* **2017**, *888*, 012156. [CrossRef]
49. Underground Experiment Sites. Available online: http://www.skbinternational.se/laboratory-services/underground-experiment-sites/ (accessed on 5 November 2021).
50. Schlueter, R.; Mischo, H. Potential and Applications of Underground in Situ Bioleaching. In Proceedings of the 3rd International Future Mining Conference, Sydney, Australia, 4–6 November 2015.
51. Eisen, N.; Schlömann, M.; Schopf, S. Bioleaching of Indium-Bearing Sphalerite under Underground Mining Temperatures. In Proceedings of the IMWA 2016—Mining Meets Water—Conflicts and Solutions, Freiberg, Germany, 1 July 2016.
52. Wiatowski, M.; Stańczyk, K.; Świądrowski, J.; Kapusta, K.; Cybulski, K.; Krause, E.; Grabowski, J.; Rogut, J.; Howaniec, N.; Smoliński, A. Semi-Technical Underground Coal Gasification (UCG) Using the Shaft Method in Experimental Mine "Barbara". *Fuel* **2012**, *99*, 170–179. [CrossRef]
53. Prostański, D. Experimental Study of Coal Dust Deposition in Mine Workings with the Use of Empirical Models. *J. Sustain. Min.* **2015**, *14*, 108–114. [CrossRef]
54. Kramarczyk, B.; Pytlik, M.; Mertuszka, P. Effect of Aluminium Additives on Selected Detonation Parameters of a Bulk Emulsion Explosive. *Mater. Wysokoenerg. High Energy Mater.* **2020**, *12*, 99–113. [CrossRef]
55. Mertuszka, P.; Fuławka, K.; Pytlik, M.; Szastok, M. The Influence of Temperature on the Detonation Velocity of Selected Emulsion Explosives. *J. Energ. Mater.* **2020**, *38*, 336–347. [CrossRef]
56. Saigustia, C.; Robak, S. Review of Potential Energy Storage in Abandoned Mines in Poland. *Energies* **2021**, *14*, 6272. [CrossRef]
57. Hahn, F.; Jagert, F.; Bussmann, G.; Nardini, I.; Bracke, R.; Seidel, T.; Konig, T. The Reuse of the Former Markgraf II Colliery as a Mine Thermal Energy Storage. In Proceedings of the European Geothermal Congress 2019, Den Haag, The Netherlands, 11–14 June 2019.
58. Menendez, J.; Ordóñez, M.A.; Alvarez, R.; Loredo, J. Energy from Closed Mines: Underground Energy Storage and Geothermal Applications. *Renew. Sustain. Energy Rev.* **2019**, *108*, 498–512. [CrossRef]
59. Li, B.; Zhang, J.; Ghoreishi-Madiseh, S.A.; Brito, M.; Xuejie, D.; Kuyuk, A. Energy Performance of Seasonal Thermal Energy Storage in Underground Backfilled Stopes of Coal Mines from China. *J. Clean. Prod.* **2020**, *275*, 122647. [CrossRef]
60. GreenForges Website. Available online: https://www.greenforges.com/team (accessed on 10 May 2021).
61. Van Hooijdonk, R. Vertical Farming Goes High-Tech and Underground. Available online: https://www.hortibiz.com/newsitem/?tx_news_pi1%5Bnews%5D=37302&cHash=4a0918ebe1ad8b0653f72a5be5c27757 (accessed on 10 May 2021).
62. Callio, P. Edible Insects. Available online: https://callio.info/natural-resources-business/edible-insects/ (accessed on 10 May 2021).
63. Osterwalder, A.; Pigneur, Y. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers | Wiley*; Wiley & Sons: Hoboken, NJ, USA, 2010; ISBN 978-0-470-87641-1.
64. Moritz, S. Service Design—Practical Access to an Evolving Field. *Köln Int. Sch. Des.* **2005**, *246*.
65. Stickdorn, M.; Edgar Hormess, M.; Lawrence, A.; Schneider, J. *This Is Service Design Doing. Applying Service Design Thinking in the Real World*; A Practitioner's Handbook; O'Reilly Media, Inc.: Sebastopol, CA, USA, 2018; ISBN 978-1-4919-2718-2.
66. Stickdorn, M.; Schneider, J. *This Is Service Design Thinking: Basics, Tools, Cases*; BIS Publishers: Amsterdam, The Netherlands, 2011; ISBN 978-1-118-15630-8.
67. Clardy, A. Strengths vs. Strong Position: Rethinking the Nature of SWOT Analysis. *Mod. Manag. Sci. Eng.* **2013**, *1*, 100–122.