
Article

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

Katarzyna Pactwa ^{1,*}, Martyna Konieczna-Fuławka ¹, Krzysztof Fuławka ², Päivi Aro ³, Izabela Jaśkiewicz-Proć ² and Aleksandra Kozłowska-Woszczycka ¹

¹ Faculty of Geoengineering, Mining and Geology, Wrocław University of Science and Technology, 15 Na Grobli Street, 50-421 Wrocław, Poland; martyna.konieczna-fulawka@pwr.edu.pl (M.K.-F.); aleksandra.kozlowska@pwr.edu.pl (A.K.-W.)

² KGHM Cuprum Ltd. Research & Development Centre, 2-8 Sikorskiego Street, 53-659 Wrocław, Poland; kfulawka@cuprum.wroc.pl (K.F.); ijaskiewicz@cuprum.wroc.pl (I.J.-P.)

³ School of Business and Information Management, Oulu University of Applied Sciences, Business, Yliopistonkatu 9, 90570 Oulu, Finland; paivi.aro@oamk.fi (P.A.)

* Correspondence: katarzyna.pactwa@pwr.edu.pl; Tel.: +48-71-320-68-51

Supplementary Materials

SWOT analysis of Underground mine reclamation methods

Table S1. Way of underground space repurposing: underground farming.

Strengths	Weaknesses	Threats	Opportunities
Constant temperature and other atmospheric conditions	The need to provide artificial lighting	The occurrence of natural risks like floods, gases, seismic activity, lack of lightning	The possibility of breeding species that are difficult or impossible to maintain due to climate in certain country
Sustainable agriculture - no need to convert land into agricultural (often by deforestation)	Lack of natural ventilation	Legal obstacles and regulations (or lack thereof) to new underground activities	The possibility of guided tours
Isolating invasive species from the natural ecosystem (e.g. In the case of exotic farms)	Limited and relatively expensive space	Safety issues - accidents might be caused by old infrastructure	Accelerated vegetation
Infrastructure	Safety issues (personal protection)	Big investment costs	The possibility of breeding both plants and animals - for example, some insects
Closed ecological system	The need for constant monitoring of safety parameters	Need for an entirely new business model	Cooperation with schools and universities
The ability to control weather conditions	Possible seismic activity	New, qualified staff is needed	New workplace for local people
Environmentally friendly	More strict/limited working hours due to harsh environment	Environmental restrictions	The possibility of obtaining a subsidy
Farming possible all year round	Possible seismic activity and problem with ground control	Space/area limitations	Farming in closed-loop system requires less water consumption
Prepared infrastructure		In urbanised areas, further incidents related to seismicity and ground settlement may be observed	Alternative source of food production and minimization of food shortages
Reclamation has support from local authority			Academic assistance
Support of mine employees will be required			Diversification of income sources
			Public private Partnerships (PPP)
			Fulfil the requirements of circular economy and sustainable development.

Table S2. Way of underground space repurposing: physical, asrtophysical, measurements.

Strengths	Weaknesses	Threats	Opportunities
Closed ecological system,	Need of additional specialized staff	The occurrence of natural risks like floods, gases, seismic activity, lack of lightning	The possibility of obtaining a subsidy
The ability to conduct (even dangerous) experiments without affecting the external environment	Limited and relatively expensive space	During the underground research water poisoning is possible	Cooperation with schools and universities
Constant temperature and other atmospheric conditions	Safety issues (personal protection)	Legal obstacles and regulations (or lack thereof) to new underground activities	The possibility of conducting even dangerous experiments without affecting the environment
Isolation from external factors	The need to provide artificial lighting	Safety issues - accidents might be caused by old infrastructure	Wide range of research possibilities
Interdisciplinary research approach	Lack of natural ventilation	Scaling down of facilities and loss of scientific potential if case of lack of external funding	A place for testing new technologies for the military, space organizations, etc.
Researched and documented geology and Geophysics	The need for constant monitoring of safety parameters	Need for an entirely new business model	Fulfil the requirements of circular economy and sustainable development
Prepared infrastructure	More strict/limited working hours due to harsh environment	New, qualified staff is needed	Workshops and camp of science
Room for laboratories without need of major changes	Once disturbed formation is not adequate to study natural conditions	Environmental restrictions	Opportunities of new technology development
Support of mine employees will be required	Possible seismic activity and problem with ground control	Uncertain future – profits may be not enough to maintain whole infrastructure and staff	Safety storage for documents or servers
		Space/area limitations	Lobbying or research organizations support
		In urbanised areas, further incidents related to seismicity and ground settlement may be observed	Establishing a new business environment
			Diversification of income sources
			This type of reclamation has a great possibility of getting support from local authorities and EU found
			Incubator of business
			Public private Partnerships (PPP)

Table S3. Way of underground space repurposing: development of new mining technologies.

Strengths	Weaknesses	Threats	Opportunities
Unique environment which allows to test new technologies in real working conditions	Safety issues (personal protection)	The occurrence of natural risks like floods, gases, seismic activity, lack of lightning	The possibility of obtaining a subsidy from local government, or EU
Occurrence of multiple factors affecting efficiency of equipment which cannot be simulated in laboratory conditions	Risk that there will be no external customers which will provide sufficient incomes	During the underground tests ground control problems may be induced	Cooperation with business, universities and R&D centres
Prepared infrastructure	The need to maintain infrastructure and media what is related to high costs	Legal obstacles and regulations (or lack thereof) to new underground activities	New technologies, will affect the efficiency and sustainability of mineral and CRMs extraction
Room for laboratories without need of major changes	Lack of natural ventilation	Safety issues and high accident rates related to the risky environment	The best trail site for new mining technologies testing and development
No need of additional highly qualified staff	The need for constant monitoring of safety parameters	There is a risk that innovative equipment, machines and sensors will be damaged or even destroyed	Due to the lack of such facilities, there is high possibility of international cooperation
Support of mine employees will be required	More strict/limited working hours due to harsh environment	Uncertain future – profits may be not enough to maintain whole infrastructure and staff	Such facilities may be set up during the process of regular mine exploitation. There is no need for waiting until the end of mining works.
		In urbanised areas, further incidents related to seismicity and ground settlement may be observed	Allow to maintain jobs for local community with no need to retrain of the employees
		Lack of clients	Fulfil the requirements of circular economy and sustainable development.

Table S4. Way of underground space repurposing: tourism.

Strengths	Weaknesses	Threats	Opportunities
Interesting and unique infrastructure and environment	Safety issues (personal protection)	The risk of accidents, heart attacks and other health detriment due to the harsh environment	The possibility of obtaining a subsidy from local government and EU
There is no need to incur additional significant costs	Risk that tourists won't come back again (underground site won't change significantly due to safety regulations)	Legal obstacles and regulations (or lack thereof) to new underground activities	Cooperation with schools and universities
Affect on development of local tourism - Historical area with mining traditions	The need to provide artificial lighting	Safety issues - accidents might be caused by old infrastructure	Virtual tour
Qualified staff is available	Lack of natural ventilation	Tourism might not generate enough income to maintain the infrastructure	Entertainment events
Open all year round	The need for constant monitoring of safety parameters	The constant need to acquire new customers and promote facility	Historical centre of knowledge About the mine
Prepared infrastructure	Difficult access to particular places in the mine due to safety issues	Environmental restrictions	Mining study area for mining schools
Highly probable that this way of reclamation will be supported by local authority	Additional security measures are required to ensure the safety of visitors	Lack of clients	Academic assistance
Support of mine employees will be required	Possible problems with ground control	Need for an entirely new business model	Workshops and camp of science
	Only the safest part of the mine may be part of the tourist route		Possible development of underground facilities for purposes different than tourism
			Possibility to create attractions such as adventure park or escape rooms
			School and academic trips
			Public private Partnerships (PPP)
			Fulfil the requirements of circular economy and sustainable development

Table S5. Way of underground space repurposing: research and development.

Strengths	Weaknesses	Threats	Opportunities
Closed ecological system,	Need of additional specialized staff (depend on type of R&D activities)	The occurrence of natural risks like floods, gases, seismic activity, lack of lightning	The possibility of obtaining a subsidy
The ability to conduct (even dangerous) experiments without affecting the external environment	The need to maintain infrastructure and media what is related to high costs	During the underground research water poisoning is possible	Cooperation with schools and universities
Constant temperature and other atmospheric conditions	Safety issues (personal protection)	Legal obstacles and regulations (or lack thereof) to new underground activities	The possibility of conducting even dangerous experiments without affecting the environment
Isolation from external factors	The need to provide artificial lighting	Safety issues - accidents might be caused by old infrastructure	Wide range of research possibilities
Interdisciplinary research approach	Lack of natural ventilation	Scaling down of facilities and loss of scientific potential if case of lack of external funding	A place for testing new technologies for the military, space organizations, etc.
Researched and documented geology and geophysics	The need for constant monitoring of safety parameters	Need for an entirely new business model	Academic assistance
Prepared infrastructure	More strict/limited working hours due to harsh environment	New, qualified staff is needed	Workshops and camp of science
Room for laboratories without need of major changes	Once disturbed formation is not adequate to study natural conditions	Environmental restrictions	Opportunities of new technology development
Support of mine employees will be required	Possible seismic activity and problem with ground control	Uncertain future – profits may be not enough to maintain whole infrastructure and staff	Safety storage for documents or servers
Highly probable that this way of reclamation will be supported by local and EU Funds	More strict/limited working hours due to harsh environment	Space/area limitations	Lobbying or research organizations support
Suitable place for innovative R&D projects		In urbanised areas, further incidents related to seismicity and ground settlement may be observed	Establishing a new business environment
Diversification of income sources			

Public private
Partnerships (PPP)
Fulfil the requirements of circular
economy and sustainable
development

Table S6. Way of underground space repurposing: liquidation by backfilling/flooding.

Strengths	Weaknesses	Threats	Opportunities
A well-known, widely used solution	No new workplaces after mine closure	Not an innovative approach	Socially accepted by the general public
Once the mine is closed, no further maintenance will be required	Long-time monitoring of the backfill and shaft condition might be needed	Affects of high local unemployment rate after mine closure	Prevent further costs related to compensation for damages of buildings, roads and trails.
No additional cost after the mine is closed	Does not fulfil the goals of CE and SD		Using energy from the mining waters of closed mining plants/flooded mines
Short time required for liquidation	Facility is permanently damaged, destroyed and any repurpose activities in future are related to high costs		
Relatively low costs of mine liquidation			
Cheap and available backfilling materials			
Prevent ground settlement and infrastructure damages			
Prevent mining induced seismic activity			

Table S7. Way of underground space repurposing: waste disposal.

Strengths	Weaknesses	Threats	Opportunities
A well-known, widely used solution	No new workplaces after mine closure	Not an innovative approach	Backfilling with waste (for example post-flotation waste)
Once the mine is closed, no further maintenance will be required	During the waste storing process, the mine generates only costs, without significant incomes.	After filling up with wastes the mine cannot be reused	Possibility of storage highly dangerous radioactive wastes.
No additional cost after mine closure	Does not fulfil the goals of CE and SD	Possible contamination of underground water	Socially accepted by the general public
Relatively low costs of mine liquidation			
It makes it possible to slow down the increase in local unemployment			

during the phase of
filling mines with wastes

Prevent ground
settlement and
infrastructure damages

Prevent mining induced
seismic activity

Table S8. Way of underground space repurposing: multi-purpose facility.

Strengths	Weaknesses	Threats	Opportunities
Diversification of costs and incomes	Need of additional specialized staff (depend on type of R&D activities)	The occurrence of natural risks like floods, gases, seismic activity, lack of lightning	The possibility of obtaining a subsidy national and EU
The ability to conduct (even dangerous) experiments without affecting the external environment	The need to maintain infrastructure and media what is related to high costs	During the underground research water poisoning is possible	Cooperation with schools and universities
Constant temperature and other atmospheric conditions	Safety issues (personal protection)	Legal obstacles and regulations (or lack thereof) to new underground activities	The possibility of conducting even dangerous experiments without affecting the environment
Isolation from external factors	The need to provide artificial lighting	Safety issues - accidents might be caused by old infrastructure	Wide range of research possibilities
Interdisciplinary research approach	Lack of natural ventilation	Scaling down of facilities and loss of scientific potential if case of lack of external funding	A place for testing new technologies for the military, space organizations, etc.
Mine may be divided into segments for different parts of activities (tourism, R&D, Backfilling)	The need for constant monitoring of safety parameters	Need for an entirely new business model	Academic assistance
Prepared infrastructure	More strict/limited working hours due to harsh environment	New, qualified staff is needed	Workshops and camp of science
Room for laboratories without need of major changes	Once disturbed formation is not adequate to study natural conditions	Environmental restrictions	Opportunities of new technology development
Support of mine employees will be required – slow down or even prevent unemployment after mine closure	Possible seismic activity and problem with ground control	Uncertain future – profits may be not enough to maintain whole infrastructure and staff	Safety storage for documents or servers
Highly probable that this way of reclamation will be supported by local and EU Funds	More strict/limited working hours due to harsh environment	Space/area limitations	Lobbying or research organizations support
Suitable place for innovative R&D projects		In urbanised areas, further incidents related to seismicity	Establishing a new business environment

Strengths	Weaknesses	Threats	Opportunities
		and ground settlement may be observed	
		Need for an entirely new business model	Diversification of income sources
			Public private Partnerships (PPP)
			Fulfil the requirements of circular economy and sustainable develop- ment
			Attractive for commercial custom- ers, scientists and tourists
			Combination of different research facilities with tourism will affect on tourist potential (if possible to show underground labs/facilities to visitors)
			Partly backfilled workings will al- low to reduce wastes on surface and will affect on safety in under- ground