Post-mining for a better future: The development of the research centre of post-mining at the TH Georg Agricola University

J. Kretschmann, P. Goerke-Mallet, C. Dauber, and M. Hegemann

TH Georg Agricola University, Germany

The European Union (EU) energy policy favours the decarbonisation of Europe to reduce the risks of global climate change. Germany, for example, has committed to phasing out the use of coal for power generation by 2038, possibly earlier. This strategy ensures responsible and sustainable management of the climatic consequences of more than 200 years of coal production and use. The Research Center of Post-Mining (FZN) at the TH Georg Agricola University in Bochum, North Rhine-Westphalia, Germany, has developed a holistic approach to meet the challenges of the post-mining era. It includes four strategic pillars: (1) Perpetual tasks and mine water management to prevent and mitigate groundwater-related environmental risks; (2) Geo monitoring to protect the surface from mine subsidence and related damage; (3) Material science for the preservation of industrial heritage to secure and reuse brownfields such as mine sites; and (4) Reactivation and transition of mining regions to support future generations with sustainable living perspectives. A dynamic process is unfolding within the research centre based on a steady expansion of the scientific challenges in a complex and new academic field. The research centre aims to meet the UN Sustainable Development Goals by becoming responsible and sustainable stewards of the earth's resources. The FZN is part of a national and international network of science and practice in the interest of all social groups that depend on these resources.

Keywords: Education, mine life cycle, earth's resources, risk, opportunities, research, network

HISTORY OF THE THGA AND THE FOUNDATION OF THE RESEARCH CENTRE OF POST-MINING (FZN)

The predecessor of the THGA, the Märkische Bergschule (School of Mines) Bochum, was founded in 1816 by order of the Prussian Mining Authority. The aim was to train supervisors - pit foremen and mine managers - who were needed to run the Ruhr coal mines in the early phase of the industrial age. The rapid growth of the coal industry in the Ruhr area started in the mid-19th century, characterised by industrial and technological development, a rapidly growing demand for labour, and a steady influx of people from neighbouring regions. The Bergschule became part of the Westfälische Berggewerkschaftskasse (WBK), a nonprofit support organisation for the mining industry, jointly financed by the mining companies. WBK established scientific research institutes and departments to support mine rescue, mine fire, explosion prevention, safe blasting technologies, coal chemistry, rope testing, mine surveying, and geology. Figure 1 shows a photo of students and faculty of the Bergschule in 1895.

Figure 1. Students and teachers of the Mining School Bochum in 1895.

After World War II, the British occupying powers recognised the importance of the mining school in the German coal industry's recovery. They permitted the Bergschule to re-open in November 1945. Increasing mechanisation and technological development in the German coal industry led to curricular reforms that adopted modern engineering and academic standards. In 2016, the School of Mining Engineering was renamed Technische Hochschule Georg Agricola (THGA) University (Kretschmann and Düppe, 2016).

In 2007, the industry, government, and unions decided to phase out the German hard coal mining activities by 2018. This planned cessation of active coal mining implied substantive and financial implications for the THGA. New study programmes were created for the aggregates industries, geotechnical engineering, applied geology, environmental engineering, and THGA re-focused to support all mineral commodities. Today, THGA offers eight Bachelor of Engineering and six Master of Engineering programmes related to mineral resources, mechanical, and electrical engineering. In more than 150 years of industrial coal mining, around 10 billion tons of coal have been extracted in the Ruhr region, massively transforming the region and the landscape. However, the cessation of active mining has not erased the impacts of mining on the surface, landscape, and region. Reclaiming mine lands and other post-mining tasks in the densely populated Ruhr region are extensive, technically challenging, and will continue over a long period of time. THGA decided to make post-mining issues a focal point in its teaching and research to meet these challenges. The university had been actively supporting coal mining in Ruhr for over 200 years; now the post-mining, reclamation and restructuring tasks must be carried out responsibly and sustainably. In 2011, THGA introduced a master's degree called geoengineering and post-mining as a first step. This programme aims to provide students with the knowledge and scientific skills they need to address the technical challenges of post-mining. A further and significant step was founding the FZN in June 2015.

Post-mining education – the basis for post-mining excellence

Post-mining excellence requires high motivation and a high level of abilities and skills. Without crucial elements like ideas and vision, research and development, integration of surface and underground challenges, and risk management, post-mining will be inefficient, based on short-term thinking, muddling through, or in the worst case, on lip service. High motivation needs a change of mindset: post-mining strategy no longer means simply avoiding certain hazards but has to be seen as an evolutionary, sustainable process that is based on the management of risks and the utilisation of opportunities. This process should be encouraged by relevant governmental regulations and incentives to promote ideas, support research and development, and run high-profile 'flagship' projects profitably. Implementing such innovative projects at old mine sites is often a milestone for mining communities on their long road to a brighter future. To improve abilities and skills, the existing network of

companies, universities, government institutions, mining authorities, and research centres can be used. Its members can promote the transfer of both knowledge and technologies.
To competently develop post-mining management, a sufficient number of experts and executives have to be qualified in this field (Figure 2). To this end, THGA offers the Master of Engineering programme in geoengineering and post-mining.

Figure 2. Researcher from THGA examining mine water from an old adit (Photo by THGA).

The goal is to train engineers at the interface of mining, mine surveillance, and geotechnical engineering, enabling them to plan, execute, and direct the complex processes of mine closures, rehabilitation, and aftercare in a leading position. The curriculum allows graduates to analyse mining, geological, and hydrogeological conditions qualitatively and apply scientific methods to express quantitatively, and further process these results using engineering methods.

About the term post-mining
In Germany, the Federal Mining Act, the Bundesberggesetz (BBergG), regulates the mining of minerals such as hard coal, brown coal, ores, salt, and potash. Supervisory authorities are the mining authorities of the federal states. They are in charge of ensuring that mining is operated without threats to people or the environment during all stages of the mining process, i.e., from exploration to post-mining. As a rule, this mining charge ends after closing production with the installation of a final operation schedule where the long-lasting impact of mining is recognised and regulated as far as possible. The mining companies or their legal successors must cover the costs. The mining authority is responsible if danger results from old, desolate and unknown underground work. If the former owner is unknown, the federal state must bear the costs. At this point, a note on the use of the term "post-mining" is helpful: In the German mining industry and science, the term "altbergbau" (mines no longer operating) is traditionally used. Until the end of the 20th century, it was primarily used and understood to define technical rehabilitation and mitigation of risks to public safety after mine closure. Since 2012, the THGA has used the term "post-mining." In a sustainable view of the mining process from exploration to production and closure, the last stage, "post-mining" (Figure 3), represents the longest and most lingering and positively shapeable phase.

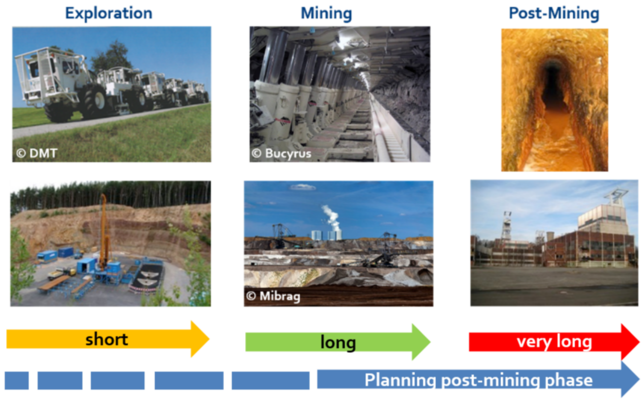

Figure 3. Mine life cycle.

Risk fields and post-mining opportunities

Until the beginning of this century, abandoned mine management has focused on the issue of defending and preventing risks. In the last years, however, the situation in the energy industry has undergone fundamental changes. Some keywords in this context are the finite nature of fossil fuels, global warming, CO_2 emissions, and the risks of nuclear power. Therefore, German politics has made it its mission to achieve a change toward regenerative forms of energy without CO_2 emissions. Solar energy, wind power, and geothermal energy focus on public funding. This move towards renewable energy sources boosted creativity and innovation, which also captured post-mining areas. Because brownfields from mining encompass opportunities to generate renewable energies besides other options for future uses, post-mining management has to incorporate these opportunities, as the sustainable management of the mining areas will have a significant impact on the acceptance of the mining industry. Post-mining offers sustainable options. Mining activities are performed in two ways: opencast mining with visible consequences on the regions and underground mining, where the results will emerge later and less directly. The public only perceives the 'tip of the iceberg' regarding the impact of underground mining as the entire underground infrastructure remains hidden for a considerable period (Kretschmann and Hegemann, 2012). The negative impacts of mining can be enormous. Massive efforts may be necessary to recover from them. This is an essential issue that mining companies must face in the communities, especially when mines are closed. Identifying and handling risks systematically provide a basis for responsible and sustainable mining management. There are no opportunities in mining without risks. They are two sides of the same coin. What principally matters is the successful control and management of post-mining risks and the effective use of the opportunities that arise.

Table I. Impacts of mining - risks, and opportunities

	Impact	Risk	Opportunity
1	Close to surface extractions	Safety, damages	Geologic park
2	Surface openings, shafts	Safety, damages	Methane production, Pump-storage power plant, Heat storage
3	Subsidence, uplift	Waterlogging, damages	Wetland habitats
4	Discontinuous fault	Damages	-
5	Mine gas emission at the surface	Safety	Methane production
6	Surface water	Continuous load of pumping	Wetland habitats, recreation areas
7	Pumping of mine water	Continuous load of pumping	Heat production, algae for CO2 reduction
8	Refuse dumps	Stability	Wind wheels, biomass
9	Operation areas	Ground load	Trade and industry, photovoltaic, culture

Table I shows an overview of risks and opportunities for former mines. The FZN is scientifically investigating such risks and opportunities in detail.

The four pillars of post-mining

Since 2015, the FZN has expanded its activities to a holistic research approach based on four pillars (Figure 4).

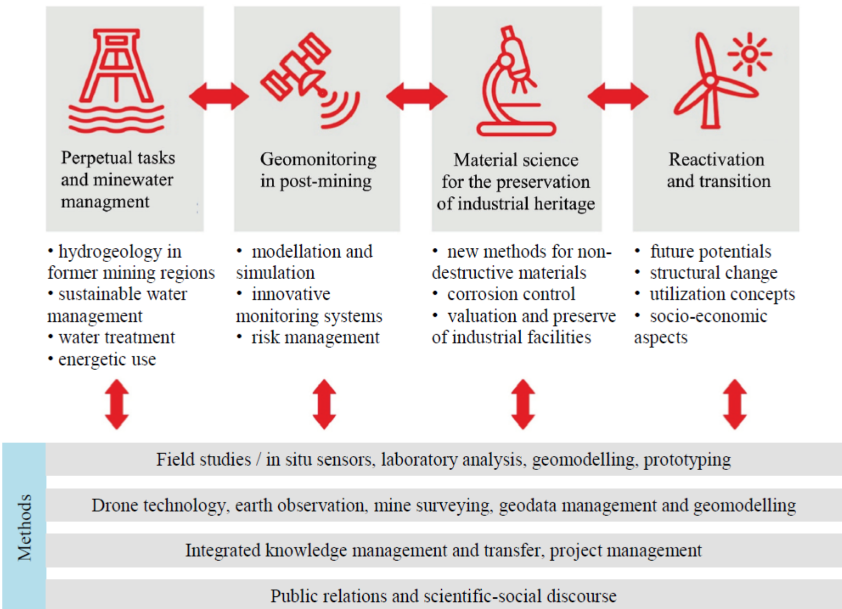

Figure 4. Overview of the FZN's research areas (https://fzn.thga.de/en/forschung/).

- Perpetual tasks and mine water management: Extracting raw materials from open or underground pits has manifold effects on the regional water balance. Closing the pits usually implies subsequent mine water rebound up to the original groundwater level. Within this process, hydrogeological, hydrochemical, and geomechanical changes are associated. The related research activities focus on modelling and monitoring these complex processes and interdependencies. Furthermore, the FZN is developing innovative technologies to tackle the most efficient use of the resource – water – including approaches to convert the mine water's thermal energy into electricity and separation techniques to remedy clean water from mining areas and industrial brownfields.

- Geomonitoring: Intrinsic features of mining processes include significant area coverage and long-lasting operations. At the same time, processes are happening on a smaller scale and with shorter duration - as in the breaking of dams at tailing ponds. The FZN develops technical systems for the holistic monitoring of mining impacts by combining remote sensing, classic sensors, robotics, modelling and/or simulations. Together with partners, we also work on additional data usage concepts – here, the focus is on groundwater management, ground movements, land use, and coverage. Significantly, the reliable monitoring data offered from space is linked to information generated by the satellite-supported ground-based sensors and terrestrial expertise.
- Material science for the preservation of industrial heritage: Mining has left related objects of industrial heritage and culture. The preservation of these requires material-oriented solutions and specifically tailored material handling. Only when the aging processes of the materials have been researched and fully understood can their decay be slowed down or, at best, the object can be preserved. Methods to estimate the durability of materials under specific stress conditions need to be developed. In addition, researchers examine corrosion processes, test preservatives on damaged materials, and analyse to what extent materials can be stabilised and the process of deterioration be reduced. The interests of all stakeholders concerned are considered to ensure successful preservation. The election of the Ruhr region as the cultural capital of Europe in 2010 can serve as a best practice example.
- Reactivation and transition: Sustainable transformation is actively developing a mining region while looking far ahead into the future. It takes long-term enhancements in the region's economic, ecological, and social capabilities into account and considers the long-term consequences. In the post-mining research, the effects of reactivation and transition under socio-economic aspects are crucial for every research project. A significant increase in unemployment has to be avoided, and new jobs must be created, e.g., in the renewable energy sector (Figure 5). Therefore, we analyse the market and innovation potential arising in post-mining regions. These investigations help stakeholders develop strategies, consider innovations, and market the potential.

The research work at FZN

Figure 5. Creating renewable energy, an opportunity for post-mining. (1) Photovoltaic plant on a mud pond; (2) heat from mine water; (3) wind turbine on a dump.

The structure of the FZN outlines the holistic approach and visualises the need for transdisciplinary methods in research. This is described and illustrated by the following examples. The first one deals with the geotechnical and chemical analysis of methane emissions from old coal beds, and the second one with innovative monitoring methods based on satellite-borne sensors. The third example shows aspects of material science to preserve brownfields as a mining heritage, while the last one deals with the reactivation and transition of mining areas.

Effects of mine water rebound on methane emissions from hard coal mines

One of the largest sources of anthropogenic methane (CH_4) emissions is coal mines. This is important since methane is a potent greenhouse gas with a global warming potential up to about 36 times that of CO_2 for a 100-year time horizon. Without comprehensive mine gas extraction, the methane would escape unused into the atmosphere and contribute significantly to global warming. In this respect, the economic utilisation of mine gas for energy generation and understanding the processes taking place are of considerable importance. International experts assume that, despite declining hard coal production, methane released from abandoned mines will continue to increase (Kholod *et al.*, 2020). Consequently, knowledge of the behaviour of methane outgassing during a mine water rise is of great importance (Döppenschmidt *et al.*, 2021). The project explores the relationship between the flooding of hard coal mines and the release of methane-bearing mine gas at the surface. A special focus is on investigating biogenically produced methane and its quantification. A prerequisite is a differentiation between thermogenic and biogenic methane, which is accomplished with the help of the isotopic composition of all hydrocarbon components of the mine gas.

The objectives of the project are:

- Investigation of the long-term outgassing behaviour of methane during mine water rebound.
- Acquisition and evaluation of the potential formation of secondary (biogenic) methane concerning opportunities and risks.
- Spatiotemporal simulation of processes and migration pathways.
- Identification of potentially hazardous areas.

Within the project's scope, mine gas samples are taken at shafts and CHP plants (Protego hood and combined heat and power plants) in the German hard coal deposits (Ruhr and Saar area) and analysed concerning their chemical and isotopic composition. At the same time, a gas database is being set up.

Figure 6. Sampling of mine gas at a Protego hood to sample mine gas and determine the gas composition and concentration (Photo: B. Teichert, THGA).

Multi-sensor geomonitoring for the optimisation of water management in post-mining

The long-lasting coal production in the Ruhr area resulted in vast subsidence troughs at the surface, and the subsidence formed so-called polder areas. These areas need to be dewatered artificially to avoid flooding. The water management for the polder areas considers heavy rainfall as a risk and the possibility of retention as an opportunity. Moreover, the water typically pumped into the next river or creek could be valuable in dry seasons, e.g., for agricultural or forestry use. This research project aims to develop and optimise solutions for sustainable water management. Where the terrain has subsided, the soil moisture has changed. In some places, even new bodies of water have been created. In the Ruhr area, many artificial lakes are to be found. This naturally affects the use of land. Due to climate change, the lower precipitation levels, and increased dry periods, and droughts of recent years have shown that the Ruhr area needs more efficient water use.

In this project, the available historical data will be evaluated with modern satellite data. Various sensors are in operation to record and evaluate soil moisture and water levels, among other things. Drones with suitable cameras to record plant health are used. The on-site information is combined with remote sensing data provided by the European Earth Observation programme Copernicus with its Sentinel satellites. These data consist of radar interferometric and infrared data, multispectral data and photos using seeable light. A multisensorial approach integrates data from satellites and UAV-borne sensors in combination with terrestrial-monitoring equipment and sensors in boreholes. All different information will be fused in a so-called 4D scenario with the factor 'time' as a fourth dimension. This allows for tracking changes in the water balance over the decades, modelling them digitally, and making recommendations for long-term land and resource use under sustainable environmental conditions.

Environmental influences on objects of mining heritage

The FZN is developing technical applications to monitor post-montane objects and activities. In the long term, these applications should be able to digitally simulate possible post-mining processes regarding environmental influences, e.g., due to climate change with extended periods of heat and heavy rainfall, extreme temperature fluctuations, or shrinking of the soils due to prolonged droughts. These effects result in mining brownfield material damages such as cracking, flaking of coatings/protective paints, rust, and lichen/moss growth. They can influence the structural integrity of these - partly monumental – industrial buildings. Questions arise like: (1) How can sensor-borne aerial robots be used to derive knowledge for rapid assessment for material scientists? (2) How should a data fusion of in situ data (e.g., temperature measurement) and optical remote sensing (RGB, thermal IR, multispectral) be performed to derive this knowledge? (3) Can methods be easily automated to offer them to a broad user community?

The first results of preliminary work give answers to these questions. For example, using a thermal sensor, drone flights can detect pitting corrosion and material damage to old buildings like shafts (Figure 7). Detection was successful on a head frame in rust, moss, and lichens overgrowth. In future, the monitoring data will support object-based condition assessments and planning of remediation and preservation measures.

Figure 7. Headframe of shaft 'Pluto': thermal and optical picture.

The project 'Potentials'
The research area reactivation and transition aims to find new uses for former mining regions and sites. It integrates technical and socio-economic aspects. This includes, for example, business opportunities and employment effects in the affected region (Research Center of Post-Mining, 2022a). Such issues are also addressed in the project 'Potentials' launched last year. The project is funded by the EU Research Fund for Coal and Steel. It analyses the business potentials of former coal mines and coal-fired power plants and closely related neighbouring industries to develop transition plans (Research Center of Post-Mining, 2022b). The main goal is to create new purposes for abandoned mine sites by "[…] taking advantage of their joint potential to stimulate new economic activities, developing jobs and economic value in Coal Regions in Transition" (Potentials RFCS AM project, 2022). For the conceptual development, prospective analysis is used to create business models regarding the circular economy, energy storage, and renewable energy as opportunities for former mine sites. This enables efficient use of already existing resources sustainably, and has a major impact on the economic and social development of the entire mining region.

OUTLOOK

Based on its history and extensive dialogue with mining companies, the THGA has planned and implemented its strategy for post-mining research. This includes the master's degree programme geoengineering and post-mining and the establishment of the Post-Mining Research Center (Forschungszentrum Nachbergbau, FZN). Research at FZN addresses challenges like digitalisation, energy and mobility transition, a changing raw materials mix, increasing transparency in the supply chains, the circular economy, and the quest for greater sustainability and stewardship of the earth's resources. Research questions are solved by combining science with practical experience. This approach requires a national and international network of like-minded researchers and academic institutions. The aim is to address and coordinate the various interests of those involved and impacted by mining projects. Of particular importance is the international dialogue and cooperation to bundle the mining universities' expertise and reach the target: "We want to make mining possible, in harmony with the United Nations sustainable development goals."

ACKNOWLEDGMENT

The authors would like to sincerely thank Prof. Dr. Jürgen Brune, Colorado School of Mines, for significantly improving the paper's readability.

REFERENCES

Döppenschmitt, S., Schemmer, F., Melchers, C., Möllerherm, S. 2021. Grubengasnutzung aus stillgelegten Bergwerken an Ruhr und Saar. *Bergbau,* vol. 72, no. 2, pp. 70-71 and p. 74.

Kholod, N., Evans, M., Pilcher, R. C., Roshchanka, V., Ruiz, F., Coté, M., Collings, R. 2020. Global methane emissions from coal mining to continue growing even with declining coal production. *Journal of Cleaner Production*, vol. 256, 120489. https://doi.org/10.1016/j.jclepro.2020.120489

Kretschmann, J., Düppe, S. 2016. Zukunft seit 2016 - 200 Jahre Technische Fachhochschule Georg Agricola. *Mining Report,* vol. 152, no. 2, pp. 105-108.

Kretschmann, J., Hegemann, M. 2012. New changes from old shafts. Risk management in abandoned mine sites in Germany. *Proceedings of the Annual Meeting of the Society for Mining 2012,* Metallurgy & Exploration, Curran Associates, Seattle, Washington, USA. Red Hook, NY, pp. 153-158.

Melchers, C., Westermann, S., Reker, B. 2019. Evaluierung von Grubenwasseranstiegsprozessen – im Ruhrgebiet, Saarland, in Ibbenbüren sowie weiteren deutschen Steinkohlenrevieren und dem angrenzenden europäischen Ausland. Projektbericht. (Berichte zum Nachbergbau 1). Selbstverlag des Deutschen Bergbau-Museums Bochum, Bochum. https://doi.org/10.48771/43qw-vp33

Potentials RFCS AM project 2022. Potentials Project focuses on… https://potentialsproject.eu/ [accessed 26 April 2022]

Research Center of Post-Mining. 2022a. Our research focuses. https://fzn.thga.de/en/forschung/ [accessed 26 April 2022]

Research Center of Post-Mining. 2022b. Project POTENTIALS, online: https://fzn.thga.de/en/forschung/potentials/ [accessed 26 April 2022]

United Nations. 2015. The 17 Goals. https://sdgs.un.org/goals [accessed 05 May 2022]

Dr. Jürgen Kretschmann

President
TH Georg Agricola University, Bochum, Germany

1980-1985 Business and Management Studies at the Universities in Aachen, Bochum, Dortmund, Degree: Dipl. Kaufmann (equivalent to MBA)

1986-1989 Doctorate at the Georg-August University of Gottingen, Department of Economics, Degree: Dr. rer. pol.

1994-1998 Habilitation at the RWTH Aachen, Department of Mining, Metallurgy and Geosciences, Degree: Privatdozent

Since 2005 External Professor at RWThl Aachen University

2006-2022 Chairman of the Management Board of DMT-Lehre und Bildung GmbH and President of the TH Georg Agricola University, Bochum, Germany