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Invisible Mining: Addressing EU Raw Material Challenges Through Technological Innovation

This paper examines the challenges in implementing the EU's raw materials policy, including conflicts between minerals extraction, Green Deal objectives, nature restoration targets and public opposition to mining projects. It explores innovative approaches such as invisible mining, enabled by advancements in robotics and miniaturisation, comprehensive and integrated resource recovery principles and materials-as-a-service business models, which can minimise environmental impacts and enhance social acceptability. The paper argues that successful implementation of the EU's Critical Raw Materials Act requires a multifaceted approach, building on technological advances and encompassing policy harmonisation, socio-economic innovation and skills development. By adopting this comprehensive strategy, the EU can create a more sustainable and socially responsible mining industry, addressing the immediate need for critical raw materials while positioning itself as a global leader in responsible mining.

Policy initiatives such as the EU Green Deal (European Commission, 2019) and Net-Zero Industry Act (European Union, 2024a) are driving increased demand for mineral raw materials as the economy transitions to renewable energy systems (Michaux, 2021; IEA, 2023).

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The shift in energy policy has increased demand for previously underutilised resources, including rare earth elements, as well as "conventional" commodities such as copper, nickel, cobalt (IAE, 2022) and lithium (IAE, 2021). Additionally, the shift has heightened the need for metals and metalloids, including gallium, germanium, selenium, indium and tellurium, which are often only obtained as by-products during the extraction of primary commodities and have low recycling rates, further complicating their supply chain and availability (CSIRO, 2023).

Moreover, in accordance with the EU Green Deal and the Circular Economy Action Plan (European Commission, 2020), these raw materials must be obtained by EU industries with full respect for human rights and compliance with social and environmental standards. This presents a complex dilemma: importing minerals from outside the EU may raise ethical issues, while sourcing within the EU often faces local resistance (Tost et al., 2021).

Enabling the energy transition and addressing critical raw material supply challenges

The EU's policy on critical raw materials (CRM) is now principally expressed through the Critical Raw Materials Act (CRMA), a regulation that defines strategic raw materials, prescribes benchmarks for their domestic

production, processing and recycling, and introduces a CRM club of like-minded countries (European Union, 2024b). It was prepared with a view to address the EU's heavy reliance on imports, often from a single third country, and to mitigate strategic dependencies.

China not only produces the lion's share of such minerals, but also controls a significant portion of global processing capacity (European Commission, 2023). If the EU can access certain resources from a wider variety of countries, as well as develop its own EU domestic resources, it could partly resolve its supply problem by also (re-)establishing processing capacity within Europe.

The CRMA aims to create secure and resilient EU CRM supply chains, reduce administrative burdens and simplify permitting procedures for critical raw materials projects in the EU. The Act recognises the need for comprehensive reform in the EU's approach to CRM management, addressing issues such as, among others, outdated knowledge of CRM occurrences and inadequate legislation on waste management. Consequently, the CRMA has four main objectives:

- strengthening the different stages of the European CRM value chain
- diversifying EU imports of CRM to reduce strategic dependencies
- improving the EU capacity to monitor and mitigate current and future risks of disruptions to CRM supply
- ensuring the free movement of CRM within the Single Market while maintaining a high level of environmental protection by improving their circularity and sustainability.

A key aspect of the CRMA is the designation of strategic projects, which will benefit from support for access to finance and fast-tracked permitting procedures (15 months for processing or recycling permits and 27 months for extraction permits).

The CRMA significantly affects the role of European National Geological Survey Organisations, requiring them to work closely with governments on CRM exploration programmes (Hollis et al., 2023).

Additionally, due to the focus on expediting and streamlining permitting procedures, member states' competent authorities will need to reconsider their existing procedures and processes to align with the CRMA objectives and in many cases to rebuild their capabilities.

Conflicts in the EU's raw materials policy implementation

The EU's mineral raw materials legislation is complex, fragmented and at times contradictory, potentially hampering the attainment of the goals and benchmarks defined in the CRMA. This complexity is exemplified by:

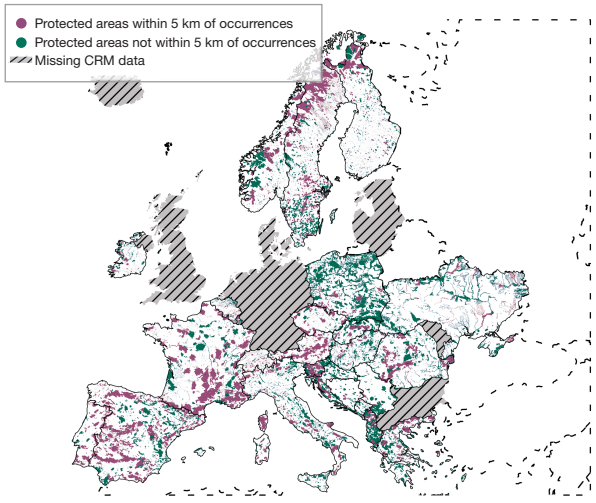
- spatial planning and land-use decisions being made at local or regional levels in member states, with territorial management remaining a member state prerogative (Barnes & Berne, in press)
- the requirements of EU nature protection regulations, such as the Nature Restoration Law of June 2024.

The latter demands the restoration of at least 20% of the EU's land and sea areas by 2030 and all ecosystems in need of restoration by 2050 (European Commission, 2024). This benchmark is aligned with the EU Biodiversity Strategy for 2030 (European Commission, 2022), which includes the target of having at least 10% of the EU's land and sea areas under strict protection. These regulations would limit the availability of land for mining activities, as extractive projects will likely face stricter environmental assessments, and areas designated for restoration may be off-limits for mining projects.

However, the locations of mining operations are intrinsically linked to the geographical distribution of mineral deposits. In the EU, this factor presents unique challenges due to the region's high population density and the prevalence of protected areas. The overlap between potential mining sites and these protected areas creates a complex landscape for resource extraction within the EU (Figure 1). Moreover, there is a growing push to expand EU environmentally protected areas (Araújo & Alagador, 2024), and most protected areas prohibit mining activities (Falck & Correia, 2023), further complicating the EU's efforts to source raw materials domestically.

Mineral extraction within the EU operates under more rigorous regulations compared to most other countries globally. This, coupled with shorter and more secure supply lines to EU end users, offers distinct advantages, including enhanced economic resilience and a reduced carbon footprint associated with raw material sourcing. Nevertheless, many citizens across the EU continue to harbour strong reservations about mining activities, and despite the potential benefits, public opposition to extraction projects remains a significant hurdle (Tost et al., 2021).

Figure 1
Protected areas and known critical raw materials occurrences in Europe



Note: The analysis shows that more than 80% of critical raw materials (CRM) deposits are located in the vicinity (less than 5 km) or inside environmentally protected areas.

Sources: Map of European protected sites, European Environment Agency, April 2023 and EGDI/MIN4EU Map of critical raw materials occurrence points, 2023.

Correia et al. (2024) identify two primary reasons for opposition to mining projects: the fear of change and the negative image of mining shaped by historical practices and their environmental and social impacts. This negative perception stems partly from many mining companies' historically cavalier attitudes towards environmental concerns and their lack of respect for local communities. The fear of change is, *inter alia*, rooted in scepticism about scientific assurances that domestic CRM extraction is the optimal strategy to combat climate change. This reveals a significant disconnect between EU policymakers and local populations, as well as other stakeholders, regarding the most effective approaches to achieve the EU's Green Deal objectives. The situation also presents a dilemma for environmental NGOs, who support the transition away from fossil fuels but grapple with its consequences (Nature Reviews Materials, 2021).

The complexity of this issue is best exemplified by the public opposition to Rio Tinto's Jadar lithium project in Serbia, which stands as the most striking illustration of a multifaceted conflict surrounding a mining project in Europe (Stuehlen & Anderl, 2024). The resistance movement targeted Rio Tinto, the Serbian government and the EU, questioning the legitimacy of external actors dictating local behaviour. The protests became deeply intertwined with national politics, with Rio Tinto symbolising broader government-led expropriation driven by foreign capital.

Such rhetoric against what are perceived as EU impositions and global companies resonates strongly with populist movements and aligns with growing nationalist ideologies across Europe. The discourse capitalises on local grievances and fears, framing EU policies and multinational corporations as threats to national sovereignty, cultural identity and economic self-determination. This narrative typically portrays the EU as a distant, bureaucratic entity imposing its will on member states, while global companies are depicted as exploitative forces prioritising profits over local interests. This is a perspective that neatly dovetails into broader trends of Euroscepticism and anti-globalisation sentiment (Correia et al., 2024), ultimately undermining the CRMA implementation and impeding the EU's energy transition efforts.

The resulting tension between EU-level objectives and local concerns inevitably leads to increased opposition to mining projects, often seen as embodiments of the broader conflict between global ambitions and local interests, but most importantly showing a disconnect between the use of materials in society and their production.

The situation is further complicated by the EU's aim to maintain current living standards while moving towards a greener economy, a goal that requires increased resource extraction in the short to medium term. The apparent contradiction – needing more raw materials to achieve environmental goals – provides additional ammunition for those opposing mining projects.

This paradox brought into focus the narrative of "sufficiency", which pits the growth-based capitalist economic model against one that supplies only sufficient energy, materials and services to the people (Princen, 2005). However, it remains unclear who would have the right, and by what justification, to determine what is "sufficient" for individuals or societies as a whole.

The promise of low-visibility mining

It is undeniable that all human activities, mining included, have some degree of impact on the environment. However, advancements in modern mining technology and improvements in governance practices have shown that these effects and their long-term consequences can be

Table 1
Examples of EU-funded research projects advancing automation and robotics applied to mining

Programme/Year	Project acronym (Name)/ Coordinator	Funding received (in million euros)	Outcomes
FP7/2011-2016	I2Mine (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future)/LKAB	~25.9	This project marked the start of EU-funded research activities into the concept of an invisible, zero-impact mine. It investigated autonomous, highly selective mineral extraction processes and machinery based on new sensor technologies as well as innovative concepts for mass flow management and transportation.
H2020/2016-2019	Unexmin (Autonomous Underwater Explorer for Flooded Mines)/University of Miskolc	~4.8	Prototype of autonomous robotic equipment to explore (abandoned) flooded mines, equipped with advanced navigation and sensing capabilities. It utilises sonar, LIDAR, and machine vision systems for precise underwater navigation and obstacle avoidance. The robot employs non-invasive methods such as multi-spectral imaging and acoustic sensors for 3D mine mapping and gathering geological and mineralogical information.
H2020/2017-2020	SIMS (Sustainable Intelligent Mining Systems)/ Epiroc	~16	5G connectivity and sensors to enhance the automation of underground machines, mine-ready autonomous aerial platforms that can navigate along tunnels and a robotised loading machine for underground applications.
H2020/2019-2023	Robominers (Resilient Bio-inspired Modular Robotic Miners)/Madrid Polytechnic University	~7.4	Prototype of a modular, bio-inspired robot-miner designed for small and difficult-to-access mineral deposits, incorporating artificial intelligence for autonomous operation. It features advanced capabilities in navigation, perception, excavation, material transport and in-line material analysis, utilising machine learning algorithms for adaptive decision-making and optimised performance in varied mining environments.
H2020/2020-2024	illuMINEation (Bright concepts for a safe and sustainable digital mining future)/Leoben University	~8.8	Multi-level distributed industrial internet of things platform based on large sensor networks featuring wireless communication capabilities.
			Advanced user interfaces, dashboards and Augmented Reality. Virtual Reality applications.
Horizon Euope/2024-2026	Persephone (Autonomous Exploration and Extraction of Deep Mineral Deposits)/ Lulea University	~5	Autonomous drilling machines with reduced size and advanced perception capabilities, employing machine learning algorithms for adaptive navigation, precise face drilling and efficient core extraction. Full digitalisation of mining processes through digital twins, leveraging predictive analytics and reinforcement learning algorithms to optimise operations.

Source: ACORDIS - EU research results.

significantly reduced. The mining sector has made substantial progress in developing methods and implementing strategies to mitigate its environmental footprint, balancing the need for resource extraction with responsible stewardship of the natural environment (Luodes et al., 2024).

Analyses of existing mining projects in environmentally sensitive areas reveal a correlation between mining methods and the level of public opposition (Dunlap & Riquito, 2023; BBC News, 2022; Dilthey, 2018). Projects operating without obvious levels of public opposition are typically underground mining operations. These are more efficient at reducing or eliminating negative impacts on surface ecosystems, whether in designated nature protection sites or in areas used for other sensitive purposes, such as public recreation or animal husbandry (Luodes et al., 2024).

The increasing demand for raw materials is driving mining companies to exploit smaller deposits and excavate at greater depths. To address these challenges and foster sustainable development in the industry, a key focus is on developing and deploying innovative technologies (Buchholz et al., 2022). Such technologies aim to enable resource-efficient extraction of mineral raw materials and facilitate near-mine exploration of critical resources in currently unexploited ore bodies within existing or abandoned mines.

European researchers are harnessing converging technologies in robotics, miniaturisation and cost-efficient drilling to advance low-impact, low-visibility underground mining, a concept first promoted in the 7th Framework Programme (FP7), the EU's research funding programme between 2007 and 2013. Recent EU-funded projects have built upon this foundation, each contributing to significant advancements in the field (Table 1).

The adoption of mining robots with a reduced size is set to trigger a transformation in the mining industry. Unlike current equipment, which is designed to accommodate

human operators, these robots will operate in narrow drifts, where their compact size will allow for smaller diameter galleries with less need for geotechnical support, and the absence of humans will eliminate the need for ventilation and drainage. This innovative mining ecosystem will minimise the extraction of waste rock and non-mineralised areas, while maximising the recovery from higher-grade zones. Consequently, this approach promises to significantly enhance efficiency and reduce the environmental impact of mining. In addition, this breakthrough would enable mining at greater depths, encompassing both small and large mineral deposits.

Such developments will stimulate research and innovation in scalability, resilience, reconfigurability, collective behaviour and operation of robots in challenging environments, alongside ore metallurgy and closed-loop processing systems. The integration of these technologies and the robotisation of underground mining facilitates the creation of "invisible mines" (Correia et al., 2021). Invisible mines have the potential to lessen the environmental impacts and surface footprint of mining operations due to a reduced need for extractive waste management sites, thus increasing the prospect for social and regulatory acceptance of mining.

These innovative approaches point to a future in which mining can coexist more harmoniously with local communities and environments. They represent a significant step towards low-impact resource extraction, aligning with the EU's goals for responsible mining practices and technological innovation in the raw materials sector. The success of the invisible mine concept could potentially revolutionise public perception of mining activities and pave the way for more widespread acceptance of responsible resource extraction in sensitive areas.

Rethinking economic feasibility in modern mining

Despite efforts to minimise the environmental impact and footprint of mines and increase societal acceptance of mining, traditional economic reasoning continues to underpin feasibility studies. As a result, many minerals are either not extracted or are deemed waste and discarded. However, advancements in mining and ore processing methods designed to optimise robotic mining are poised to bring about a fundamental shift in conventional business models.

The extraction and maximisation of value from all materials will intensify interactions in downstream industries, necessitating a change in standard feasibility assessments. This shift demands the development of business models capable of delivering comprehensive analyses that integrate a variety of different value streams. This approach serves multiple purposes: preserving potentially important mineral raw material sources from becoming inaccessible due to previous mining works avoiding technical difficulties and safety risks of re-entering and re-mining an area, and conserving energy by moving material only once before multiple extraction steps. This aligns with the UN's call for "comprehensive and integrated resource recovery" proposed by Hilton et al. (2018). This paradigm assumes that a mine site should be disturbed only once, aiming to recover useful materials through an optimised integrated flowsheet and to future-proof resources that are not of immediate interest, rather than discarding them as waste. When a viable market exists for a constituent mineral or metal, comprehensive extraction becomes a logical business decision, consistent with recent sustainable development recommendations.

While traditional economic feasibility studies often lead to neglecting minerals that are not immediately profitable, new holistic business models are emerging (Xerri, 2023). These consider the long-term value of all materials present in a deposit, including those that may become valuable in the future. To make such decisions economically attractive, external incentives might be needed, such as tax credits for contributing to strategic autonomy, tradeable CO_2 credits for avoiding additional mining energy expenditure, direct subsidies for stockpiling minerals or government purchases of strategic materials.

The CRMA already discusses such possibilities. Speculative stockpiling, supported by technology foresight studies, could be considered a societal investment funded by governments. However, it would require rethinking current legislation, namely the Extractive Waste Directive (European Parliament and Council of the European Union, 2006), to permit extended stockpiling periods and facilitate the return of designated extractive waste to value chains.

Another crucial step to consider in feasibility analyses is progress towards a circular economy, namely through closing resource loops (Geissdoerfer et al., 2018), which enables the convergence of mining and recycling activities (Rizos & Righetti, 2023). Some authors have advanced "materials as a service" business models, where suppliers no longer sell mineral raw materials or semi-finished parts outright to manufacturers (Zeeuw van der Laan & Aurisicchio, 2019; Al-Aomar & Alshraideh, 2019). Instead, they offer manufacturers temporary access to these materials, and once the products made from these materials reach the end of their useful life, the suppli-

ers recover them. This approach, which is fully aligned with circular economy principles, would create shorter resource loops while maximising resource efficiency and minimising waste generation. It fundamentally changes the traditional mining business model from a linear extract-sell-dispose system to a circular extract-lease-recover-reuse cycle. Mining companies would transform from being mere extractors to becoming long-term material stewards.

The concept of materials as a service in the context of mining and resource management represents a paradigm shift that pushes resource efficiency. By maintaining ownership of the materials, suppliers have a vested interest in designing for longevity, repairability and recyclability. This could drive innovation in material science and product design, leading to more durable and easily recyclable products.

Moreover, this model could stabilise revenue streams for mining companies, as they would receive ongoing payments for material use rather than one-time sales, mitigating cyclicity and market volatility in mineral raw material prices. Additionally, incentivising the recovery and reuse of materials would significantly reduce the need for new mining activities, thereby decreasing environmental impacts associated with extraction.

Transforming the mining industry

The adoption of comprehensive and integrated resource recovery combined with materials-as-a-service business models can be driven by progress in four key areas: technological advances; business models; raw materials policies; and skills, education and knowledge. These areas, individually or in combination, play a crucial role in transforming the mining industry.

Modern mining operations are increasingly adopting autonomous and robotic systems, such as those developed in EU-funded research projects like Robominers and Persephone (see Table 1 for details). These innovations enable more precise and efficient extraction, minimising waste and environmental impacts. Advanced sensing technologies and real-time data analytics allow miners to accurately identify and extract valuable minerals from complex ore bodies, while equipment miniaturisation permits access to previously uneconomic or unreachable deposits. Improvements in processing technologies facilitate the recovery of a wider range of minerals from a single ore body, aligning with the principle of comprehensive resource recovery. To fully realise the potential of these advancements and support materials-as-a-service business models, sophisticated tracking and inventory systems need to be developed. Such systems should enhance supply chain transparency and traceability while also enabling the long-term monitoring of materials throughout their lifecycle. This integration of cutting-edge extraction techniques with advanced material tracking systems creates a synergy that addresses both the technological challenges of comprehensive resource recovery and the logistical demands of closing resource loops.

By integrating advanced data analytics and predictive modelling, novel business models can optimise resource extraction and processing across entire value chains, encompassing material ownership, liability and end-of-life product management. They more accurately factor in environmental and societal costs, aligning the provision of raw materials with sustainability goals. Furthermore, these comprehensive approaches facilitate partnerships across industries, creating new value streams and markets for previously overlooked minerals and materials. Consequently, a shift towards more comprehensive and forward-thinking business models is essential for maximising the value of mineral resources while minimising waste and environmental impact.

Governments would need to adapt regulations to support the implementation of comprehensive and integrated resource recovery and materials-as-a-service business models, potentially including incentives for companies adopting circular practices and penalties for those adhering to linear models. This would require new legal frameworks for dealing with conflicts between surface land use planning and underground uses (Hámor-Vidó et al., 2021), materials ownership, liability and end-of-life product management. The benefits for nations dealing with resource scarcity are obvious, as this approach could reshape global trade patterns in raw materials, potentially reducing dependency on primary resource-rich countries and empowering nations with advanced recycling capabilities.

The creation of invisible mines, coupled with materials-as-a-service business models, will shift the skills and competencies of the mining workforce towards more advanced cognitive domains. This shift will increase requirements in areas such as robotics, data science, environmental management and advanced materials processing. Educational institutions, professional organisations and mining companies will need to work together to adopt new qualification frameworks and develop curricula and training programmes that blend traditional mining knowledge with cutting-edge technologies and sustainability practices. Besides, there is a growing emphasis on interdisciplinary skills, as mod-

ern mining requires professionals who can understand and integrate aspects of geology, engineering, materials processing, environmental and social sciences, as well as business management. Consequently, the industry is also placing greater importance on soft skills, such as stakeholder engagement and communication, recognising the need to build positive relationships with local communities and regulatory bodies. Regulatory bodies will also need to develop a complementary skill set that goes beyond traditional environmental and mining permitting.

Conclusions

The EU faces the complex challenge of securing a sustainable supply of critical raw materials while adhering to its environmental and societal commitments. The CRMA represents a significant step towards addressing this challenge, but its implementation is fraught with obstacles rooted in the EU's complex governance structure, environmental protection mandates and public opposition to mining activities.

The concept of invisible mines, enabled by technological advancements in robotics, miniaturisation and data analytics, offers a promising solution to many of the concerns associated with traditional mining practices. By minimising surface disturbance and environmental impact, these innovative mining methods could potentially increase public acceptance of mining activities within the EU.

However, the transition to a new mining paradigm requires a fundamental shift in approach, embracing comprehensive and integrated resource recovery principles and materials-as-a-service business models. This transformation hinges on innovative business strategies, supportive policies, and the development of new skills. Such a multifaceted approach necessitates collaboration between industry, government, educational institutions and civil society.

Ultimately, the EU must strike a delicate balance between meeting its raw material needs and respecting environmental and societal concerns. By bolstering support for robotics research and innovation, the EU can secure a leading position in mining technology. This commitment, combined with transparent communication and stakeholder engagement, will enhance mining efficiency and safety while minimising environmental impacts, enabling the EU to emerge as a global leader in sustainable, technologically advanced mining solutions and set new industry standards worldwide.

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