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Critical and Strategic Raw Materials and Mining Technologies in the European Regions

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ABSTRACT

Under the ongoing technological paradigm shift, mineral resources have become essential inputs for emerging industries and technologies. As technological change accelerates, demand for some materials that once played a marginal role (e.g., lithium, graphite, or dysprosium), and for base metals already used in large volumes (e.g., copper and nickel), is expected to increase dramatically by 2050. The scale and speed of global demand growth have raised serious concerns about the ability of economic systems to respond timely and to overcome constraints and vulnerabilities along the entire raw-materials supply chain.

In this context, technological progress in mining plays a crucial role. Innovation in extraction methods, automation, digital monitoring systems, and advanced processing technologies are becoming essential to improve productivity, expand economically viable reserves, and reduce operational and environmental constraints - especially where profitable mineral resources are scarce, and extraction and processing costs are high. Technological solutions adopted by mining firms differ substantially across stages and applications, often involving a high level of technical sophistication. They range from airborne and drone-based survey systems with high-precision GPS and advanced sensors for geological mapping, to remotely operated robots and autonomous driving vehicles, smart safety equipment and collaborative cloud platforms, to mechanical drilling systems for rock and soil penetration, and to bioleaching and other chemical and magnetic separation processes used to isolate valuable minerals from waste material.

However, over the last decades, the European Union's response to these technological, productive, and geopolitical challenges has been slow and inconsistent, somehow moving in the opposite direction to major competitors, and positioning itself as a late follower in revitalising a sector that has undergone major technological and productive transformations elsewhere in the world. Using PATSTAT to capture patent trends over time, this divergence is visible both at the beginning of the millennium, when global mining patents intensified while Europe's relative position started to weaken, and after 2015 and the Paris Agreement, when European mining patenting activity shows a marked downturn and global activity continues to expand. The share of patents attributable to European actors (applicants) starts to decline

after 2006 and continues to fall in the following years. In 2006, Europe accounted for around 39% of these patents; by 2021, its share had dropped to about 1%. It should also be noted that, from the early 2000s, the share of mining patent technologies increased steadily up to 2014, before shifting to a negative trend from 2015, bringing the share in 2021 back to pre-2000 levels. Over the last period, the absolute number of mining patents filed in Europe also declined, with an average decrease of about 15.5% per year, whereas worldwide the trend was the opposite, with mining patents increasing by an average of about 9.24% per year.

With recent initiatives such as the Critical Raw Materials Act (CRMA), under the umbrella of the Open Strategic Autonomy (OSA), the EU has shown a regained interest in the sector. At the same time, the strategy appears more focused on attracting business investment to expand domestic supply than on rebuilding the upstream capabilities needed for primary raw-material extraction and production in a more sustainable fashion. The geography of mining technologies and the factors driving their development remain largely understudied at the European level, preventing a clear understanding of how the strategies can foster innovation and support the EU's potential to expand and diversify the supply of Strategic and Critical Raw Materials (SCRMs). To further complicate the picture, it remains unclear how the intensity and structure of mining sector activities support the local conditions under which technology suppliers can develop and scale up mining innovations. Relatedly, the technological progress in the mining sector tends to be largely supplier-driven, originating from specialised equipment manufacturers and service providers, rather than developed in-house by mining companies.

In this paper we analyse the determinants of the development in mining technologies, considering them across distinct technological subcategories and adopting a geographical perspective on European regions. We rely on WIPO classification of mining technologies, and we use PATSTAT (2024) to map nine mining technology subclasses: Exploration, Blasting, Mining (Operational), Transport, Automation, Environmental, Processing, Metallurgy, and Refining across European regions between 2000-2021. Considering different subclasses makes it possible to capture, in a more granular way, which stage of the supply chain a given technology affects. Especially in the production of critical mineral commodities, the bottlenecks do not stem only from the presence or discovery of profitable mineral deposits; but they often emerge at the processing and refining stages, and environmental constraints may prevent—or make less profitable—both the processing and the extraction of certain minerals. Operational difficulties for a mining firm can arise already at the exploration stage. In fact, even the granting of extraction permits is conditional on exploratory studies that must demonstrate the project's economic viability and sustainability in line with local regulations. Moreover, extractive activities are generally subject to royalty payments, as well as additional environmental taxes and charges that vary across regulatory regimes. And even after completing all these steps, mining projects often face long pre-production periods before reaching full operational capacity, implying large upfront expenditures and returns that are typically realized only over the long term.

Using econometric techniques, we rely on a knowledge production function augmented with mining specialization and mining sector intensity indicator (built from Eurostat and Orbis Europe data) to investigate the relationship between these determinants and granted mining patents per capita as a proxy for innovation. Estimates are performed using panel regressions with fixed effects, and we also employ Poisson Pseudo Maximum Likelihood (PPML) to properly handle the large share of zero outcomes. Our

preliminary results suggest that comparative advantages in mining, and mining firms concentration, strengthens the local conditions under which mining technologies are generated in the case of mining operational technologies, which are potentially less scalable and more tightly connected to the specific territories in which extraction takes place. However, when we move from mine-site (ground-based) technologies toward processing, automation, environmental, and transport technological sub-class, this effect attenuates and often disappears. Results hold after controlling for standard regional covariates on innovation capacity and development, including R&D intensity, GDP per capita, and human capital.

These patterns carry direct implications for the EU's policy agenda. A substantial part of the innovation in mining appears to emerge where extraction activity is located: however, this effect weakens or disappears as we move toward more transversal technologies. Some domains seem less dependent on proximity to the ore source and more tied to general industrial and technological ecosystems, which can also develop far from extracting areas. Therefore, policies aimed at revitalizing extraction and strengthening strategic autonomy in critical and non-critical raw materials should, beyond leveraging local mining capabilities, also support and stimulate innovation along the mining supply chain, knowledge infrastructure, and specialized competences and industrial networks.